JUL 28 1961

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NAA-SR-6303

TRW REPORT No. ER-4443

THE SNAP II POWER CONVERSION SYSTEM

TOPICAL REPORT No. 11

ORBITAL FORCE FIELD BOILING AND CONDENSING EXPERIMENT

AEC RESEARCH AND DEVELOPMENT REPORT

PREPARED UNDER SUBCONTRACT
N 843 FS - 101221 FOR ATOMICS
INTERNATIONAL, A DIVISION OF
NORTH AMERICAN AVIATION, INC.

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

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PROJECT

512-208252-08

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CONDENSING EXPERIMENT
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Prepared under Subcontract N843FS-101221 for Atomics International,
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DATE

Prepared: 15 January 1960
Published: 15 March 1961

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0868

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ABSTRACT

This report provides the basis for a program to investigate the characteristics of Rankine space power plants in the zero gravity aspect of the environment of space. It justifies the need for this work by presenting the expected effects on Rankine space power plants. Discussions of experimental techniques for studying these phenomena show that this information can be obtained rapidly and economically.

Recommendations for a program to supplement SNAP II and similar Rankine space power development efforts in this vital area are made, and consist of: 1) the development and testing of a small system that adequately simulates a complete Rankine system, first in zero gravity and finally, in the complete orbital environment; followed by, 2) the development and similar testing of a complete Rankine system using SNAP II hardware.

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1.0 INTRODUCTION

The studies described in this report have been performed in order to evaluate the various systems and methods which can be used to experimentally determine zero gravity effects on boiling and condensing phenomena. These studies have also been performed to predict the effects of zero gravity, and of other aspects of the space environment, upon the operation of a complete mercury Rankine power system. The present report will allow a logical choice to be made of a system for performing Orbital Force Field Boiling and Condensing Experiments. Justification for the expense involved in conducting such experiments is also provided.

The Orbital Force Field Boiling and Condensing Experiments which are proposed and recommended in this report will allow complete proof of the feasibility of using the Rankine method of power conversion in a zero gravity environment to be made. These experiments will also provide a rapid and economical means for obtaining performance data on Rankine system components and economical means in order to optimize their designs. The experiments that are recommended will make a direct and specific contribution to the SNAP II development program and will establish a basis for design of larger Rankine cycle space power systems.

Personnel from New Devices Laboratories of the Tapco Group, Thompson Ramo Wooldridge Inc., have prepared this report under Contract Number N 843-FS-101221, Change No. 11, from Atomics International, Division of North American Aviation. This work is being performed for the United States Atomic Energy Commission, under prime contract Number AT (11-1)-GEN-8.

2.0 PURPOSE OF OFFBACE

The primary purpose of the Orbital Force Field Boiling and Condensing Experiment will be to obtain experimental verification, under actual gravitationless conditions, of the condenser and boiler design principles of the SNAP systems. There is at this time, however, very little doubt as to the fundamental feasibility of these design principles. Additional analyses, which have been performed during these Orbital Experiment Planning studies, and evaluation of ground tests and limited zero gravity tests of boilers and condensers, which have recently been conducted, have given complete assurance that the condensers and boilers will function reliably in zero gravity conditions.

As a consequence of this increased assurance of the fundamental feasibility of the condensing and boiling principles, the planning for the OFFBACE program has begun to place emphasis on obtaining detailed boiler and condenser design data to aid in the optimization of these components. Emphasis has also been placed on the importance of operating complete systems in zero gravity to obtain detailed information on component interrelationships.

In view of the above considerations, the purpose of the OFFBACE program is as follows:

1. Investigate condenser and boiler dynamics and heat transfer in zero gravity conditions.
2. Investigate component interrelationships, particularly the condenser-centrifugal pump, in zero gravity conditions.

The OFFBACE program has the immediate purpose of contributing to the SNAP II development. The evaluation program that has been conducted, however, has also clearly shown that OFFBACE is of major importance, in its own right, since it will be a major factor contributing to the development of Rankine cycle space power.

Commercial Rankine cycle power plants using either water or mercury as a working fluid have well-known operational capabilities, but their design and operation are dependent upon the static earthbound environment. Rankine power plants for space use must be modified to operate in an environment completely free from both an atmosphere and an orienting force field. A space Rankine engine must reject all waste heat by radiation rather than convection. Moreover, in the space Rankine system shaft bearing loads will result only from unbalance since the rotating element will be weightless, no buoyant forces will separate the liquid and gaseous phases of the working fluid, and pressure forces due to a vertical column of fluid will be nonexistent.

A fair idea of the space environment and a knowledge of the behavior of Rankine systems on the ground permit valid extrapolations of ground Rankine data into the orbital environment. However, since any extrapolation involves sufficient unknowns to require that it be done conservatively, a system designed in this manner would not be optimum. Extrapolations of ground data to new environments of the upper atmosphere and beyond are, also, not always reliable, as illustrated by the fact that extrapolated ground level performance of rocket engines has been found by test to be at considerable variance with the high altitude performance and this factor is thought to be the cause of several failures or the subnormal performance of certain missile and space probes.

High reliability and low weight and volume are prime considerations in the design of space power systems. To meet these criteria the designer must have valid and complete information concerning the intended environment and the effect of that environment on the space Rankine power system. Obtaining an optimum design is now hampered by the lack of means to duplicate completely or even partially the intended environment. The use of test apparatus described in this report combined with vehicles capable of simulating or duplicating the orbital environment will permit the rapid acquisition of the information needed to pursue successfully and economically, the several Rankine space power development programs so vital to the national interest.

The Orbital Force Field Boiling and Condensing Experiment will study the effects of the zero gravity environment upon Rankine space power systems to provide:

1. Complete proof of operational feasibility of Rankine space power systems.
2. Actual operating data to assist in optimizing the design of Rankine space power systems.

The information obtained will be of immediate value to all Rankine space power development programs.

3.0 THE RANKINE SYSTEM IN SPACE

Throughout history, man's progress has been directly dependent upon the power available to him. This will remain true as man enters the new environment of space. Capability to explore and use the space outside of our atmosphere waits upon the development of power – power for communications and reconnaissance satellites and power to propel space vehicles. Space power systems based upon the Rankine cycle give every indication that they will meet the rigorous requirements imposed by the space environment. To degrees not before seen, however, the power plant in space must have the virtues of low weight, small size, long unattended life, and the utmost reliability. To attain these characteristics, subjected to the space environment, will require extensive analysis and experiment.

The Rankine cycle method of converting heat energy into electrical energy has long been the world's largest supplier of electricity. Nearly all large power producing stations, burning a wide variety of fuels to provide thermal energy, use Rankine engines to convert this energy to a more usable form.

This is accomplished by using the thermal energy to convert a fluid from its liquid form to vapor within a boiler. This high temperature, high pressure, vapor passes through a turbine which extracts energy from it. The turbine shaft energy is used to drive an alternator to develop electrical energy. The unusable heat, contained in the low pressure and temperature vapors leaving the turbine, is removed in a radiator-condenser and the fluid is changed into liquid form once again. This condensate then enters a pump which returns it to the boiler to begin the cycle once again.

It is seen that a Rankine type power plant is made up of four major components: 1) boiler, 2) turboalternator, 3) condenser, and 4) pump. The design of these components and their integration into a system is based heavily upon the type of service required of them and the environment they will be subjected to. It is to be expected then, that these components and the resulting system designed to meet the rigorous requirements for space power plants will differ considerably from their earthbound counterparts.

One obvious difference is that of rejecting the unusable heat from the system. In the absolute vacuum of space the usual convective cooling of the condenser is impossible, requiring that all heat be transferred from the system by radiation. Thus, a radiator is required. This component makes one other aspect of the space environment important – that of meteoric particles. Possible damage to the radiator and methods for protecting it from the hazards caused by this space debris become important considerations.

Another significant difference between ground and space Rankine systems is that of

zero gravity. Rankine systems on earth depend heavily on gravity. Forces due to gravity are responsible for maintenance of the stable liquid regions in the boiler and condenser required for satisfactory system operation. In space, these forces are absent, and new techniques must be devised to assure stable operation.

It is the purpose of this section to describe the Rankine system phenomena affected by zero gravity. The significant phenomena occurring in each component of the Rankine space power system, notably, the boiler, condenser, turbomachinery package and the overall system, will be discussed. Immediately prior to these discussions, however, a brief description of the acceleration environment that such a power supply will be subjected to will be presented.

3.1 Acceleration Environment of a Rankine Space Power System

The aspects of the orbital environment that particularly affect a Rankine system are 1) zero gravity, 2) vehicle-caused accelerations, 3) meteoric particles, 4) absence of atmosphere, 5) incident solar radiation, and 6) other cosmic and nuclear radiation. OFFBACE has as its primary purpose the study of the effects of the acceleration environment - particularly zero gravity - upon the operation of the Rankine system.

Zero Gravity

A major requirement for space power plants is that they should be able to function in the so-called "zero gravity" condition. This condition is variously referred to as "weightlessness", "free fall", "zero force field", etc. This is the condition which a non-rotating system would experience if it were located in a field free space, that is a zero force field, remote from the attraction of any gravitational mass. It is also the condition of a system which is freely falling, or accelerating, in response to the net force of gravity acting upon it and which is, furthermore, not influenced by any other external force acting upon it, except this force due to the gravitational attraction upon its own mass. Since all particles which compose the system are accelerating equally, in response to gravitational attraction, the normal buoyant or hydrostatic forces do not exist. Separation of liquid and vapor phases by density difference and maintenance of liquid-vapor interfaces requires special techniques.

Following the D'Alembert technique for problem solving, the zero gravity condition may also be thought of as the condition where the gravitational forces are balanced by the "inertia forces" due to radial or centripetal accelerations.

The above discussion is not meant to provide a rigorous definition of terms. It has been presented, however, since clarification is needed for the concept of "zero gravity" and for procedures for obtaining this condition. In this report the various terms describing "zero gravity" will be used interchangeably.

The condition of "zero gravity" may be obtained by any procedure which allows a body to fall freely, eliminating or counterbalancing all externally applied forces. This may be accomplished by a number of techniques, including the following:

1. A straight fall in a vacuum.
2. An aircraft following a free fall or Keplerian trajectory.
3. A satellite in a circular or elliptic orbit, above the atmosphere.
4. A missile following a ballistic trajectory above the atmosphere.

Vehicle-Caused Accelerations

A satellite in orbit is in the zero gravity state since its mass center is falling freely in response to the force of gravity. It is possible, however, for regions within the satellite to be experiencing appreciable accelerations. This will occur if the satellite has an angular velocity about its center of mass, that is, if it is spinning or tumbling.

The acceleration at any point within the satellite is then determined by the rate of spin and its distance from the satellite's center of mass. Figure 3.1-1 shows the amount of radial acceleration compared to "one g" acceleration ($32.2 \text{ ft per sec}^2$) resulting from such rotation. For slow rates of spin, even at relatively large radii, the resulting accelerations are low.

The operation of a Rankine system mounted within a vehicle that is rotating about its axis could be aided or degraded. Properly oriented, the radial accelerations would make the system experience an acceleration environment more similar to that on earth. If the resulting radial acceleration produced negative accelerations with respect to the Rankine system, successful operation of the system might be impossible unless it were designed for such a case.

In addition to meeting the requirement of long-term operation in the orbital environment, the Rankine cycle power system must withstand the environment associated with the transient conditions of vehicle launch and orbital injection. The particular environment caused by the satellite being boosted into orbit is of special concern to the designer of this type of power conversion device.

The linear accelerations experienced during launch and orbital injection are in the order of 6 to 10 g's, usually coupled with lateral accelerations due to wind loads, vectoring of the rocket motor, etc., which are usually in the order of less than 2 g's. The above-mentioned linear accelerations are for the boost phase of large satellites. For orbital

FIGURE 3.1-1

Injection phases of the trajectory, depending heavily upon the mass of the satellite and the thrust of the final stage, linear accelerations as high as 20 g's could be experienced, but normally are about the same magnitude as boost accelerations. A typical acceleration versus time curve for the Scout satellite vehicle is found in Figure 5.1-1 of Section 5.0. Figure 3.1-2 shows a typical, large, liquid propellant booster acceleration versus time curve for comparison with the Scout's solid propellant thrust-time characteristics.

For Rankine systems that will operate through this launch transient, one aspect should be emphasized. If the booster rocket burns out while the vehicle is still within the earth's atmosphere, and if the upper stage rockets do not fire immediately, the aerodynamic drag during this coasting period will result in a negative longitudinal acceleration. This characteristic is shown by the Scout acceleration schedule (Figure 5.1-1). Depending upon its magnitude, this negative acceleration could be harmful to the operation of the Rankine system or could compromise its design. However, the boosters normally employed to place the large satellite vehicles capable of utilizing Rankine systems into orbit continue to provide thrust while the vehicle is within the denser portions of the atmosphere.

A further factor which must be considered is the effect of the sudden changes in acceleration which occur at burnout. As later discussed, it is expected that sudden changes in vehicle thrust will be capable of affecting the condenser and pump fluid dynamics.

3.2 Boiler

In recent years, and even more so in recent months, great strides have been made in the development of mathematical models which describe the heat transfer mechanism in the nucleate and film boiling regimes. In all of these new analyses and theories gravity plays an important role. The development of zero gravity models requires judicious extension of these available theories and analyses as well as new techniques for experimental verification. The design of zero gravity boilers poses design problems not normally encountered in conventional boiler design. In particular, the boiler designer must become aware of the proper design variables at his control for holding the demarcation zones between the liquid preheating and boiling sections and between the boiling and superheating sections. In a gravity environment this is accomplished with relative ease, whereas in zero gravity, the problem is more difficult. Fluid dynamics of flow regimes, hydrodynamic stability, heat transfer, and inventory become important considerations.

Generally, four distinct types of boiling phenomena are recognized and are distinguished by their respective heat transfer mechanisms. These boiling domains and the effect of a zero gravity environment on them are discussed below.

ACCELERATION HISTORY TYPICAL OF LARGE LIQUID-PROPELLANT SATELLITE BOOSTERS

FIGURE 3.1-2

Forced or Natural Convection Boiling

When boiling occurs in this manner, heat is added to the liquid phase at the heat transfer surface through the medium of convection. The liquid is superheated slightly above saturation temperature and then evaporates at an interface between the liquid and vapor phases. The heat transfer coefficient in this region can be computed by conventional means. The equations are relatively independent of gravity forces since inertia and viscous forces play the predominant roles in transferring the heat.

The basic design considerations for zero gravity become the definition of the flow regime, the interface or demarcation between the two phases and the stability thereof. Basic fluid dynamics, including hydrodynamic wave stability analyses, are required with the gravity term omitted from the equations. If the flow regions prove to be unstable and the flow goes, for example, from stratified to slug flow, pressure disturbances due to thermodynamic as well as dynamic effects will occur. In addition, slugs of liquid may pass completely through the boiling section without completely evaporating. Both of the above occurrences could prove of considerable consequence to the power plant system served by the boiler section.

To predict flow types from principles of fluid dynamics is difficult and efforts along these lines are in the pioneering stage. Theoretical considerations along these lines include hydrodynamic wave stability analyses, a difficult aspect of fluid mechanics. To predict the flow regime in a gravity-free field, the gravity term must be omitted from the dynamic-wave equations and the stability must be analyzed.

Nucleate Boiling Region

In this region the bubble dynamics and its effect on the liquid become important. Since most of the heat is transferred from the wall to the liquid—not to the bubble—the high heat transfer coefficients are attributed to the agitation of the liquid by the bubbles. The various types of nucleate boiling mechanisms are:

1. Micro-convection in the sublayer. The bubble activity causes random micro-convection in the laminar sublayer.
2. The bubbles produce an apparent surface roughness. In this phenomenon the apparent increase in surface roughness increases both pressure drop and heat transfer.
3. Latent heat transport by bubbles. This theory fails to explain the high heat transfer rates observed in boiling.
4. Vapor-liquid exchange action. This mechanism is the most satisfactory.

When nucleate boiling occurs, the bubbles grow and detach or collapse on the surface depending on whether the liquid is saturated or subcooled. This high frequency pumping action pumps large quantities of hot liquid from the heated surface into the bulk of the fluid. The fluid which is "pumped" from the surface is replaced by cooler bulk fluid. This convective type heat transfer is much more effective than the transport of heat by either molecules (conduction) or eddies (conventional convection). This microscopic transfer of fluid by "bubble pumping" also transports momentum if the bulk fluid has velocity. This accounts for the higher pressure drops encountered in boiling two-phase flow compared to single phase forced convection. This was noted by Sieder and Mulligan who found that

$$C_F = 2 C_H$$

where C_H is a dimensionless heat transfer number and C_F is the friction coefficient. This is a sort of "Reynolds Analogy" in nucleate boiling.

Mathematical analysis of bubble dynamics has resulted in some very useful equations for computing the nucleate boiling heat transfer coefficient for pool boiling. They are the Forster-Zuber equation and a generalized correlation of S. Levy. Both of these equations, however, are based on bubble dynamics involving surface tension and buoyant or gravity forces. To apply these equations to a gravity-free environment will involve an extension of the bubble dynamics. These dynamics include the inertia forces of the bulk fluid when in forced convection. The inertia forces will now replace the gravity forces in causing bubble detachment and the corresponding "pumping" action which results in high heat transfer coefficients. Obtaining basic data on nucleate boiling heat transfer coefficients is of major importance for attempting a correlation on this basis.

Partial Film and Film Boiling Region

In this region the bubble population becomes so dense that a vapor blanket forms on the heating surface. This vapor blanket is unstable in partial film boiling and stable in film boiling. This phenomenon is susceptible to hydrodynamic wave theory in which stability plays an important role in establishing the stable or unstable interfacial boundary between the vapor and liquid phases.

Gravity-Free Boiling and the Use of Induced Force Fields

Forced-convection boiling will be utilized to a great extent in Rankine space power systems. The following section discusses some of the fluid mechanics of this phenomenon. The procedures for creating force fields by means of swirl devices, as a means of improving film stability and heat flux, are also partially analyzed.

The gravity-free boiling mechanism is a difficult problem to analyze. Since there always exists a boundary layer in a flowing real fluid, regions approaching zero inertial forces (at wall) must be contended with in any dynamic analysis of nucleation with zero pressure gradients. This brings up the possibility of a very thin stable vapor blanket on the heating surface, which is, of course, referred to as film boiling. In the last few years, great strides have been made in the application of hydrodynamic stability theory to heat transfer. In addition, much has been published on the hydrodynamic stability of two fluid flows in relative motion. The heat transfer coefficient with a stable vapor film will be determined by its thickness. If Couette flow is assumed in the vapor film the heat transfer coefficient will be

$$h = \frac{k}{\delta_v} \quad (1)$$

where k is the vapor conductivity
 δ_v = thickness of stable vapor film

The heat transferred along the surface by the film is ignored in this equation. In addition, radiation is also ignored; however, indications are that it may be important. If stability were not present, the vapor surface film would grow until it reached the center of the tube and the evaporation process completed. However, due to disturbances produced by fluid turbulence and vibrations of the boundaries, the vapor film can only build up to a certain thickness and then it becomes unstable. Vapor bubbles or slugs would then be torn from the vapor-liquid interface and mixed with the liquid phase. The thickness of the vapor film, which will determine the heat transfer coefficient, is difficult to predict by hydrodynamic stability theory. (This is one of the most difficult and complicated subjects in fluid mechanics.)

There are some equations available which can be used to compute the film thickness. These equations, in most cases, have yet to be verified by experiment. One equation is

$$m \rho_L (u_L - c)^2 \coth m \delta_L + m \rho_v (u_v - c)^2 \coth m \delta_v = g (\rho_L - \rho_v) + \sigma m^2 \quad (2)$$

$$m = \frac{2\pi}{\lambda} \quad (\lambda = \text{wavelength of disturbance})$$

c = wave propagation velocity

σ = surface tension

δ = phase layer thickness

ρ = density

u = velocity

subscript L = Liquid

v = Vapor

This equation can be used to investigate the conditions under which a wave of small elevation can be propagated at the interface. The condition for stability is that c^2 shall be positive, so that c is real. In zero gravity the term $g (\rho_L - \rho_V)$ is zero and capillarity and inertia become primary factors in stability. If viscous forces are important, which may be the case, this equation should be replaced by one containing viscosity terms. If c is made equal to zero—the borderline condition between stability and instability—and solved for δ_V , the heat transfer coefficient can be found from equation 1. If no real value for c exists for any value of δ_V and the conditions substituted into equation 2, then the inertial vapor film will be unstable (referred to as partial film boiling). This may be undesirable for various reasons, namely:

1. Undesirable pressure fluctuations due to slugging, etc.
2. Alternate quenching and heating of surface which could produce fatigue cracks.

This is, of course, speculative and comprehensive analysis and experimentation should be conducted for verification.

Artificial "gravity" forces could be produced in a tube containing boiling mercury in zero gravity by inducing a vortex type flow by spiral inserts. The rotation of the fluid will force the liquid phase to the heating surface and the vapor phase to the center. The radial pressure gradient built up in the liquid phase replaces the hydrostatic pressure in a gravity field.

The buoyant force acting on a submerged object such as a bubble in a liquid is the difference between the bubble weight and the sum of the surface forces summed up in the direction of the weight, namely,

$$\int P_y dA - \int \rho g dV = F_b \quad (3)$$

where P - pressure
 A - surface area
 V - volume
 ρ - density
 g - acceleration due to gravity
 F_b - resultant buoyant force

Sketch A

In other words, the buoyant force is the difference between the surface force of the control volume and the body forces. Applying this to the phenomena of bubble detachment in nucleate boiling, the buoyant force is equated to the surface tension, namely

$$\int P dA_y - \int \rho g dV - \int \sigma \sin \theta ds = F_y \quad (4)$$

where σ = surface tension
 θ = contact angle
 s = common line contact between solid surface, liquid and vapor phases
 F_y = resultant force

Sketch B

Note the surface integral (Sketch B) involves both the interfacial surface area between liquid and vapor and heating surface.

If F_y is zero, the bubble will be held to the surface, and if $F_y > \text{zero}$, the bubble will detach from the surface and accelerate.

In a gravity field, if the liquid pressure P acting on the control volume of Sketches A and B varies in the y direction due to gravity only, the P is said to vary hydrostatically, that is, due to the weight of the liquid. This is expressed as

$$\frac{dP}{dy} = \rho g \quad (5)$$

If the force of gravity acts in the y direction. It is this variation in pressure with y which can make the surface integral of Equation 4 greater than the sum of the volume and line integrals resulting in detachment. The correlation for the diameter of a bubble as it leaves the surface is written in the form

$$D_b = C_d \theta \sqrt{\frac{2 \sigma}{g (\rho_L - \rho_V)}} \quad (6)$$

where D_b is the bubble diameter and C_d is a coefficient. Equation 6 is a solution of Equation 4 for $F_y = \text{zero}$ and for a gravity field in which Equation 5 applies. Bubble detachment was observed during nucleate boiling from a heated surface facing down. Here each integral in Equation 4 should give a force toward the surface thus preventing detachment. This phenomenon should be studied more thoroughly.

In order to maintain high heat transfer coefficients in zero gravity nucleate boiling, bubble detachment with its effective stirring action must be induced by establishing a liquid pressure gradient in the direction in which the bubble is to be accelerated. Thus, the sum of the pressure forces around the bubble can be such as to break the bubble from the surface. Rotating a fluid will produce a radial pressure gradient due to acceleration, and this phenomenon can be utilized in nucleate boiling in a zero gravity environment. Assume a rotating saturated liquid being heated by the walls of a tube as in Sketch C. The vapor phase will occupy the inner portion of the tube. If the radial pressure difference is balanced by the centrifugal force, we can write

$$2 \pi r \left[(P + dP) - P \right] = 2 \pi \rho U_T^2 dr \quad (7)$$

where mass of element of unit length = $2 \pi \rho r dr$

acceleration of the layer = U_T^2/r

centrifugal force acting on the layer = $2 \pi \rho U_T^2 dr$

U_T = tangential velocity

Sketch C

Equation 7 becomes

$$\frac{dp}{dr} = \rho \frac{U_T^2}{r} \quad (8)$$

Equation 8 can be evaluated for the pressure gradient which would then replace the pressure gradient defined by Equation 5 for a gravity field. To do this the type of velocity profile from the vapor-liquid interface to the wall must be determined. If a free vortex (irrotational flow) is assumed we have

$$U_T r = \text{constant} \quad (9)$$

If a forced vortex is assumed we have

$$U_T = \text{constant} \quad r \quad (10)$$

A combination of the two types of vortex motion could also be assumed. This would require some research into the field of Hilsch or Raugue tubes in which the fluid mechanics of various types of vortices are covered.

Equation 5 indicates that a hydrostatic pressure gradient exists undiminished even in the boundary layer of a fluid, whereas Equation 8 shows that dp/dr decreases with U_t as would be the case in the low velocity regions of the boundary layer. In fact, the pressure gradient at the wall, when U_t is zero, is also zero, that is

$$\left(\frac{dp}{dr} \right)_{r=0} = 0 \quad \text{since } U_T = 0 \text{ at } r = r_o$$

If the flow outside the boundary layer is assumed irrotational, Equation 8 and Equation 9 can be combined to give

$$\frac{dP}{dr} = \rho \frac{\text{const}^2}{r^3} \quad (11)$$

which indicates the pressure gradient varies inversely as the cube of the radius. A plot of pressure versus radius might appear as shown in Sketch D.

Sketch D

In a gravity field where a hydrostatic pressure variation exists (see Equation 5) a plot of pressure versus distance would appear as shown in Sketch E.

Sketch E

It would appear that the problem of detaching vapor bubbles from a surface might be more difficult in a centrifugal field (Sketch D) and that bubbles would grow larger in size before detachment; that is, the bubbles should be large enough to extend beyond the boundary

layer into a region of pressure gradient. In addition, the inertia or drag force exerted by fluid velocity outside the boundary layer would aid in sweeping the bubbles from the surface. It may be that the pressure drop and velocities required to maintain reasonable pressure gradients near the heating surface, thin boundary layers, and substantial "sweeping" velocities might be prohibitive in a practical boiler design. This, of course, must be determined by detailed analysis and experiment.

If a rotating layer of liquid is to be maintained around a core of vapor, the liquid layer must be stable, otherwise slugging and other forms of instability may occur. The presence of a liquid velocity of rotation and high axial vapor velocities in the core of a flow passage may induce high interfacial shear stress resulting in atomization of the liquid. To prevent this, the Weber number must be held within specified limits. Values for the Weber number near one are recommended for the stable liquid film.

In addition, the viscous forces in a liquid film will damp out disturbances of all wavelengths and frequency if the film Reynold's number is held near 1.5. If the interface between liquid and vapor is destroyed and "fog" or mist flow is produced, then pressure gradients will be reduced according to Equation 11 because the density decreases. This may reduce the strength of the centrifugal force field, but the high moisture velocities may provide enough "scrubbing" action with bubbles on the heating surface to keep the heat transfer coefficient high. Bubbles should form on the heating surface even in "fog" flow since there should always be a thin stable liquid film near the wall wherein the velocities are low.

3.3 Condenser

Condensers of earthbound Rankine power plants make heavy use of gravity. It is gravity that separates liquid from vapor, collects it and provides the head required by the condensate pump. Complete absence of this force in space requires significant innovation in the design of condensers for Rankine space power plants. To do this requires detailed analyses and experimentation in the realms of fluid dynamics of flow regimes, hydrodynamic stability, and heat transfer.

In a condenser operating in the absence of gravity the condensing mechanism must be understood and the problems defined before a solution can be obtained.

Consider the process occurring in a condenser tube. Vapor enters the tube and it flows along the tube which is being cooled by radiation. The vapor that contacts the cool tube surface is condensed. The liquid is formed on the walls of the tube and is moved along the condenser length by the drag of the vapor on the liquid and the pressure gradient in the tube. The mass flow rate of vapor decreases and the mass flow rate of the liquid increases along the length of the condenser tube. The point is reached where all of the vapor is condensed and the liquid completely fills the tube. At this point the condenser ends and the subcooling section begins. In the subcooler the initially saturated

liquid is cooled as it flows to the pump to provide a net positive suction head.

In the condenser the two-phase flow, liquid and vapor, presents the main problem in zero gravity. The liquid is partially in contact with the tube wall and has a free liquid surface in contact with the vapor.

The presence of a free liquid surface (not in contact with a solid boundary) makes two phase in zero gravity flow very sensitive to disturbances. Vibration from machinery, fluid turbulence and meteoric impacts could all cause instabilities between liquid and vapor interfaces. The interacting dynamics of liquid and vapor phases flowing together through passages determine in what form the two phases will co-exist. Some of the possible flow forms or flow regimes are (1) vapor bubbles dispersed within a liquid; (2) liquid droplets dispersed within the vapor (fog or mist); and (3) stratified flow in which the liquid and vapor are separated by a continuous interface. Stratified flow can be classified according to the type of interface present: (a) smooth interface; (b) interface with capillary or gravity waves; or (c) interface with intermittent slugs of liquid filling up the flow passage.

These various flow regimes require different inventories of liquid and vapor; and for a fixed inventory system (total fluid mass in condenser and subcooler) this means that if any external disturbances produce the onset of a new flow regime the heat transfer area relationship between the subcooler and condenser could be altered. This is illustrated in Figure 3.3-1 in which the mass of liquid required to form a slug comes from the subcooler liquid mass which results in a decrease in subcooler area.

This phenomenon not only causes pressure fluctuations due to the dynamics of the moving liquid slug, but also causes thermodynamic pressure changes, due to the variations in equilibrium condensing temperature with interchanges between condenser and subcooler heat transfer area. The magnitude of the pressure pulses are a function of the size of the slugs which in turn depend on the passage dimensions. In a condenser operating at low pressure levels, these pressure disturbances may be a relatively large fraction of the absolute pressure which may result in erratic system operation. If the absolute pressure in the condenser is high, then pressure fluctuations approach small perturbations and thus become negligible.

Thus, we find that the problems associated with a condenser operating in the absence of body forces are primarily fluid mechanics problems. We can separate these problems into the general two-phase flow problem and the interfacial stability problem although they are certainly related. The two-phase flow problem involves flow regime, inventory, and pressure drop determination. Interfacial stability cannot be pursued until the type of interface is determined from the study of flow regimes and inventory.

STRATIFIED FLOW

SLUG FLOW

FIGURE 3.3-1

Many experimenters have qualitatively described various types of two-phase flow regimes. When two-phase flow patterns were visually observed, it was found that the flow regimes depended on the relative amount of flow of each phase and the attitude of the passage with respect to the direction of gravity. After the initial cataloging of flow patterns, attempts were made to correlate the flow regimes; however, at this time no general correlation using dimensionless flow parameters is available. This lack of understanding poses a difficult problem in the design of a condenser for a Rankine space power system. For example, no accurate computation can be made for pressure drop without first knowing the flow regime that will prevail.

After many observations experimenters have had encouraging results in attempting to correlate two-phase flow pressure drop data. Since most of these data were obtained using a non-condensable gas-liquid, further attempts were made to obtain correlations when using single component fluids undergoing a change of phase, i.e., boiling and condensing. Here the results have been less favorable because of the difficulty in predicting the exact flow conditions at every point in a condenser tube. However, the application of the fluid mechanics of liquid films and drops can provide the necessary information to predict the flow patterns and energy exchange mechanisms between the liquid and vapor phases in a condenser tube. The fluid mechanics of liquid drops is covered in the technology of sprays and atomization and an insight into the mechanics of liquid drops being transported by a vapor stream can be gotten from the theoretical and experimental results of sediment transport in a fluid. Experimentation in the mechanics of film cooling has resulted in some useful parameters predicting the stability of liquid films, which has application to a condenser containing a fluid which wets the condenser walls.

The fluid mechanics of a condenser is a complex problem. The existing theories and results for two-phase flow at one g must be tested and modified for the actual conditions of an orbital environment.

At the New Devices Laboratories of Thompson Ramo Wooldridge, the fluid mechanics of mercury vapor condensing in glass tubes and of mercury and gas flowing adiabatically in glass tubes has been investigated both analytically and experimentally. The large volume ratio of vapor to liquid associated with liquid metals tends to force the flow regime into one in which the liquid forms the discontinuous phase and the vapor forms the continuous phase. This flow pattern was encountered for the two-phase flow of mercury, as shown in Figure 3.3-2 (a). The destabilizing effect of the vapor velocity and the high surface tension of non-wetting liquid mercury forced the continuous liquid film to break up into droplets dispersed in a vapor phase. When condensing, the liquid droplets grew on the surface to a critical size, were swept away by the flowing vapor, and impinged on the liquid-vapor interface which forms the beginning of the liquid subcooler.

A - LIQUID DROPLETS DISPERSED IN VAPOR
DURING CONDENSATION OF MERCURY.

B - STRATIFIED FLOW RESULTING FROM
STABLE LIQUID FILM.

FIGURE 3.3-2

The effect of wetting agents, which might possibly produce a flow regime in which a thin, tenacious liquid film is made to cling to the surface as in Figure 3.3-2 (b), has not yet been investigated.

Pressure drop equations based on such considerations as drop size, drop population, and drop stability, as affected by surface tension and vapor drag or pressure forces, have been derived and are being compared with the experimental data.

Accurate pressure drop data is of prime importance for a space radiator design. The designer will attempt to design for maximum allowable pressure drop in the condenser. This will result in a condenser with the tubes occupying a very small percentage of the radiating area. Since only the condenser tubes need be shielded from possible meteorite puncture, a minimum amount of shielding will be required. Thus, a lightweight system results.

In analyzing test data, the following equation was applied to the flow regime of liquid droplets dispersed in vapor:

$$dP_{TP} \frac{\pi D^2}{4} = N \frac{\pi}{4} D^2 C_d \frac{\pi d^2}{4} \rho_g \frac{U_r^2}{2g} dx + \tau_w \pi D dx$$

where

dP_{TP} - two-phase pressure drop

D - tube diameter

C_d - coefficient of drag on droplets

N - number of droplets per cubic foot

ρ_g - gas density

d - drop diameter

U_r - relative velocity of gas with respect to drop

x - distance along tube

τ_w - wall shear stress

This equation shows that the two-phase pressure drop is the sum of the shear stress on the vapor and the drag on the drops.

In order for this equation to be applicable, two other equations were formulated for determining the unknowns, N , d , and U_r . One equation was experimentally determined by measuring the critical drop diameter and the corresponding gas velocity at which the liquid droplet was entrained into the gas. The other equation involved the interfacial stability between the liquid and gas. A relationship between the external drag forces and the surface tension forces was assumed, which is, in effect, applying the Weber number as a stability criterion.

Measurement of pressure drops for the mercury condensing in glass tubes revealed ΔP 's from two to five times those predicted by this equation. It is felt that because the test apparatus was under one g , the condensate drops were of much larger diameter than those that would be present if the experiment would have been performed in zero gravity. These large condensate drops caused an increase in drag on the vapor and consequently resulted in a higher pressure drop. This significant discrepancy points up the need for performing these types of tests in zero gravity.

It can readily be visualized that if a conventional earthbound condenser were turned upside down, the condensate in the "hot well" would be dumped into the vapor inlet. Similarly, a glass of water will spill its contents although sufficient barometric pressure exists to support a 34 foot column of water. Instability and wave formation at the interface between the liquid and gas are the major factors breaking the liquid phase into drops and ligaments during spilling.

When a liquid interface, such as that shown in Figure 3.3-3 is placed in a zero gravity environment, it may be exposed to 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". For example, zero gravity tests made on large diameter containers of liquid aboard the C-131 B at Wright Field showed that the disintegration of the interface was caused by engine vibration.

Instabilities such as these have been analyzed in texts on classical fluid mechanics by Rayleigh, Helmholtz, Lamb, and others. A simple experiment involving mercury in a tapered glass tube demonstrates this phenomenon. When a tapered tube is inverted, as in Figure 3.3-3, the interface is unstable to all disturbances, and the mercury will spill unless a diameter is used which can support a stable interface, as in Figure 3.3-3 (b). If the glass is struck so sharply that disturbances of wavelength greater than the diameter are imposed on the surface, further spillage will occur as shown in Figure 3.3-3 (c).

Consideration of interfacial stability criteria results in the prediction that wave type instabilities may be avoided if small passage diameters are used. Experimental data of two-phase flow with a range of tube diameters is needed to verify this prediction.

SIMPLE EXPERIMENT ILLUSTRATING INTERFACIAL INSTABILITY

A

Tapered Tube Filled With Liquid

B

Tapered Tube Inverted.
(Unstable Interface Drops
Excess Liquid. Stable In-
terface is Obtained When
Tube is Filled to Proper
Diameter.)

C

External Disturbance Causing
Further Instability.

FIGURE 3.3-3

To apply interfacial stability equations to a prototype space condenser the effect of temperature and stainless steel on surface tension must be taken into account. In addition, a value for g must be estimated based on a knowledge of the type of disturbance (machinery vibration, launch accelerations, meteoric impacts) that may be encountered in an orbital environment. Obtaining data on this effect is a fundamental reason why condenser testing in zero-gravity is required.

Preliminary tests have been conducted at TRW to determine the effect of vibration, interfacial pressure, surface tension, and diameter on the stability and the cohesive capability of a mercury column. These and other tests have indicated that a tapered tube may be a desirable configuration to test in a satellite vehicle for the flow passages of a condenser operating under zero gravity conditions. Vapor velocities can be held constant along the tube, large drop size was observed near the interface where the velocities are low, and small drop size at the vapor inlet where the velocities are high. Slugging or erratic drop movement was observed near the interface when negative $-g$ forces were imposed on these relatively large drops in the low-velocity vapor. Small droplets kept small by a tapered tube reduce mercury inventory and smooth the flow. The small diameter of the liquid interface tends to produce stability. In addition, minimum probability of meteoric impact and minimum tube weight are obtained by tapering.

If a wetting fluid is used in a condenser tube with low vapor velocity, the appearance of the liquid-vapor interface will be as shown in Figure 3.3-2 (b). This problem, of the liquid retaining its shape in zero gravity with disturbances, becomes more complex since the destabilizing effect of the vapor shear stress is involved whereas for the flow form of Figure 3.3-2 (a) this is not the case.

This brief discussion has indicated that while a great deal can be accomplished by laboratory testing coupled with mathematical analyses, the most fruitful method for studying zero gravity condensing phenomena is by testing in that environment.

3.4 Turbomachinery

The design of the turbomachinery package of a Rankine system for use in space presents its designer with many interesting problems. Satisfactorily solving problems arising from the various facets of the space environment, however, can be achieved by judicious selection of materials and design techniques. This section discusses the special problems that arise in the design of the turbomachinery components of a Rankine space power system with emphasis on the zero gravity aspect of the environment. It will also be shown how the design of these components is influenced if the Rankine system must be operating through the launch transient.

A typical turbomachinery unit for a Rankine space system is shown in Figure 3.4-1. This is the unit being developed for the SNAP II power conversion system and consists of four major components mounted on the same shaft: the mercury vapor turbine; the alternator; on the turbine end, the reactor coolant pump; and on the alternator end, the mercury

SNAP II TURBOMACHINERY PACKAGE

pump. This shaft is supported by mercury lubricated journal and thrust bearings. This unit is probably typical of the type of turbomachinery units that will be developed in succeeding years to provide for the increased power requirements of space and satellite vehicles.

In the design of these units, as well as utilizing materials proved to be compatible with the environment present, the designer must keep the zero gravity condition continually in mind. If the Rankine system is to be started on the ground and must run through the launch transient, then not only zero gravity but the effects of large positive accelerations must be seriously considered. How the accelerations to which the unit is subjected affect its design are summarized below.

1. Bearings

The design of hydrodynamic or hydrostatic shaft bearings for operation in zero gravity presents two design considerations for the designer. The first is that there is no gravity force available to collect and channel the lubricant discharge from the bearings. There would be no assurance that the discharging lubricant would reach the bearing drain, or have enough pressure head to overcome pipe friction in the return lines.

It is important that the lubricant discharge not build up around the high speed shaft or enter the labyrinth seal areas of the shaft to avoid viscous drag on the shaft. A device that will convert the kinetic energy of the lubricant discharging from the bearing into pressure head is needed. A collecting annulus with a diffusing section or jet pump can perform this function.

The other aspect of bearing performance is that the shaft becomes "weightless". Generally, overall performance should be negligibly changed by this, since, at least for hydrodynamic type of bearings, viscous and pressure forces are large compared to gravitational forces. However, one factor may be important when going from one gravity to zero gravity operation - the bearings may become unstable. By this is meant that the shaft may enter into the phenomena known as whirl, which is usually not severe enough to cause bearing contact. If experimentation by operating a turbomachinery unit in zero gravity shows that whirl manifests itself, and is objectionable enough to require elimination, several techniques are available to accomplish this.

A journal bearing can be modified by changing the bearing design (specially grooved, lobed, etc.), reducing the clearance ratio or viscosity, or changing the support to provide damping.

Although the hydrosphere type bearing has not been extensively tested for stability, it is expected that the small running clearance will allow it to be inherently stable. If the Rankine power system is to be started on the ground and operated through the launch transient, the requirements of the load carrying capacities of the bearings are increased. They must withstand the added radial loads due to the shaft mass under linear acceleration. The return of the spent lubricant to the subcooler is also a problem, in this case due to hydrostatic heads, since there is the problem of keeping the turbine and alternator cavities completely free of liquid.

Depending on the type of particular layout of the Rankine system, the turbine design may have to include considerations for the launch transient. The vapor exhausting from most turbines has a degree of wetness to it and may have to rise vertically to the condenser inlet. If turbine exhaust vapor velocities are kept high enough to assure that liquid particles are swept along with the vapor even during the launch transient, the pressure drop from turbine exhaust to condenser inlet may reduce the available energy that the turbine could extract from the working fluid.

2. Pump

The operation of a centrifugal pump of the type shown in Figure 3.5-1 should present no problems regardless if the pump is operating in zero gravity or a high positive acceleration environment, as long as it is supplied with the inlet conditions that it requires. These inlet conditions, however, are significantly affected by the acceleration environment. When the Rankine system is in zero gravity, the net positive suction head required by the pump must be provided by the combination of condenser pressure and the amount of subcooling of the liquid. Both of these factors, in turn, depend upon the heat transfer characteristics of the condenser-radiator; therefore, any change in the heat rejection rate will affect the pump. Of course, pumps can readily be tested on the ground under a wide range of inlet conditions such that a level of confidence can be established for a particular pump design. One effect, however, that perhaps cannot be investigated adequately on the ground is the effect of a suddenly changing pump inlet condition. If the Rankine system must be operating through the launch acceleration, the pressure at the pump inlet would undergo a significant change upon rocket motor burnout, due to the sudden loss of hydrostatic head. The pressure level would change, from a value consisting of the condenser pressure plus the hydrostatic head above the pump to a value of the condenser pressure only. This problem can be partially studied on the ground but a complete duplication of the conditions just described is required for a high level of confidence.

As was mentioned earlier, the Rankine system operating through the launch transient could be subjected to cooling of the radiator surface. Since the condenser pressure is determined by the radiator temperature, booster burnout at a time of low radiator temperature could result in cavitation of the pump and subsequent system shutdown. These effects should be investigated for a system which must function during launch.

3.5 Overall Rankine System

The four preceding paragraphs have dealt with the major components of the Rankine space power system. This paragraph will present some general considerations of the entire system.

All Rankine space power systems must operate for long durations with no maintenance; the plumbing of such systems, therefore, has rigorous requirements. It must not permit leakage of any surrounding atmosphere into the system or of the working fluids out of the system. This connotes that a system be essentially a hermetically sealed one. While not a major factor, it will be desirable to operate an OFFBACE system in the high vacuum of space to verify that no loss of working fluid occurs due to pinhole leaks or diffusion through metals.

It is also necessary to eliminate air, and, in general, non-condensable gases from a Rankine system for several reasons: they interfere with the condensing heat transfer, their presence could be detrimental to the condensate pump, and they may prove detrimental from a corrosive standpoint. The non-condensibles in the system can arise from leakage at joints, diffusion through metals and may be evolved within the system itself by the outgassing of containing materials and the working fluid. It is possible to test complete Rankine systems on the ground to verify that inward leakage of non-condensibles does not cause trouble. It will also be desirable to determine this in zero gravity since bubbles of non-condensibles may more easily affect the pump.

Further development of Rankine systems may show that the fluids of the system cause small but definite amounts of mass transfer from the containing materials. Perhaps the use of additives to inhibit corrosion may be required. In either event, the effects of component and plumbing configurations and the zero gravity environment may have an effect upon the form and deposition of any solids in the fluid. Any solid particles existing in a fluid within a Rankine system will be either dispersed or concentrated in the system depending upon the relative importance of several factors. One of these important factors is that of buoyance. When the system operates in zero gravity, the form and location of concentrations of these particles within the system could be significantly altered by the complete absence of buoyancy forces.

In order for the efficiency of a Rankine space power plant to be high, careful attention must be given to techniques to prevent unwanted heat losses. The use of effective insulation for the components and plumbing will be required. While the effectiveness of these insulations can be undoubtedly determined with a fair degree of precision in a ground laboratory utilizing vacuum chambers, their actual performance in the space environment will be desired. Verification will be desirable that vacuum conditions do not cause system problems, either by changing the heat balance on system parts, or because of trapped air in insulation.

There is one aspect of Rankine space power systems that affects the vehicle in which they are placed. This is due to the fact that a Rankine system possesses angular momentum. Any change in this angular momentum will necessarily result in a torque being applied to the vehicle. These torques can either disturb the vehicle's motion or they can tend to stabilize it. A Rankine system has angular momentum from two sources: the turbomachinery and the circulating fluids.

Torques will be applied to the vehicle if either the magnitude or the direction of the angular momentum vector is changed. A change in the magnitude (change of rotational speed) results in an impulse torque applied to the vehicle, while rotation of the angular momentum vector will cause a gyroscopic torque to act on the vehicle.

If the vehicle is non-rotating, no gyroscopic torques will result. However, certain vehicles - reconnaissance satellites for example - do rotate once for every revolution about the earth. Properly designing and orienting the components of the Rankine system with respect to the vehicles can essentially eliminate any torques applied to the vehicle by the system's operation. The shaft speed control of the system will eliminate impulsive torques from this source and by aligning the turbomachinery shaft parallel to the pitch axis of such a vehicle, no gyroscopic torques will result from this rotation. The angular momentum of the turboalternator can be, in fact, utilized as a device to help stabilize the satellite vehicle.

Gyroscopic torques due to fluid flow can be effectively minimized by proper design of the Rankine system's flow passages. This is accomplished by so routing these flow passages that the angular momentum of any fluid loop is balanced by counter-rotating flow in another loop. However, fabrication tolerances, non-precise information as to geometric distribution of densities, varying cycle conditions make complete balance difficult.

An OFFBACE package designed for orbital use on board an attitude stabilized vehicle could furnish quantitative data for determining the correctness of the design to cancel these torques and thereby permit refinement of design techniques.

4.0 EXPERIMENTAL APPARATUS

Several components are required to complete a Rankine system test package for use in OFFBACE:

1. A boiler to accept the fluid in liquid form and add heat to completely vaporize and superheat the liquid to vapor.
2. An expansion device to permit the high pressure vapor to expand to the condenser pressure.
3. A condenser to convert the fluid from the vapor form to liquid once again by rejecting the required heat to a proper sink.
4. A condensate pump to cause the fluid to flow into the boiler at the proper pressure.

Two other major components are required to complete the OFFBACE test package: 1) an energy source, and 2) instrumentation and auxiliaries to measure and record the performance parameters of the Rankine system and its environment. Although the fact that this equipment must work in the space environment automatically limits the types of components that can be used, many variations are possible within the category of Rankine space components. Although this section will discuss several possible alternatives to the various component designs, the criterion for selection of components to comprise an OFFBACE test package, at this time, is based on considerations for current development programs. This means that all component designs must be tied quite closely with the design requirements and hardware configurations which will be used for SNAP II.

4.1 Boilers

The boiler for an OFFBACE test package must accept fluid in liquid form and add heat to completely vaporize and superheat the liquid to vapor. The conventional earthbound boiler is generally a loop in which heat is added on one vertical leg. The liquid is evaporated to vapor in this leg, with the vapor generally amounting to 10 to 20% by weight of the liquid vapor mixture exiting from the heated leg. The vapor separates from the liquid in a drum above the heated leg, by virtue of buoyant forces, and the liquid is recirculated through a downcomer. Sufficient additional liquid is provided to compensate for the vapor which is removed from the boiler. Boiler circulation is generally caused by the difference in average densities of fluid in the two vertical legs. The circulation rate is, therefore, determined by percentage of vapor in the riser, ratio of vapor density to liquid density (function of pressure), and degree to which the flow path is constricted. Since no external means are utilized to aid circulation, these boilers are called natural circulation boilers.

In order to provide an increased flow rate and more stable operation, a pump in the down-comer is utilized. These forced circulation boilers generally have higher heat rates since the danger of localized boiler tube burnout is diminished by the more dependable circulation. No gravity-circulation boiler exhibiting good performance shows a quality at the exit of the riser tubes of more than about 25%. Heat transfer rates become unacceptably low at higher exit qualities.

As boiler pressures have become greater, the diminishing difference in density between vapor and liquid, resulting in less of a driving head, has clarified the need for forced circulation. Some boilers have reached the extreme in that no water is recirculated. These boilers, known as "once-through" boilers, depend almost entirely on a pressure gradient for circulation. One variety, the supercritical boiler, does depend entirely on pressure gradient which may be 20% of the mean boiler pressure.

Since buoyancy forces are absent in a zero gravity environment, a boiler which will operate satisfactorily in space must be of the forced circulation variety. Two boiler types are available: the recirculating type and the once-through type. To date, the once-through boiler has been studied most intensively, because space power plants of relatively small output have been of major interest and the addition of centrifugal separators to these small systems would increase their complexity and size an unwarranted amount. The penalty which is frequently paid for using once-through boilers is low average heat transfer coefficients. Superheaters characteristically have low heat transfer coefficients, but since the percent of total heat added in the superheater is quite small, the low heat transfer coefficient doesn't cause a significant increase in total boiler size. When the low heat transfer coefficient occurs in the evaporation section, however, boiler size may be seriously affected.

The major portion of the heat added to a working fluid is used in the evaporation process. The effectiveness of the heat transfer surface depends strongly on keeping the liquid phase in close proximity with the surface. In recirculation boilers this is not particularly difficult because of the large ratio of liquid to vapor flow. In once-through boilers, however, the heat transfer surface rapidly becomes blanketed with vapor, reducing heat transfer. Boilers which have been constructed to date include features to offset the blanketing effect of the vapor. The most effective device is a swirl promoter located within the boiler tube. This produces an artificial gravity field which tends to separate the liquid to the wall and the vapor to the tube center. The effectiveness of the heat transfer surface can be increased approximately threefold by this method. Pressure drop is also increased significantly when swirl devices are added. Since pumping power is a very small percentage of the system's parasitic power losses, an increase in boiler inlet pressure does not significantly affect overall performance.

Use of a recirculating boiler and liquid-vapor separator must be considered for large power applications. With a direct boiling reactor this arrangement will probably be

mandatory to keep the void fraction down to a reasonable value. In an indirectly heated boiler, the added complexity and weight of the separator must be balanced against the savings in heat transfer area resulting from the higher heat transfer coefficient.

Small scale boiler tests, particularly of once-through boilers, can be very meaningful. These boilers can be simulated accurately with reduced-size models requiring a relatively small amount of energy. Boilers which will be utilized in OFFBACE tests will be similar, if not identical, to boilers being developed under the SNAP programs. Early small-scale experiments should utilize models of the full-size boilers. A full-size SNAP II should also be tested in an aircraft zero gravity experiment, in which case the prototype two-fluid boiler would be utilized with the primary fluid heated, perhaps electrically, external to the boiler. A SNAP II type boiler consists of a bundle of tubes contained within a larger tube, with the whole assembly formed into a helix. The boiler tubes are of the once-through type connected in parallel, and the primary fluid counterflows over the outside of the tube bundle.

Much boiler information has been generated during ground testing of the SNAP I type of once-through boiler. Operation of this boiler type in a zero gravity environment will give a direct comparison of the effects of the two environments. Since there is not a great deal of difference in concept between the SNAP I once-through boiler and SNAP II, tests of a SNAP I type boiler would provide meaningful data for SNAP II design.

During later phases of the OFFBACE program, recirculating boilers should be considered for large Rankine systems. In the case of boiling reactors where heat transfer coefficients must be high and void fractions must be low, the recirculation-type boilers in conjunction with liquid-vapor separators will be required for tests. Zero gravity testing of these components may prove to be of even greater importance than tests for once-through boilers. Tests of this type of boiler in zero gravity are strongly recommended as a later step in the OFFBACE program. Boiler instrumentation will necessarily provide good frequency response. Previous test experience indicates that pressure and flow rate sensing devices should be capable of responding to at least 10 cps without noticeable attenuation. Boiler instrumentation which will be included in every test includes outlet temperature and pressure, pressure drop, inlet temperature and both liquid and vapor flow rates. Thermocouples mounted within the boiler in the flow stream and on the tube wall will be added to more completely instrumented systems. This should give some delineation between the pre-heating, boiling and superheating sections, although it is recognized that a considerable overlap of these areas may exist.

4.2 Condensers

Condensers for use in a space environment, like boilers, require a set of design criteria considerably different from their earthbound counterparts. Space condensers must have special features to compensate for the absence of the gravitational phenomenon which causes separation of fluids of different densities. Fluid flow problems which result from

this aspect of a space environment provide the greatest difficulties in condenser design. Pressure drop through the condenser is the only force available for causing fluid flow. System considerations, however, require that pressure drop be low. Further, a stable interface between liquid and vapor must be maintained or unsatisfactory operation in the form of varying condenser pressure, varying subcooler temperature, and pump cavitation will result.

Rankine space power systems can utilize two types of condenser designs. Condensation can take place either directly, in a combined condenser-radiator, or inside a compact heat exchanger using a liquid coolant to transfer the heat to the radiating surface. A comparison of these two means is given below:

Comparison of Direct and Indirect Condensers

Advantages of the Direct Condenser

Simplicity of direct cycle.

Smaller radiator area (not necessarily smaller weight at large heat rejection rates since large vapor headers are involved)

Disadvantages

Large power plants will require huge vapor headers and manifolding.

Flow stability problems exist.

Difficult operational testing.

Advantages of the Indirect Condenser

More flexible design arrangement.

Very small liquid headers are required.

Simplified testing of compact condenser can be accomplished.

Greater assurance of "zero gravity" operation in which compact condenser design could further be integrated into cyclone vapor-liquid separation.

Secondary coolant exists as means of control.

Disadvantages

Additional pump and coolant loop.

Thermal resistance of additional coolant loop and a non-isothermal radiator lowers radiator effectiveness.

Additional power is required by the pumps.

In general, the Indirect condenser is attractive for large power systems where ease of development testing and flexible design arrangements are desirable. The direct condenser is attractive for low power systems, such as SNAP II where vapor headers are small in size, radiator surface areas low and vapor passages not so numerous that both development testing and flow stability are problems.

Condensers to be used for OFFBACE systems must meet not only the requirements for a Rankine space power plant, but must also permit the study of the phenomena occurring. They, therefore, must be properly instrumented and be capable of providing data over a wide range of operating conditions.

The type of vehicle used to provide the test environment will also determine the design of an OFFBACE condenser. In general, it is desirable to utilize the smallest size of condenser that will provide realistic data. As size increases, the vehicles available for providing the required environment become fewer, due not only to merely the increased mass of the system, but its greater energy requirements.

The degree of instrumentation sophistication and methods of cooling will vary considerably from one type of experiment to another. The aspect of space environment which is presently most important to the condenser of a Rankine system is zero gravity. Therefore, any method for examining the zero gravity condensing process would be of immediate value. Early OFFBACE systems would, therefore, utilize simple condenser concepts aimed at obtaining as much general information as possible.

Testing of OFFBACE systems within the atmosphere will probably require that convective cooling of the condenser be used for simplicity. Rejecting heat from a combined condenser-radiator by radiation could be realistically performed with more elaborate designs. Whatever the method of cooling, provision for obtaining data over a range of condenser heat rejection rates at variable condensing temperatures would be required to make possible study of the effects of varying these parameters.

Instrumentation for the condenser will be required to provide steady state and transient data as the OFFBACE system experiences the environments provided by the vehicle. The parameters of interest to determine overall condenser performance are primarily inlet vapor and outlet liquid - primarily pressure and temperature flow rates, pressure drop, surface temperatures. Detailed investigation of the processes within the condenser can best be carried out by being able to see the flow patterns within it. High speed motion pictures of the condensate droplet growth rate, droplet size and population, interface position and motion allow this to be done as no other instrumentation technique can.

Small-scale condenser tests can furnish much of the data needed to understand zero gravity condensing phenomena. Such a condenser could consist of simply one or more straight cylindrical tubes, made of metal or high temperature glass. Glass condensing

tubes would be utilized only where photographic instrumentation could be employed.

Larger scale condensers of more elaborate design may be employed in OFFBACE systems to study particular facets of Rankine space power plant condensing. For example, a prototype SNAP II condenser should be tested to provide not only general information on the phenomena but specific data for use in optimizing the SNAP II condenser for its final application.

4.3 Fluid Feed Devices

The fluid feed device for an OFFBACE test package must provide liquid to the boiler at the proper flow rate and pressure level. The attractiveness of OFFBACE is greatly enhanced if this device will also accept the subcooled condensate and return it to the boiler, for instead of merely testing the boiler and condenser in an orbital environment, the test package could more nearly simulate a complete Rankine system. Further, if the condensate pump can simulate the class of pumps presently developed for space Rankine systems, data can be obtained on the performance of these prototype pumps in a Rankine system subjected to the space environment.

The fluid feed device for an OFFBACE system should have the following characteristics:

1. Provide non-pulsating constant flow to the boiler at the desired flow rate and pressure level.
2. Be capable of accepting subcooled condensate and raising the pressure level of this flow to the desired boiler inlet.
3. Be capable of simulating the type of pumps contemplated for Rankine space power systems. (The pump must not permit non-condensable gases to leak into the system.)
4. Comply with the usual requirements for apparatus capable of being used in missiles or space, namely, low power consumption, low weight, small size, high reliability, and the particular requirement of the program, minimum cost.

The following sections describe possible pumps and methods that can be used to meet these requirements.

4.3.1 Centrifugal Pumps

The centrifugal pump best meets the overall requirements for the OFFBACE fluid feed device. Experience with this type of pump in the SNAP I and II programs has shown that it can supply flow rates at the pressure levels desired for very small expenditures of

pumping power. The pumps developed for these programs are also capable of excellent performance at the low inlet pressures required of Rankine systems, are inexpensive, and have proved to be capable of long life. The interaction of the condenser and the pump can be studied if the centrifugal pump is incorporated in the OFFBACE test system.

Since it is desired to obtain information on the pump operating in a manner that may be correlated with prototype pumps of Rankine space systems, two conditions of similarity must exist:

1. Geometric similarity as described by pump specific speed and inlet specific speed.
2. Kinematic similarity which requires that the model operate at its heat efficiency point.

These similarity conditions permit a pump to adequately simulate its design application and still allow flexibility in its integration with an OFFBACE system. For example, a true pumping test is obtained with a pump designed to run at 40,000 RPM if the pump is run at lower speeds with an increased flow rate.

Several pumps developed during the SNAP I and II programs could be used for this application. Figures 4.3.1-1 and 4.3.1-2 indicate their characteristics. These pumps were designed to supply both the working fluid to the boiler and the lubricant to the shaft bearings; therefore, either pump possesses capacity well in excess of requirements for contemplated OFFBACE systems. In the design application these pumps are driven on the same shaft as the turbine and alternator of the SNAP I or II Rankine space power systems. This same system of driving the pump would be attractive for OFFBACE, but it would be also possible to drive the pumps by electric motors.

If the OFFBACE system selected utilizes the complete SNAP I or II system, the task of supplying a device to pump the fluid from the condenser to boiler is automatically satisfied by the combined rotating unit which contains the condensate pump. This subject will be discussed in greater detail in Section 6.0. If it is desired to evaluate Rankine phenomena without the use of a turbomachinery package, the SNAP type of pump may be driven by an electric motor under conditions that adequately duplicate operating conditions. This may be accomplished in two basic ways: driving the pump through shaft seals with a commercial motor or by a totally enclosed motor-pump combination.

A cross-sectional view of the first type of motor pump is shown in Figure 4.3.1-3. The seal arrangement shown is a direct result of requirements of this pump as mentioned earlier. The double seal arrangement was devised to eliminate leakage of non-condensibles into the system. The cavity between the seals is maintained at a pressure lower than that existing in the pump impeller cavity, so any leakage past the seal will consist of pumped fluid exiting rather than any gas entering the system. The second seal restricts the amount of atmosphere leaking into the low pressure cavity; therefore, the requirements

PERFORMANCE COMPOSITE SNAP I DEVELOPMENT PUMPS
PUMP SPEED - 40,000 RPM FLUID - MERCURY INLET PRESSURE - 2 PSIA

FIGURE 4.3.1-1

FIGURE 4.3.1-2

MOTOR - PUMP FOR OFFBACE

FIGURE 4.3.1-3

of the vacuum system to keep this cavity at a low pressure are minimized.

The totally enclosed motor pump concept is presented in Figure 4.3.1-4 and is based on a minimum cost approach to this problem. Completely canned motor pumps have been built and run, and, in fact, are commercially available. However, the commercially available pumps are all characterized by two degrading features: (1) they require high net positive suction heads and (2) power consumption is very high. The net positive suction head performance could undoubtedly be improved, but the high power consumption of these devices is a direct result of the design philosophy used (i.e., all electrical components of the motor are sealed by metallic means and the motor-rotor cavity is completely submerged in the liquid being pumped, causing high eddy current and viscous losses.)

The totally enclosed motor pump uses an induction motor with the stator protected from the mercury vapor by inorganic potting compounds proved to be compatible with mercury. The rotor is encapsulated in a very thin non-magnetic stainless steel can; the eddy current losses in this can are low since the exciting frequency is only the slip frequency. The shaft rests on the hydrosphere bearings developed in the SNAP I program. For this application the bearings are considerably over-designed and, therefore, are highly reliable from a load-carrying standpoint. The pump is identical to the SNAP II pump. The input electrical power required by this motor pump is very reasonable, primarily due to the almost complete absence of eddy current and viscous power losses. The non-metallic protection of the stator results in low total eddy current losses. The capability of the stator to operate at high temperatures assures that any liquid entering the cavity will be vaporized.

The cost and time required to develop a totally enclosed motor pump for OFFBACE would be higher than for the motor-driven pump previously discussed. The many other potential uses of a totally enclosed motor pump may, however, be sufficient justification for its development as part of the OFFBACE program. One of the potential applications of this unit is as an auxiliary pump for bearing pressurization or startup of a Rankine system in orbit. With the greatly increased usage of liquid metal systems in the nuclear and space activity, a pump with the characteristics of no seal problems and no absolute known leakage will undoubtedly have many attractive applications.

4.3.2 Miscellaneous Fluid Feed Devices

Several other techniques available for providing flow to the boiler or for receiving condensate and returning it to the boiler are (1) a blow-down system using either gas pressurizing a mercury accumulator or heat input into a mercury reservoir, (2) reciprocating pumps, (3) vapor injector pumps, and (4) electromagnetic pumps.

TOTALLY ENCLOSED MOTOR PUMP BASED UPON USING EXISTING SNAP I HARDWARE

FIGURE 4.3.1-4

Blowdown System

A method for providing constant flow to the boiler at a constant pressure is shown in Figure 4.3.2-1. The gas supplied at constant pressure to the mercury accumulator forces liquid mercury out of the bladder-type reservoir through a throttling orifice to the boiler. Essentially, constant flow rate is maintained by supplying gas to the bladder reservoir at a constant pressure by means of the gas regulator and by the pressure dropping or the throttling orifice which is used to mask changes in pressure drop occurring downstream from the orifice.

The flow of liquid from the condenser is further subcooled so that it remains liquid after expanding to the very low pressure of the receiver chamber. Provision can be made for additional plumbing to recharge the condensate collected in the receiver into the mercury accumulator and repeat the discharge cycle.

This system is relatively simple and probably quite easily developed. Since the blow-down system will always be heavier than a pumping system (the increase becoming highly significant when operating duration increases) and it does not allow examination of a complete Rankine system and the interactions of the components, it is not so attractive as the pumping method. However, for cases where boiler and condenser information only is desired, this method is inexpensive.

Heating a closed container of the fluid is another method of providing fluid to the boiler. The significant increase in the specific volume of the fluid upon vaporization is sufficient to force liquid from the closed container to the boiler. Figure 4.3.2-2 shows such a scheme. This method suffers one very crippling drawback for OFFBACE application - it depends upon buoyancy forces both to maintain the liquid in contact with the heaters to insure a good supply of vapor and to assure that only liquid is supplied from the device. In a free-flight atmosphere buoyancy forces are non-existent and hence, the operation of the system degrades. Techniques have also been considered for designing a device of this kind which would not depend on buoyancy. These appear possible, but generally are too complicated to be attractive.

Reciprocating Pumps

A reciprocating-type condensate return pump capable of meeting most of the OFFBACE requirements is possible. The output of such a pump, without resorting to complexities, would be pulsating. This would be objectionable from the system standpoint. Furthermore, it would be difficult to create a reciprocating pump that can operate at the low net positive suction heads required of the system and at the same time provide the high discharge pressures. Such a pump completely sealed by the use of bellows could perhaps find certain applications, but the development expenses would not be warranted by later applicability.

GAS-PRESSURIZED MERCURY SUPPLY AND RECEIVER

FIGURE 4.3.2-1

FIGURE 4.3.2-2

Vapor Injector Pumps

Figure 4.3.2-3 shows a vapor injector type pump. This type has no moving parts and offers a very simple design. High-pressure vapor from the discharge of the boiler is expanded in the primary fluid nozzle to convert its pressure energy into kinetic energy. The pumped fluid mixes with this stream of high-velocity fluid, assuming momentum at the expense of primary fluid momentum. The moving stream is then diffused to low velocity and hence, obtains an increase in pressure. This type of pump is characterized by very low pumping efficiency. When used to supply fluid to a boiler, however, it has a good efficiency since it is acting as a preheater as well as a pump. For this reason an OFFBACE system utilizing a vapor injector type pump would realize significantly low power expenditure to provide recirculating flow.

This type of pump may have poor cavitation performance, and since it is not capable of properly simulating the types of pumps presently envisioned for Rankine systems, it is not considered applicable to an OFFBACE system.

Electromagnetic Pumps

Electromagnetic pumps have found many applications in liquid metal applications as a result of the one key feature also required of an OFFBACE system. This advantage is that these pumps are completely sealed. For OFFBACE application, however, other characteristics eliminate these pumps from consideration. Whether the pumps operate by an alternating magnetic field or a rotating magnetic field caused electrically or electromechanically, large size and weight coupled with low efficiency characterize their operation. While electromagnetic pumps do not appear feasible for pumping the Rankine system working fluid, they may be used to circulate the hot fluid between the energy source and the Rankine system boiler in OFFBACE tests where the boiler is heated by a primary fluid.

4.4 Energy Sources

The energy source for an OFFBACE test package must be compatible with the requirements of the experiment itself and the requirements of the overall developmental program. The experiment demands

- 1) maximum energy per weight
- 2) maximum energy per volume
- 3) maximum reliability (not complex)
- 4) capability of withstanding the environmental stresses (shock, acceleration, vibration, the zero gravity, temperature)

FIGURE 4.3.2-3

- 5) capability of supplying energy in the form required by the boiler
- 6) minimum hazards, and
- 7) stable energy output

The program requires a short development time, conservative design with no need for state-of-the-art advances, and low development costs.

The several methods available for obtaining the required energy are listed below.

Chemical Reaction

- Electric storage battery
- Fuel cell
- Combustion or decomposition

Thermodynamic Methods

- Change of phase
- Specific heat

Solar Energy

Nuclear Energy

- Reactor
- Radioisotope

Electrical Energy

4.4.1 Chemical Energy Sources

Methods of providing energy through chemical reactions include electrical batteries, fuel cells, and combustion or decomposition.

Electric Batteries

The creation of electrical energy from a chemical reaction within a battery appears attractive. Electrical energy from a battery allows flexible boiler design and permits auxiliary equipment to be powered from the same energy source. A battery energy source is a simple, versatile device. Individual cells may be arranged to fit an existing space envelope and output is easily controllable. Energy can be easily restored, with no direct servicing required in certain cases.

Table 4.4.1-1 lists the specific energy per pound rating of various battery types. Since most experimental applications that could use batteries as the energy source would be one-shot missions, a primary battery - one that cannot be recharged - of high energy per weight would be best. The use of a silver peroxide zinc or Andre cell is recommended. Commercial versions of this type of battery are available with very short delivery times and are the secondary type, i.e., they can stand a number of discharge cycles. These off-the-shelf batteries have specific powers of about 50 watt hours per pound. Primary silver zinc batteries developed for satellite applications are available to produce about 70 watt hours per pound. However, this high value of specific energy is obtained at very low discharge rates not applicable to OFFBACE systems.

Fuel Cell

A fuel cell is an electrochemical device for the continuous direct conversion of chemical energy into electrical energy. It is distinguished from a battery in that it operates with a continuous replenishment of the fuel and oxidant and thus does not require recharging. Since it bypasses the intermediate conversion to heat, it is free of Carnot cycle limitations and thus has high conversion efficiency. It is, therefore, a highly attractive method for obtaining electrical from chemical energy.

For use as the energy source for an OFFBACE system, the fuel cell is not feasible. Their present status is that of having laboratory models working, but with much effort remaining until they become practical for applications such as this one.

Combustion and Decomposition

Use of a chemical reaction of mono or bi-propellants to provide the required thermal energy appears attractive from an energy to weight or volume viewpoint. For example, the decomposition of 100% hydrogen peroxide results in 87 watt-hours of thermal energy per pound when the 1820°F gases resulting from the decomposition are cooled to 1100°F. Higher specific energies are obtained with bi-propellant mixtures that yield flame temperatures higher than this. If a hydrocarbon is burned with 90% hydrogen peroxide yielding a flame temperature of 3500°F, cooling this gas to 1400°F releases 325 watt-hours per pound.

Since the energy source is composed of much more than the propellants, the values of specific energy per pound given for the complete energy source would be lower. The high flame temperatures provided by some bi-propellant combinations could result in heat exchangers of low weight due to the high ΔT 's that would be attained, but would also cause more complex design problems, particularly in the materials area. A further disadvantage of this type of energy source is the fact that the form of heat provided for the boiler is not the type presently envisioned for Rankine space power plants. This would compromise the value of the test from the boiler standpoint.

TABLE 4.4.1-1
BATTERY SUMMARY

Cell Name	Cell Type	Achieved	
		Amp-hr/lb	Watt-hr/lb
LeClanche (Dry Cell)	Primary	22.7	28.3
Clark	Standard Primary	---	---
Perchloric Acid	Primary	11.1	20.9
Main	Primary	---	---
Caustic Soda	Primary	---	---
Water Activated	Primary	14	22
		11	15
Plante (Lead-Acid)	Secondary	7	14
Ruben	Primary	37	44
Andre (Silver/Zinc)	Primary and	Pri. 47	70
	Secondary	Sec. 34	52
Edison	Secondary	8	10
Nicad (Junger)	Secondary	15	17
Silvercad	Secondary	22	25

From Lockheed Report
LMSD-2870

Even utilizing the simplest techniques available for construction of this type of energy source, the development program would be more costly than that for other energy sources of comparable performance. Supplying heat to the boiler by this method appears attractive, however, for systems involving large heat requirements and long operating durations.

4.4.2 Thermodynamic Methods

Change of Phase - Certain substances upon changing phase from vapor to liquid or liquid to solid liberate sizeable quantities of thermal energy. If this process occurs at a temperature in the range of interest, this type of energy supply has several advantages. These are:

1. The device is very simple (no high temperatures, simple design procedures)
2. The energy is delivered at a constant temperature.
3. The energy can be originally stored in the system by simple methods, e.g., electrical heating.
4. Developmental experience with such an energy source could be directly applicable to providing information required for energy storage devices operating in orbit as could be the case with a solar-powered space power plant.

Table 4.4.2-1 lists several materials possessing attractive combinations of high heat and attractive fusion temperatures. For the application here lithium hydride provides an almost optimum material because of its uniquely high energy content per pound and attractive fusion temperature. A brief discussion of this substance is presented, because these attractive characteristics make it likely that this would be the material used for such an energy source.

The latent heat of fusion of lithium hydride has been estimated to be 465 watt-hours per pound. However, recent experimental data indicate that values of approximately 345 watt-hours per pound are obtained. This lower value might be attributed to impurities in the lithium hydride. It has only been recently, however, that experimental work to determine accurately the heat of fusion of lithium hydride has been undertaken. The freezing temperature of lithium hydride is approximately 1270°F. There have been no direct measurements of the heat capacities of lithium hydride in the temperature range of interest. However, extrapolation of existing data combined with theoretical calculations indicate that the specific heat for solid lithium hydride is 1.86 Btu's per lb per °F and that for the liquid is 1.95 Btu's per lb per °F.

The volume of lithium hydride increases approximately 18% upon melting and 12%

TABLE 4.4.2-1

HEATS OF FUSION OF CERTAIN SUBSTANCES

<u>Material</u>	<u>Freezing Point °F</u>	<u>Heat of Fusion Watt-Hrs/lbm</u>
Aluminum	1220	51
Copper	1980	26
Germanium	1720	59
Lithium Fluoride	1558	132
Lithium Hydride	1270	345
Magnesium	1202	47
Red Phosphorous	1094	83

In going from room temperature to its melting point. The density of the solid at the melting point is 43 lb per cu ft and that of the liquid at the melting temperature is 36.2 lb per cu ft.

As in the case of heat of fusion data, only limited information is available on thermal conductivities of the solid and liquid lithium hydride in the temperature range of interest. The thermal conductivity of the solid at the melting temperature is approximately 2 Btu per hr per ft $^{\circ}$ F. No data are available on the thermal conductivity of the liquid but estimates indicate that it may be approximately one-third that of the solid.

Lithium hydride is not a particularly hazardous material to handle but certain precautions must be observed. It will react with any trace of water or water vapor left in the air to produce lithium hydroxide, a very caustic and corrosive material. Lithium hydride in contact with the moisture of the skin may produce severe burns, so protective clothing is a necessity. To eliminate possible contact with water, all work with lithium hydride should be performed in an inert atmosphere. As is the case with many materials, the finely divided powder of lithium hydride may ignite spontaneously in the atmosphere. However, the flame is not intense and can be extinguished by lithium chloride.

Lithium hydride dissociates upon heating above the melting point, resulting in a positive hydrogen pressure above the melt at all times. This hydrogen equilibrium pressure varies with the temperature and purity of the melt, becoming greater at higher temperatures and higher percentage composition of lithium hydride in lithium. The hydrogen pressures resulting are moderate for the temperatures that will be used and would not present a structural problem for the containing materials.

Containing materials for lithium hydride should be stainless steels, preferably Type 347, cleaned of all oxides and welding flux. Attention should be paid to the diffusion of hydrogen through the container to ascertain the total heat loss from the heat of fusion since as hydrogen escapes, a definite amount of lithium hydride degrades to lithium.

The only design problem connected with lithium hydride as a heat storage material centers around the large volume change previously mentioned. Properly designed, the container should be completely filled at the desired temperature but assurance of this may be obtained by the addition of a small expansion chamber. If, during the freezing process, the lithium hydride shrinks away from the heat transfer area, the rate of heat transfer will decrease. However, most salt exhibits a tenaciously adherent effect at the transfer area. One other characteristic of lithium hydride is adverse with respect to obtaining long operating durations: the low thermal conductivity demands a large heat transfer area. However, recent analysis shows that the effective thermal conductivity of lithium hydride can be significantly increased by mixing approximately 3 wt % titanium wool with the lithium hydride. This increases the thermal conductivity of solid lithium hydride by a factor of 8 and of liquid lithium hydride by a factor of about 25.

It is also possible to obtain high thermal energy release per pound of substance during the change from vapor to liquid. Table 4.4.2-2 lists several substances and their corresponding energy release upon condensing. While high specific energies such as some of these are desirable, the volume of the vapor per pound is also very high. For this reason, the energy per unit volume is very low, requiring large containers. The large containing vessels would be required to withstand the vapor pressure of the energy storage material at the temperature desired and would therefore be heavy. For these reasons, this type of energy source cannot be considered.

Specific Heat

Systems utilizing specific heat properties, although possible, are not practical. This can best be seen by referring to the basic heat - specific heat relationship.

$$dQ = w c_p dT$$

where

$$c_p = \text{specific heat}$$

$$Q = \text{heat energy}$$

$$T = \text{temperature}$$

$$W = \text{substance weight}$$

In general, c_p values expressed in engineering units is less than unity; therefore, in order to obtain large values of Q , either the temperature range or the weight of heat sink material required must be large. Neither of these factors is desirable. For these reasons, no further consideration will be given to this type system.

4.4.3 Solar Energy Sources

Immediately outside the earth's atmosphere are found 125 watts of thermal energy per square foot oriented toward the sun. Converting this energy to forms usable on board satellites is the subject which is of interest. A satellite experiment combining both solar energy conversion and the requirements of the OFFBACE program may be attractive. The apparatus could consist of a solar collector that would gather heat and focus it on a boiler to permit the Rankine experiment to operate for indefinite periods of time. This would provide valuable information concerning the operation of Rankine systems in orbit for very long periods.

The problems associated with the solar collector portion of such a combined test would be significant, however. A specific satellite vehicle would have to be developed or sig-

TABLE 4.4.2-2

HEATS OF VAPORIZATION OF CERTAIN SUBSTANCES

<u>Material</u>	<u>Normal Boiling Point °F</u>	<u>Heat of Vaporization @ BP Watt-hrs/lbm</u>
Cadmium Iodide	1465	37
Lead Bromide	1683	41
Lead Chloride	1749	56
Potassium	1394	256
Sodium	1632	553
Sodium - Potassium 56	1500	411
Sodium - Potassium 78	1440	352
Tin Chloride	1153	58
Thallium Bromide	1506	44
Thallium Chloride	1485	54

nificant modifications made to existing large satellite vehicles to meet the collector's requirements. Considerable development would be required to help assure the successful deployment of the collector once an orbit had been achieved. The orientation sensor and vehicle-collector attitude positioning devices would require significant developmental efforts to insure that the sun would be located and tracked.

The use of solar energy for an OFFBACE experiment would, therefore, better be performed as a part of the development of a specific solar powered Rankine space power system. This would permit all development and testing to be oriented toward a complete operating vehicle-collector-Rankine system.

4.4.4 Nuclear Energy Sources

Since the majority of Rankine space power plants will utilize a reactor for the thermal energy source, it is logical to consider this type of energy source for an advanced OFFBACE system. This would permit the long term study of the effects of the space environment and a complete Rankine system. OFFBACE systems for use early in the program would not use this type of energy source since the phenomena of immediate importance can be evaluated in systems receiving energy by other means. However, the use of a radioisotope or reactor providing the energy for an OFFBACE system would enable the investigation of phenomena of great importance to the long term usage of space power plants.

4.4.5 Electrical Energy Sources

As discussed in Section 5.0, electrical energy will most often be used to supply heat to the boiler. The form of heat supplied will be essentially identical to that provided by a chemical battery; however, the electrical energy is supplied from some point outside the experimental apparatus and, therefore, the weight of this energy is not chargeable to the apparatus. Such would be the case when OFFBACE testing is performed within an aircraft. Electrical energy can be supplied directly from aircraft during this type of testing and when the test package evolves to a missile or orbital type of test, substitution of batteries will require no modifications to the boiler.

4.5 Instrumentation

Basically, two types of information will be desired from any of the experiments set forth in this report: (1) operational characteristics of the system or component being tested, and (2) an accurate description of the environment to which the test apparatus is subjected. To determine cause and effect, this intelligence must be accumulated so that there is a correlation between these two basic forms.

Instrumentation and recording equipment must be chosen carefully to satisfy the goals set forth above and yet maintain a system of reasonable complexity. Ideally, a single

Instrumentation package could be designed which would meet the needs of every system - vehicle combination which might be studied. Unfortunately, the wide variation in scope of the various tests does not permit this ideal situation. Rather, at least a portion of the instrumentation must be tailored to meet the requirements of the particular experiment.

The requirements for instrumentation for operation in a closed mercury system are very demanding. The temperatures, pressures, corrosive properties of the working fluid, and the need for control of heat losses in the system make the application of conventional sensing and transducer devices very difficult. In certain cases weight limitations will be imposed on the instrumentation, and vehicle vibration and shock loadings will always be a problem.

Most of the transducers will be used to monitor temperature, pressure, and acceleration forces. Ideally, it would be best to use high level transducers to eliminate the need for amplification of signals before they can be monitored, recorded or telemetered. High level transducers include the bourdon tube potentiometer pressure transducers, the spring mass potentiometer accelerometer, and the thermistor temperature bridge.

Transducers of the type mentioned are simple, inexpensive, and require little auxiliary equipment to make them useful. Unfortunately, the types of transducers that yield high level outputs have several drawbacks. They are usually larger in size and weight, have less accurate calibration characteristics, are sensitive to acceleration and vibration, and are slow in responding to transient signals. Under conditions of shock and acceleration, high level transducers are generally noisy, and their low frequency response limits their ability to sense impulses over 50 cps without considerable attenuation. The signals from low level transducers require amplification before they can be telemetered, or in some cases, before they can be recorded. Although this fact represents a slight sacrifice in reliability, no other great disadvantages occur since the necessary amplifiers are of small and lightweight construction. Transducers in this category include thermocouples, strain gage pressure transducers and strain gage accelerometers.

Thermistor-type temperature sensors may be adversely affected by vacuum operation and their operating range is limited to about 900°F. The latter factor would require the use of several high temperature sensing elements in addition to any thermistors used.

It is recommended that all temperature sensing be accomplished with thermocouples. This will insure minimum heat loss due to conduction at critical points such as the nozzle, minimum weight, fast response, and freedom from side effects due to environment. Other devices such as resistance thermometers could be used, but these are considerably more bulky, slower, more expensive, and require highly accurate bridge equipment to make proper use of their measurement capabilities. Simple meters and a camera may be used for indicating and recording temperatures in aircraft test stages and almost all present-day telemetering equipment makes provision for handling both high and low level signals with little sacrifice in size, weight, or cost.

It is recommended that strain gage pressure transducers be used. These units are very small, insensitive to extreme shock and vibration, may be a-c or d-c excited, have no fluid capacity except lines, are very accurate, are not affected by temperature, and have very fast response. Piezoelectric transducers will not give steady outputs and transformer types require special excitation; otherwise, all three are comparable with the piezoelectric being slightly higher temperature and smaller. The strain gage pressure transducer will require cooling by frame contact and must be separated from hot vapors by a short tube run. The required short connection tubes will add neither damping (since no flow takes place) nor produce heat losses or undesirable condensation in the mercury system. Some liquid will collect in part of the line but this will remain fixed by the capillary action of mercury in the tube, and conduction loss will be only a few watts if very small lines are used. Regardless what type transducer is selected, some line loss will be encountered in this thermal isolation tube but the strain gage element will keep this at a minimum.

Recommendation for an accelerometer favors a strain gage type. A strain gage unit has higher frequency response and less sensitivity to shock and vibration than a potentiometer unit. The output is comparable with the thermocouples and strain gage pressure transducers and therefore, may simplify the selection of recording and telemetering equipment. The other factors such as size, persistence of signal, high frequency response, and d-c excitation requirements all contribute to the selection of this type accelerometer.

Some instrumentation, other than the conventional pressure, temperature, and acceleration sensing devices, must be developed to utilize OFFBACE tests to the fullest. Two of the more important quantities which will require a sophisticated approach to instrumentation concern the condenser. Knowledge of the position of the interface between liquid and vapor will aid greatly in determining condenser performance. In satellite tests, meteoric impact is expected to have an effect on the surface emissivity of the condenser. Measurement of the magnitude of this effect will influence future condenser design.

Tests are being proposed using at least three different test beds. The environments encountered by these vehicles, vehicle limitations, and objectives of test will determine instrumentation. Further requirements that the system be capable of (1) providing direct indication of performance, (2) radio telemetering essential data from remote locations, and (3) generating a permanent record of performance at the point of operation make it necessary to consider a very complete, bulky, and expensive instrumentation package. It has been further suggested that such an instrumentation package be capable of performing in an aircraft, missile and/or satellite with only minor modification.

Brief consideration of the factors listed above has led to the conclusion that it is impossible to build a single instrumentation package that will be recognized as optimum for all instances. It appears impractical to try to design a single universal instrumentation package that will meet the needs for aircraft, missile and satellite service since the

specific requirements are basically different for each application. The closest approach which may be made under these circumstances is to select transducers which will be acceptable to the several environments, the mercury system, and the variety of auxiliary equipment which may be selected for telemetering, recording, and readout. This will provide a single test system configuration of optimum design which may be augmented as required by the test environment and objectives.

The three vehicles require different pieces of auxiliary equipment as listed:

<u>AIRCRAFT</u>	<u>MISSILE</u>	<u>SATELLITE</u>
1. Package transducers	1. Package transducers	1. Package transducers
2. Amplifiers	2. Amplifiers	2. Amplifiers
3. Recorder	3. Recorder or tele- metering equipment	3. Telemetering equipment
4. Monitoring display		

Items 1 and 3 required for missile and satellite test stages would be dictated by cost, size, and weight requirements, range standard equipment, and volume and accuracy of data required.

If consideration is given to the fact that any missile or satellite package will be an expensive one shot item, it becomes obvious that a special telemetering unit is in order for each package. Both telemetering units must be small and insensitive to g-loading, vibration, etc.; but the duration of the test and the power level required to send back useful data is considerably different for each application. Present philosophy in the telemetering field is to use two different units for optimum performance.

For the aircraft test stage it makes little difference what auxiliary equipment is used. The requirement for visual indication makes slow response in the indicator mandatory. It may be possible to provide this indication with calibrated milli-volt meters and the transducers suggested for the universal package, or high level transducers and volt-meters may be used without much gain or loss. The low level transducers may also be used with a high speed optical-type recorder if suitable amplifiers are used. This would give a record of transient activity for careful analysis and a visual indication which an operator might evaluate on the spot assuming he could remember what data was displayed on each of 30 or 40 traces and what scales applied to each. It seems doubtful that any fast transient data such as high vibration or shock loading would be encountered in the aircraft test stage since an aircraft in flight cannot impose or withstand these conditions. It would appear that the simple meter and camera indicator recorder system is most suitable. Other types of recorders such as tape or optical strip chart or even pen

recorders might be used for a permanent record but this added equipment would not contribute much except cost and complexity. A point in favor of using oscillograph-type recorders during aircraft tests is that they may already be installed aboard the KC-135 which will be used for the tests.

Several basic varieties of information are desired from any OFFBACE experiment. Over relatively long periods of operation, a determination of whether the components under examination are performing satisfactorily or marginally will be of major importance. Any degradation of performance which occurs while the system is functioning should be detected. In the event of the sudden failure of a system, the component which precipitated the failure should be determinable. Finally, information concerning many facets of the environment should be observed and correlated with performance data:

The choice of instrumentation depends on the purpose of the particular experiment, test vehicle weight and space limitations, and other factors. To obtain a picture of the maximum amount of instrumentation that will be utilized during an OFFBACE experiment, we may consider a long duration test of a SNAP II system with a lithium hydride heated NaK loop, and assume that there are no stringent weight or space limitations. For this situation, instrumentation would be applied to monitor the following parameters:

- a. LIH temperatures and temperature gradients
- b. Boiler outlet pressure, temperature and temperature profile.
- c. Condenser pressure, temperature, pressure drop, temperature profile.
- d. Subcooler outlet temperature
- e. Pump inlet pressure
- f. Pump outlet pressure
- g. Boiler inlet pressure
- h. Liquid level indication in both boiler and condenser
- i. Pump outlet and boiler inlet flow rates
- j. Rotor speed
- k. Photovoltaic cells or other means for determining Incident radiation.
- l. Vehicle skin temperatures

- m. Launch transients including accelerations, shock and vibration loads
- n. Alternator power output
- o. Mercury or NaK leak detectors

The majority of the parameters listed above can be detected with conventional transducers. Some measurements will, however, require the use of specially designed instrumentation if the full use of the experiment is to be realized. Two important areas for which standard instrumentation are not presently available are detection of liquid-vapor demarcation zones and meteoric damage to the exposed portions of the test systems.

Transducers, recorders, and telemetering equipment must be of a quality consistent with the purpose of the test. Preferable types of transducers have already been discussed. Recording equipment should be comparable with magnetic tape or oscillographic recorders in the forefront. In the case of telemetered information, commutated samplings should be numerous, with each data point being read out on the order of once per tenth-second.

For the majority of the OFFBACE experiments described, the apparatus will not be as fully instrumented as the system described above. Judicious usage of the available equipment will be necessary to accumulate the greatest amount of pertinent data from a given test.

5.0 METHODS FOR PROVIDING ZERO GRAVITY

This section will discuss the several techniques capable of providing OFFBACE systems the zero gravity aspect of the orbital environment. Certain of these methods will simultaneously subject the system to other facets of the orbital environment while others are capable of providing only the zero gravity state. While subjecting an OFFBACE system to the total environment experienced in orbit is the desired goal of the program, of primary concern at this time is the study of Rankine fluid mechanics and the interrelated heat transfer under zero gravity conditions. With the exception of the meteoric particle aspect of the environment, zero gravity is the only factor not capable of being simulated in properly designed ground test facilities.

A body is in the state called zero gravity when the only force acting upon it is its gravitational force. For practical experimentation of physical and physiological phenomena in the zero gravity state it is possible to relax this definition, depending on the experiment, and make the criterion that of keeping non-gravitational forces acting on the body small compared with the gravitational force.

Obtaining extended durations of high-quality zero gravity time is a difficult task. Since an object in zero gravity near the earth's surface accelerates toward the earth, increasing its velocity 32 feet per second each second, even short durations of zero gravity result in high velocities being attained. For example, one minute of zero gravity results in a velocity change of about 1300 miles per hour. Keeping non-gravitational forces acting upon the body small while experiencing such velocities within the atmosphere is difficult indeed.

Even for satellites orbiting the earth considerably beyond the earth's atmosphere, this condition has not often been attained for the entire body, since quite often it is spinning or tumbling. The same considerations apply to the nose cone of a missile during the portion of its trajectory which is outside the atmosphere. Any rotation results in accelerations which destroy the usefulness of the test.

The following paragraphs present several techniques that have been used or are proposed to be used to provide a zero gravity environment. All of the techniques discussed will be of interest for further investigation in connection with OFFBACE planning.

5.1 Satellite

An earth satellite provides the ideal method for obtaining substantial periods of zero gravity. A properly stabilized satellite placed into a sufficiently high orbit will remain in that orbit for indefinite periods. Such a satellite would also provide all of the information concerning the interaction of a Rankine system and an orbital environment. Simultaneously with providing the zero gravity condition, the satellite would expose the Rankine system to every aspect of the orbital environment.

While the environment provided by a satellite is the ideal method of performing these experiments, it cannot be considered optimum from the overall program standpoint. Probably foremost on the negative side is the cost associated with this type of vehicle. However, as will be discussed in Section 7, there are certain types of OFFBACE systems that could be placed in very small and hence relatively inexpensive vehicles.

In any case, however, considering all of the factors involved in preparing and launching a satellite and the complexity of receiving information telemetered from it, the cost of such a vehicle to be used only for OFFBACE would be high.

If an OFFBACE system could ride along as a secondary experiment on some of the larger satellites, the cost of an orbital experiment would be greatly reduced. Such a piggyback arrangement would make it possible to obtain valuable data for essentially the cost of the flight hardware alone. This consideration makes the investigation of small OFFBACE test packages important.

This report was not intended to include a detailed investigation of applicable boosters and satellite combinations. However, Table 5.1-1 has been prepared from the open literature in order to present an estimate of satellite vehicles currently available, or that will be available in the near future. The first portion of this table presents the equipment capable of only putting a small OFFBACE system in orbit, the latter portion presents vehicles in which it is estimated an OFFBACE system could be included in the category of a piggyback experiment.

Because of its potential value to this program, one particular satellite vehicle was investigated in more detail. This is the Scout vehicle being built under the auspices of NASA. This device utilizes four stages of solid propellant rockets to boost varying payloads into orbit. For example, it can put a 150 pound payload into a 650 mile altitude circular orbit or a 250 pound payload into a 300 mile altitude circular orbit. A more detailed discussion of this satellite vehicle is being presented here since considerations raised in the discussion are generally applicable to all booster vehicles used to inject OFFBACE systems into orbit.

Figure 5.1-1 is a curve of the acceleration history of this vehicle. This is of particular interest to the designer of an OFFBACE system since it shows the accelerations the equipment must be built to withstand. If the system must operate through launching, this vehicle characteristic is especially important. As has been discussed earlier, the fluid dynamics of a Rankine system are sensitive to the acceleration that the system experiences. Hence, a rather considerable performance transient could be expected due to the levels and rates of change of the linear acceleration. Of special concern in any boost pattern like this, would be the negative acceleration indicated during the coast period after burnout of the first stage.

The Scout vehicle spin stabilizes the fourth stage to approximately 100 rpm before firing

TABLE 5.1-1

POSSIBLE SATELLITE VEHICLES FOR OFFBACE

<u>VEHICLE</u>	<u>AGENCY</u>
Jupiter C	NASA
Scout	NASA
Thor - Able	AF/NASA
Thor-Hustler	ARPA
Atlas - Able	AF/NASA
Atlas - Hustler	ARPA
Centaur	NASA

the fourth stage motor. The radial accelerations caused by this rotation would naturally affect a Rankine apparatus within the payload. A detailed analysis would have to be performed to determine the feasibility of operating an OFFBACE system through this type of launch procedure. However, if the experiment were to be started once the system had been placed in orbit, it would be possible to de-spin the payload, prior to starting the experiment. While a perfectly non-rotating satellite to contain the Rankine experiment is desired, Figure 5.1-1 indicates that if the rates of rotation are maintained sufficiently small they will probably not appreciably affect the experiment.

5.2 Missiles

A ballistic missile is capable of providing very respectable durations of zero gravity. The nose cone of an Atlas, for example, is in the zero gravity portion of its trajectory approximately 30 minutes. As in the case of the satellite, the requirements for the equipment within the nose cone to be in zero gravity are that the only force on the cone is that of gravity, i.e., it is outside of the earth's atmosphere, and that the nose cone be non-rotating or rotating very slowly.

The ballistic missile is capable of providing these long durations of zero gravity because of the vertical component of its very high velocity. The zero gravity period begins when it leaves the atmosphere and is concluded when it re-enters the atmosphere. During this period the missile is continually accelerating toward the center of the earth. The higher the initial vertical velocity, the longer it will take this acceleration to slow the missile's rise and cause it to begin its return toward earth.

While the missile is in zero gravity, it is also exposed to the same environment as a satellite. It would, therefore, permit the study of Rankine phenomena in the complete orbital environment with only time of exposure not being duplicated.

Table 5.2-1 is a listing of the several ballistic missiles capable of being the vehicle for an OFFBACE system. As with the case of the satellite, no detailed investigation of these vehicles has been done and their precise capabilities and requirements with respect to this type of experiment are not known. This type of vehicle is especially an attractive one, however, because of the possibilities of obtaining "free rides" during the missile's development testing. Here again, a small OFFBACE system could obtain valuable data at low cost.

Primarily all of the data on system performance would have to be telemetered to ground stations during the missile's flight but there is the possibility of recording more parameters within the missile. Recovery of the nose cone and contents would permit acquisition of these data.

Further investigation to determine the complete applicability of these vehicles to an OFFBACE program is required. From the technical viewpoint, such information as acceleration histories, vehicle attitude, shock during nose cone separation, payload

ACCELERATION HISTORY OF THE SCOUT VEHICLE

FIGURE 5.1-1

TABLE 5.2-1

POSSIBLE SOUNDING ROCKETS FOR OFFBACE

<u>NAME</u>	<u>MANUFACTURER</u>
Aerobee	Aerojet
Arcas	Atlantic Research
Acrcon	Atlantic Research
Asp	Cooper Development
Aspan	Cooper Development
Adder	Cooper Development
Boa	Cooper Development
Cobra	Cooper Development
Dan	Cooper Development
Diamond Back	Cooper Development
King Cobra	Cooper Development
Starseeker	Cooper Development

space and weight capabilities, telemetry capabilities, etc., would be required. General program information with regard to availability, firing schedules, ground support requirements, governmental agencies and contractors involved, liaison requirements, etc., is also vital to detailed program planning.

5.3 Sounding Rockets

The use of a sounding rocket to boost an OFFBACE system above the earth's atmosphere is a feasible method of obtaining the complete environment of space. The action of a sounding rocket in doing this is identical to that of a ballistic missile. The size of the rocket booster required to obtain comparable zero gravity durations is significantly reduced, however, since translational velocity need not be imparted to the sounding rockets' payload.

Table 5.3-1 is a compilation from the popular literature of sounding rockets that have been used primarily by governmental agencies to perform high altitude research. The payload capabilities of these rockets are sufficient to permit small OFFBACE systems to be utilized.

No data was found in the literature that would permit estimates of the zero gravity durations provided by sounding rockets. Accordingly, a simplified analysis was performed to determine this.

The zero gravity durations were obtained by calculating the time interval it would take the payload to fall from the peak altitude until atmospheric drag resulted in a non-zero gravity acceleration of $.01g$. The total zero gravity time interval is then twice the time to fall from peak altitude.

An integrated mean acceleration was used in determining the fall time in order to account for the decrease in gravitational acceleration at high altitudes. It was also assumed that the rocket motor had ceased firing prior to reaching the altitude at which the drag was $.01g$.

Figure 5.3-1 presents the results of this analysis. It is seen that zero gravity durations comparable to those of Intermediate Range Ballistic Missiles can be obtained by existing sounding rockets.

The cost of these vehicles is small and since many are solid propellant devices, the requirements for launch facilities are not rigorous. Data from the OFFBACE system could be obtained by telemetry of key parameters, but recording these data during flight is attractive since recovery of the payload is usually not difficult.

Special requirements of the OFFBACE system for the payload of a sounding rocket would require a detailed study to be made of their characteristics - especially important would

TABLE 5.3-1

POSSIBLE MISSILES FOR OFFBACE

<u>MISSILE</u>	<u>AGENCY</u>
Redstone	Army
Sergeant	Army
Pershing	Army
Jupiter	Army
Thor	Air Force
Atlas	Air Force
Titan	Air Force
Minuteman	Air Force
Polaris	Navy

ZERO-GRAVITY TIME PROVIDED BY SOUNDING ROCKETS AS A FUNCTION OF PEAK ALTITUDE

FIGURE 5.3-1

be the boost accelerations and the method of vertical guidance used. The ascent attitude of most sounding rockets is maintained by fixed aerodynamic fins or by imparting spin to the entire vehicle. Since any large accelerations resulting could compromise the Rankine experiment, this aspect must be examined.

5.4 Aircraft

The only method available to date that permits a human to observe and operate an experiment during zero gravity has been provided by aircraft. In performing a zero gravity maneuver, the airplane is essentially "flown around" the object being tested while this object is falling toward the earth. This technique for obtaining zero gravity is the same as that resulting from the use of ballistic missiles or sounding rockets, except that the aircraft is used to provide not only the initial vertical component of velocity, but is used to isolate the object under study from the drag that would result if this object were exposed to the atmosphere.

While aircraft has been used very extensively for providing the zero gravity conditions, most of the testing has been performed by the armed forces medical groups. These tests have been primarily for physiological experimentation. It has been only recently that aircraft have been utilized for performing engineering tests of the type that would be done in this program. For example, the first known tests of the condensing process during zero gravity conditions utilizing a liquid metal were performed by TRW during the Fall of 1959 in the Wright Air Development Center C131 aircraft. These tests, and others primarily concerned with fluid mechanics during zero gravity, have indicated that this type of aircraft testing needs to be very carefully performed. The results, however, are extremely satisfactory since large amounts of data (including photographs) can be obtained at a very minor expense.

The quality of zero gravity provided by an aircraft is completely dependent upon the skill of the pilot in modulating his power settings and maintaining the proper attitude of the aircraft. Flight tests at Wright Field have shown that experienced pilots can normally fly the C131 aircraft to within approximately $\pm .01g$ of the true zero gravity condition. For ideal simulation of the zero gravity aspect of the space environment, even these perturbations are not desired. These can be eliminated by allowing the object being tested to actually float within the cabin of the aircraft during zero gravity. Pilot guidance errors and, of perhaps even greater importance, miscellaneous aircraft vibrations would not be communicated to the object under test. At the WADC Zero Gravity Meeting of November 3, 1959, it was proposed that transport-type aircraft to be used for zero gravity testing be modified to permit this floating. The use of closed circuit TV to view the floating object and provide the pilot indications for corrective action would prevent the object from exceeding the limits of travel.

The duration of zero gravity provided by aircraft is a function of its maximum speed and structural capabilities. For example, the zero gravity period of the KC-135 trans-

port aircraft is limited to about 34 seconds by high speed buffet and maximum permissible wing loading.

The present upper limit on aircraft zero gravity durations is of extreme interest since it provides a long duration of zero gravity and also permits the testing of large systems, observed and operated by test personnel during flight. The maximum cargo area dimensions of this plane are approximately 80 feet long, 7 feet high, and 10 feet wide. It can carry several tens of thousands of pounds payload.

Table 5.4-1 is a listing of military aircraft capable of providing reasonable durations of zero gravity. This table also includes an estimate of the durations each could provide. In order for an aircraft to safely perform the zero gravity maneuver, it usually is modified to make its hydraulic, lubricant, and fuel supply systems insensitive to zero gravity. This normally entails the installation of accumulators to prevent pump starvation. A KC-135 is now undergoing such modifications in preparation for its use as a zero gravity test vehicle at Wright Field. This aircraft should be available for use in zero gravity testing in March, 1960.

5.5 Other Methods for Obtaining Zero Gravity

Simply releasing an object and allowing it to fall toward the earth in a vacuum will accomplish the requirement of providing a zero gravity environment. This allows this aspect of the space environment to be simulated very readily on the earth.

Figure 5.5-1 indicates the durations of zero gravity obtained by free fall. The lower line of this curve shows the time required for an object to drop a given distance.

In order to adequately study Rankine phenomena in this state, the time interval that the object falls should be significant. But since the velocity of the object increases 32 ft per second for each second of zero gravity time, a test package dropped within the atmosphere very soon has significant aerodynamic drag forces applied to it. If the test package is shrouded in a low drag envelope and the drop is made through a low density atmosphere, the onset of significant disturbing forces is delayed.

These requirements can be physically satisfied in two ways. A balloon could be used to lift a test package to altitudes in the order of 100,000 feet. Designing this package to have a low drag characteristic and utilizing the low densities at these altitudes will result in a reasonable period of zero gravity. Figure 5.5-2 shows that an object of good aerodynamic shape dropped from 100,000 feet will experience greater than 99% pure zero gravity for 22 seconds.

Durations of zero gravity could be increased by adding a simple thrust device to provide a force on the vehicle equal and opposite to the drag. This could be simply provided by a cold gas jet programmed by a timer.

TABLE 5.4-1

ZERO GRAVITY CAPABILITIES OF AIRCRAFT

Low Duration (Less Than 20 Seconds)

C-131
C-124
C-133
C-130

Medium Duration (20 to 50 Seconds)

T-33	F-86
T-39	F-94
T-38	A4D
B-47	F4D
B-52	F9F
B-66	KC-135

Long Duration (50 to 90 Seconds)

F-100
F-101
F-102
F-104
F-105
F-106
B-58
A3J
F8U
F11F

ZERO-GRAVITY DURATIONS OBTAINED

FIGURE 5.5-1

QUALITY OF ZERO GRAVITY FOR
OBJECT DROPPED FROM 100,000 FT.

FIGURE 5.5-2

A second technique for obtaining high quality zero gravity periods on the earth is to allow the test unit to fall freely through an evacuated shaft. For example, the unit could be dropped within a pipe installed in a vertical mine shaft. Vacuum pumps would be used to reduce the density within the pipe to a sufficiently low level. Reasonable aerodynamic shapes for the test units would relieve the vacuum pumps from having to meet any stringent low pressure requirements, and still result in high purity of zero gravity being obtained.

The duration of zero gravity obtained by any dropping technique can be doubled if the test unit starts at the bottom of the drop distance with a sufficient vertical velocity upward. A catapult at the bottom of a mine shaft, for example, could perform the dual task of accelerating the test unit upward and arresting it at the end of the period.

A suitable vehicle riding on a "roller-coaster" track operates on the same principle. This, as well as the mine shaft techniques, were discussed at the November 3, 1957 Zero Gravity Meeting. It was concluded that after the initial cost, such facilities would provide economical methods of obtaining the zero gravity conditions.

5.6 Summary

Figure 5.6-1 summarizes in graphical form the zero gravity durations to be expected from the various vehicles discussed in the preceding sections.

FIGURE 5.6-1

6.0 DESCRIPTION OF OFFBACE SYSTEMS

Various combinations of equipment and test beds could be utilized to explore the unknown areas set forth in the earlier sections of this report. These would include components, combinations of components, and complete systems. Sizes could range from the extremely small to the largest complete system under consideration. To achieve the desired information most economically, it has been determined that systems which closely approximate those of interest should be tested. Particularly, for the boiler and condenser, the temperatures, pressures, and heat rates should duplicate those of the actual systems. For test systems conforming to present design concepts, the minimum mercury flow rate which will result in a system having similarity to actual systems is about 0.2 lbs/min. Four systems are described below, two of which have an alternate design using this minimum flow rate.

The basic requirement of the test bed is that it provide a "zero gravity" environment of sufficient quality and duration that the effects of this particular phenomenon on the test apparatus may be accurately noted. Duplication of other aspects of space or orbital environment is desirable but is secondary to zero gravity effects for initial phases of testing.

Test system weights which are presented in this section are based on installation in two varieties of test bed - the KC-135 jet aircraft and a missile or satellite. Generally, as far as possible, the aircraft system would be packaged as a roll-on, roll-off unit with the only connections to the aircraft being power and recorder lines and tie-down straps.

This module concept probably will not be applicable to systems which are installed in missiles or satellites. Space will be at a premium on these vehicles and the test systems undoubtedly will be required to conform to the available space.

Four basic systems which would meet the OFFBACE requirements for a test system are presented below. These systems are presented in detail because each has inherent advantages and disadvantages with respect to the other three. Several permutations of each basic system are presented as an indication of the flexibility which exists within the overall OFFBACE framework. This flexibility is a requisite of a successful program since each system tested will necessarily be tailored to fit a situation having many unalterable features.

Briefly, the four basic systems can be described as follows:

- 1) Blowdown System - Liquid mercury will be supplied to the boiler from a pressurized tank. A choked nozzle and desuperheater provide a load for the boiler. Liquid mercury ejected from the subcooler will be collected in an evacuated receiver.

- 2) Pumping System - This system will be quite similar to the blowdown system except for the method of supplying liquid mercury. A sealed electric motor-driven pump will recirculate the liquid mercury from the condenser to the boiler.
- 3) SNAP I System - This system will utilize the rotating package developed for the SNAP I auxiliary power system as well as all other prototype system components.
- 4) SNAP II System - This system will utilize the rotating package developed for the SNAP II APU. This system will utilize all other SNAP II prototype hardware.

6.1 SNAP I OFFBACE Systems

"SNAP I" is the designation for a small space power system. The energy source was originally a radioisotope which supplied heat for the boiler of the mercury Rankine cycle system. The system is now of primary interest for use with a small, externally-cooled, nuclear reactor. Design features of this system which make it particularly suitable for space operation include a once-through boiler; direct radiation cooled once-through condenser; turbine, condensate and lubricant pump, and alternator mounted on single shaft; totally automatic shaft speed control; and a system designed for hermetic sealing.

The study which resulted in the SNAP I system was initiated prior to studies leading to other similar systems, and consequently, SNAP I development has been carried further than the development of similar systems. Actual systems tests have been accomplished with an electrically heated prototype boiler and a compact condenser. These system tests have demonstrated the basic soundness of the SNAP I design. It would appear, therefore, that the first OFFBACE tests of a complete Rankine system could be attractively accomplished with a SNAP I system.

The SNAP I design boiler consists of a single coil in good thermal contact with the nuclear heat source. The turbomachinery package contains a three stage mercury turbine, an alternator, and a condensate pump on a single shaft supported by two hydrosphere bearings. The condenser is a once-through tube-and-fin type which is directly cooled by radiating thermal energy to space. Two closed loop automatic controls are imposed on the system to control 1) shaft speed, and 2) superheat. Shaft speed is controlled indirectly by varying boiler inlet pressure.

A frequency discriminator varies the set point of a pressure regulator upstream from the boiler inlet. This results in a variation in boiler flow which causes a like variation in turbine power. Superheat is controlled by varying the amount of heat input to the boiler. Control of superheat is necessary to prevent excessive moisture from entering the turbine and to prevent over-temperature.

A SNAP I unit utilized for early OFFBACE type test would be modified somewhat, particularly in the boiler and condenser areas. To eliminate the expense and the additional complication resulting from radiation hazard, the nuclear heat source would be replaced with some other supply of energy. The mode of energy source will vary with the vehicle being used to provide the environment. For zero gravity tests performed in the KC-135 jet aircraft, an electrically heated boiler would be utilized. Sufficient on-board electrical power is available on this particular airplane to meet the needs of a SNAP I system. For tests conducted on board long range missiles or satellites, electric power may not be readily available. Hence, alternate power sources must be considered, and an optimum determined for each mission.

The variable which will have the greatest effect on the choice of heat source is the duration of test. Generally, three sources of heat are available; electrical, heat of fusion (lithium hydride), and heat of combustion. In general, the weight of lithium hydride and combustible materials will be approximately equal for a given mission, and will be about 15% as great as the weight of batteries which will perform the same mission. For short duration tests the weight of the energy source will not comprise the bulk of the total weight and electrical heating will be utilized because of the ease of application. For the longer duration systems, battery weight becomes so large as to rule out that method of heating. The combustion type of energy source has been ruled out because of its 1) complexity (extreme development required or low reliability obtained), and 2) this mode of supplying heat to the mercury is not typical of that to be used in Rankine space power plants.

A boiler which utilized lithium hydride would be quite similar to the present electrically heated boiler. Instead of being surrounded by electrical heaters, the boiler coil will be immersed in a container of molten lithium hydride. Internally, however, the boiler will have the same configuration as the actual SNAP I boiler.

Use of a lithium hydride heated boiler would not permit the realization of the present design turbine inlet conditions. The fusion temperature of lithium hydride is somewhat below the design inlet temperature for SNAP I. This difference would not be a major concern, however.

Lithium hydride or batteries cannot provide sufficient energy to allow operation for a period sufficient to adequately determine the effects of meteoric erosion on the radiators. The effect on emissivity is expected to occur over a relatively long period of time, longer than the test system will be operational. A chance puncture during this limited operating time would not indicate anything about the statistical probability of failure by penetration.

Condenser design would be altered somewhat in the case of the airborne system; however, every attempt would be made to preserve the internal configuration. The condenser which would be used in the satellite and missile tests would be similar to the actual SNAP II condenser, that is, radiation-cooled, tube-and-fin. The aircraft condenser would be air-cooled and modified to reduce the outside heat transfer coefficient in order to approximate

the heat flux of the radiation cooled condenser.

The aircraft air conditioning system would use additional cooling air, if required, to handle the additional load imposed by the SNAP I system. A non-mercury heat transfer loop will also be necessary to transfer heat from within the test module to an additional air-cooled heat exchanger.

Startup of the SNAP I system requires the use of an auxiliary pump and some additional plumbing. For the aircraft flight this equipment would be an integral part of the test module. For the missile or satellite shots, the auxiliary equipment would be external and removable at time of firing. This extra equipment may also be eliminated or replaced by additional development.

Since SNAP II is basically a larger version of SNAP I, condenser, boiler, and rotating package are quite similar to the respective components of the SNAP I system. Hence, virtually all experimental data collected from operation of a SNAP I system will be directly applicable to the SNAP II development effort.

Table 6.1-1 lists the major components and their respective weights for the SNAP I OFFFACE system designed for use on board a large transport type of aircraft. In the interest of maintaining a minimum cost program the use of design and construction techniques to permit a low volume, low weight, installation received secondary consideration.

This OFFFACE system with all auxiliaries and instrumentation could be mounted in an enclosure measuring 6 feet in height, width, and length. This size enclosure will readily fit into a KC-135, but if a more compact design is required it could be reduced, at the expense of more difficulty in fabrication and maintenance. This enclosure is used as a structural member for mounting of components and for assuring that no mercury vapor could enter the aircraft cabin area. This system requires approximately 15 kilowatts of electrical power from the aircraft and a sufficient supply of cooling air to accept this amount of heat from the system.

Table 6.1-2 is an estimated weight breakdown for an orbital or missile type of SNAP I OFFFACE system. Figure 6.1-1 shows the total estimated system weight when operating the system from either battery or lithium hydride energy sources.

Figure 6.1-2 is a schematic representation of this type of OFFFACE system.

6.2 SNAP II OFFFACE Systems

The SNAP II system is very similar in concept to SNAP I. It is physically larger, however, since its electrical power output of 3 KW is six times that of SNAP I. The heat source for SNAP II is a nuclear reactor cooled by a liquid sodium-potassium alloy

TABLE 6.1-1
SNAP I FIXED WEIGHTS
(KC-135)

Boiler	40
Condenser	20
Turbomachinery	25
Auxiliaries	160
Structure & Enclosure	300
Instrumentation	1200
Miscellaneous	<u>80</u>
Total	1825 lbs

TABLE 6.1-2
SNAP I FIXED WEIGHTS
(Orbital or Missile)

	<u>LIH</u>	<u>Battery</u>
Boiler	25	37
Condenser	20	20
Turbomachinery	25	25
Auxiliaries	-	-
Structure & Enclosure	50	50
Miscellaneous	<u>35</u>	<u>35</u>
Total	155	167

WEIGHT ESTIMATE SNAP I SATELLITE TYPE OFFBACK SYSTEM

FIGURE 6.1-1

SNAP I OFFBASE SYSTEM

FIGURE 6.1-2

(NaK). The hot NaK evaporates and superheats the cycle working fluid, mercury, in a second heat exchanger. The turbomachinery package contains the turbine, alternator, mercury pump, and sodium pump, all mounted on a single shaft supported on mercury-lubricated journal bearings. The SNAP II condenser, in its final configuration, will comprise a portion of the vehicle skin. It will be of tube-and-fin construction typical of a prototype space condenser.

Rotor speed control is achieved through a parasitic alternator load which is actuated by a frequency discriminator.

The SNAP II OFFBACE system for zero gravity evaluation in a KC-135 is comprised primarily of the Power Conversion System (PCS) components being developed in the SNAP II program. These components, two fluid boiler, combined radiant and convectively cooled condenser, and turbomachinery package are pre-flight design hardware. They are, therefore, not of minimum weight or size. These components would be coupled with a 'reactor simulator' -- an electrically heated NaK loop -- to complete the system's major components. Figure 6.2-1 shows a possible configuration for this OFFBACE system. Three enclosures are used for ease of handling when installing in the aircraft. Enclosure No. 1 consists of the electrically heated NaK system and the NaK-mercury boiler. An electromagnetic pump is included in this enclosure also if it is desired to have pumping capability beyond the turbine driven NaK pump. Enclosure No. 2 contains the turbomachinery package, condenser and auxiliaries (vacuum pump, auxiliary mercury pump, etc.). All of the system controls and instrumentation are located in Enclosure No. 3.

Table 6.2-1 shows the estimated weights of the system broken down by major components. Total power required by the system would be approximately 80 KW of which 65 KW is used in the NaK heater. Auxiliary generators would probably have to be installed in the aircraft to provide this amount of power.

A modification to the aircraft may be required since the present air conditioning equipment would not be sufficient to handle the condenser heat rejection. It is expected that ducting external air into an additional heat exchanger and a secondary heat transfer loop will be required.

A SNAP II OFFBACE system designed for missile or satellite testing would use SNAP II flight hardware. The configuration of this system would be identical to the final SNAP II installation except that a reactor simulator would replace the reactor. The reactor simulator selected for the system discussed here utilizes lithium hydride as the energy source, since this appears to offer the best non-nuclear method of obtaining the required heat. Table 6.2-2 is a weight breakdown for the orbital type of SNAP II OFFBACE system. The weights shown are estimates of early flight type SNAP II hardware; later versions would be smaller. Figure 6.2-2 shows the weight of the system as a function of operating time for active life times up to 20 hours.

INSTALLATION OF SNAP II OFFBASE SYSTEM IN A KC-135 AIRCRAFT

FIGURE 6.2-1

TABLE 6.2-1

SNAP II SYSTEM WEIGHT (KC-135)

NaK Heater	250
Boller	150
Turbomachinery	30
Condenser	100
Auxiliaries	160
NaK Inventory	170
Mercury Inventory	100
Structure & Enclosures	1100
Instrumentation	1200
Miscellaneous	80
Condenser Cooling System	500
Safety Equipment	<u>300</u>
Total	4140 lbs

TABLE 6.2-2
SNAP II SYSTEM WEIGHT
(Orbital or Missile)

NaK heater	300
Boiler	150
Turbomachinery	30
Condenser	100
NaK Inventory	100
Miscellaneous	<u>80</u>
Total	760

WEIGHT ESTIMATE SNAP II SATELLITE TYPE OFFBACE SYSTEM

FIGURE 6.2-2

SNAP II OFFBASE SYSTEM

FIGURE 6.2-3

Consideration should be given to using the SNAP II reactor as the heat source for an experiment of this type. This may result in a lighter weight system which would also be capable of extended operating times.

Testing of the SNAP II system described here would duplicate the environmental operation of a Rankine cycle space power plant having a definite mission. Furthermore, these tests could be performed at an earlier date than tests on any other projected similar space power system. The major drawback to the use of a SNAP II type system in OFFBACE experimentation is the large physical size and weight associated with this equipment. The basic system is fairly heavy compared to the others described here. In addition, the higher power requirement necessitates the use of an auxiliary generator in the case of the aircraft system or a large amount of energy storage material in the case of the missile system.

Two modifications of the SNAP II system described above are possible to reduce the overall weight of system plus energy storage. Either modification would result in a system having nearly the same operating characteristics as the full-size system. The additional development necessary could increase the cost, and possibly the development time, of a system incorporating either or both of the following modifications:

The NaK heating vessel and circulation loop represent approximately 35 percent of the dry system weight. If the heating medium were applied directly to the mercury boiler, all the apparatus associated with the NaK loop could be eliminated. In this case, the temperature distribution associated with a counterflow heat exchanger would be sacrificed, resulting in a boiler having slightly different operating characteristics from the prototype boiler.

A second modification involves a reduction in alternator output power. The power output of the alternator will not be utilized for useful purposes during OFFBACE tests. Power required to drive the alternator is about 75% of the turbine output. If the alternator power output were reduced to that value required for parasitic load speed control, the turbine flow rate could be reduced by approximately one-third of the design value. This would permit a like reduction in the size and weight of the boiler, condenser, and heat storage material. From a system simulation standpoint, the only penalty which cannot be fully evaluated at this time would be the results of not testing full size prototype components.

6.3 Pumping and Blowdown OFFBACE Systems

The blowdown and pumping systems are quite similar in nature, the only major difference being the method used for supplying pressurized mercury to the boiler. Neither of these systems incorporates a prototype turbomachinery package. Hence, the mercury flow rates are not dictated by turbine or bearing requirements. This fact allows a certain flexibility in design; in particular, it permits the use of systems having lower flow rates, and,

therefore, lower energy requirements, than any prototype systems.

Both systems provide the opportunity for examining the effects of orbital flight on boilers and condensers similar to those which will be used in a mercury Rankine system. The pumping system provides an additional capability for determining pump characteristics during operation in an orbital environment.

The blowdown system consists essentially of a supply of pressurized liquid mercury, a boiler, and a condenser. The pressure of a bladder-type mercury reservoir will be regulated and an orifice between the supply and the boiler will meter the flow. To maintain realistic boiler operating conditions, the liquid entering the boiler will be preheated from ambient to normal inlet temperature. A choked nozzle and desuperheater between the boiler and condenser will simulate the turbine load. Discharge from the condenser can be collected in an evacuated container or discharged from the system, depending on the vehicle being used. In the case of the aircraft zero gravity flights, a container must be provided since the ambient pressure would be too great to permit expulsion of liquid from the condenser. For an orbital system which is started in orbit, the liquid mercury could be vented to space, thereby effecting a weight savings through elimination of the mercury receiver.

The pumping system will accomplish approximately the same end results as the blowdown system. The pumping system will be recirculatory and will not require a mercury reservoir, preheater, or pump. The pump will supply liquid mercury to the boiler and will draw mercury from the condenser outlet. The resulting closed loop will be hermetically sealed.

Two pump design concepts are presently being evaluated. One of these concepts would utilize a configuration which would result in a pump-motor combination having minimum weight and a minimum energy requirement. This motor pump would provide mercury to the boiler at correct pressure and flow but would not furnish information regarding environmental operation of a prototype pump.

For a small trade-off of weight, cost, development time, and reliability, a motor-driven prototype pump, probably SNAP II variety, could be utilized as the condensate pump for the pumping system. In order that the design flow rate for the prototype pump be accommodated a pump bypass with an appropriate cooling system will be required.

For either concept, the motor drives will be commercially available types and, as such, will not be compatible with a mercury vapor atmosphere. A seal and cover gas arrangement has been devised to circumvent this problem.

As was mentioned earlier, pumping or blowdown systems could be designed for virtually any flow rate desired. Weight estimates have been made for systems having flow rates of .2 lbs/min and 2.0 lbs/min, since these particular values seem to be the most logical to consider at the present time. To obtain the minimum weight system, a low flow rate is necessary, since the sizes of the major components and the quantity of energy storage

material are roughly proportional to flow rate. However, components may become so small that they no longer bear a resemblance to their antecedents. Analyses indicate that for flow rates of less than about .2 lbs/min, the fluid mechanics associated with the models will either depart significantly from those of the full size components, or fabrication problems become significant. The two lbs/min flow rate closely approximates that of the SNAP I system which will have had extensive test experience prior to any OFFBACE tests. A system with a two lb/min flow rate would thus provide a direct comparison of orbital operation with ground test operation.

Schematic drawings of the pumping and blowdown OFFBACE systems are shown in Figures 6.3-1 and 6.3-2 respectively. Estimates of the fixed weights associated with these systems are listed in Tables 6.3-1 and 6.3-2. These weights are prepared for two sizes of systems: 1) 2 lbm per minute flow rate of mercury to the boiler. This system would utilize the boiler and condenser developed under the SNAP I program. 2) 0.2 lbm per minute flow rate. As has been indicated, the size system resulting from the use of this boiler flow rate is considered to be the minimum practical.

How the total weights of these systems vary with operating duration when utilizing stored energy is shown in Figures 6.3-3 and 6.3-4.

OFFBACK PUMPING SYSTEM

FIGURE 6.3-1

OFFBACK BLOWDOWN SYSTEM

FIGURE 6.3-2

TABLE 6.3-1

MINIMUM SIZE OFFFACE SYSTEM WEIGHT (PUMP)

	<u>KC-135</u>		<u>Missile</u>		or	<u>Satellite</u>	
Energy Source			Li H			Battery	
Mercury Flow Rate (lbs/min)	0.2	2.0	0.2	2.0		0.2	2.0
Boiler	8	37	3	25		8	37
Condenser	3	15	4	20		4	20
Motor-pump	13	13	13	13		13	13
Condenser Cooling System	5	20	-	-		-	-
Structures & Enclosures	10	140	7	50		7	50
Miscellaneous	<u>23</u>	<u>65</u>	<u>16</u>	<u>37</u>		<u>13</u>	<u>23</u>
Total (lbs)	62	290	43	145		40	143

TABLE 6.3-2

MINIMUM SIZE OFFFACE SYSTEM WEIGHT (BLOWDOWN)

	<u>KC-135</u>		<u>Missile</u>		or	<u>Satellite</u>	
Energy Source			Li H			Battery	
Mercury Flow Rate (lbs/min)	0.2	2.0	0.2	2.0		0.2	2.0
Boller	8	37	3	25		8	37
Condenser	3	15	4	20		3	20
Mercury Supply System	16	35	12	26		12	26
Condenser Cooling System	5	20	-	-		-	-
Structure & Enclosure	15	150	7	50		7	50
Miscellaneous	<u>20</u>	<u>70</u>	<u>14</u>	<u>24</u>		<u>14</u>	<u>14</u>
Total (lbs)	67	327	40	145		44	152

FIGURE 6.3-3

FIGURE 6.3-4

7.0 CONCLUSIONS AND RECOMMENDATIONS

In the previous sections of this report the reasons for conducting an OFFBACE program have been presented, methods for obtaining the zero gravity and orbital environments have been suggested, and four systems for use in OFFBACE have been described.

The purpose of this section is to summarize the conclusions which Thompson Ramo Wooldridge has reached as a result of these studies and to recommend a specific program for continuation of the OFFBACE efforts.

The conclusions of the evaluation studies may be simply and positively stated:

1. Experiments to obtain data on the effect of zero gravity on boiling and condensing are of utmost importance to permit accurate design of the SNAP II power conversion system and other Rankine cycle space power systems. These experiments should be performed as soon as possible.
2. Zero gravity testing of complete boiling, condensing, and pumping loops is the most desirable method of conducting an early OFFBACE program. This type of system will provide heat transfer and fluid dynamic information required for the design of a complete Rankine cycle space power system.
3. Operation of a complete Rankine cycle power system in a satellite or a missile is also of major importance and planning for conducting this type of test should continue. This type of test is vital to demonstrate capability of operation during the launching phase or, alternatively, the capability of making orbital startup. It is also vital for the purpose of obtaining data on the effects of operation for extended periods in zero gravity and in the complete orbital environment.
4. An OFFBACE program represents an extremely valuable means for supplementing ground-conducted environmental testing programs and, in addition, provides information that cannot be obtained on the ground. This type of experiment is essential and will prove to be an economy in the development of Rankine cycle space power systems.

A specific recommendation for the type of system for use in further OFFBACE activity is difficult to positively make. Each type of system studied has its own particular advantages. The choice of a system for further testing will depend on circumstances which develop with respect to the cost and availability. Since no detailed investigation of satellite vehicle availability has been made, it is not possible, at this time, to make an unqualified recommendation.

The applicability of the four systems studied to the OFFBACE effort is summarized below:

1. Blowdown Systems

These systems are suitable for investigating boiling and condensing phenomena in zero gravity. They provide no data on the interaction of Rankine system components, and are not feasible for long duration use in vehicles that provide the complete orbital environment. When mercury is used as the cycle fluid, they are not competitive with pumping systems due to TRW's extensive experience with mercury pumps, although, for early tests of other cycle fluids, this disadvantage may not be as clear-cut.

2. Pumping Systems

These systems permit the investigation of all major Rankine system components and how their interactions affect the overall system. They are practical in any size of mercury system having a flow rate greater than about 0.2 lb per minute. They can readily be placed in the orbital environment provided by any type of vehicle - aircraft, sounding rocket, missile, satellite. They can be made in small sizes to permit low cost "piggyback" testing. Complete experience (at TRW) with the components of these systems would allow them to provide the needed data after a short and low cost development period.

3. SNAP I OFFBACE System

A system utilizing components developed under the SNAP I program would allow the earliest testing of a complete Rankine space power system in the orbital environment. Its small size would permit a wide range of vehicles to be used to provide the environment.

4. SNAP II OFFBACE System

The use of SNAP II concepts and hardware for an OFFBACE system is very attractive. The SNAP II development program and a parallel OFFBACE program would result in a desirable interchange: the OFFBACE program would receive developed hardware from the SNAP II program, and supply valuable environmental data on this hardware. The size of an OFFBACE SNAP II, however, requires that careful planning be done to integrate economically with vehicles capable of providing the environment.

In the light of these considerations and the preceding conclusions, the following recommendations are made:

1. A small boiling, condensing, and pumping system utilizing mercury as the cycle fluid should be developed immediately. The design of the component

of this system should utilize SNAP II concepts to the greatest degree feasible in order to make a direct contribution to that program. This system should be zero gravity tested in aircraft at the earliest possible date.

2. The OFFBACE system just described should be further developed to make it capable of providing the needed data while in the complete orbital environment provided by a sounding rocket, missile, or satellite vehicle.
3. Planning for zero gravity testing of a non-nuclear SNAP II OFFBACE System in a KC-135 should be conducted.
4. Planning for orbital testing of a SNAP II OFFBACE System should be conducted.
5. The vehicles capable of being used in items 2 and 4 should be investigated in detail with respect to their availability and performance characteristics.

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