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FINAL TECHNICAL REPORT
STUDY OF ZERO GRAVITY CAPABILITIES OF LIFE SUPPORT SYSTEM COMPONENTS AND PROCESSES

GENERAL DYNAMICS
Convair Division

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FINAL TECHNICAL REPORT STUDY OF ZERO GRAVITY CAPABILITIES OF LIFE SUPPORT SYSTEM COMPONENTS AND PROCESSES

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FOREWORD

This report was prepared by Convair division of General Dynamics under Contract NAS 1-6939 with the National Aeronautics and Space Administration, Langley Research Center, Langley Station, Hampton, Virginia. Messrs. F. W. Booth and T. P. Wright, Jr., were the technical monitors for NASA/Langley Research Center. The work reported was performed during a twelve months period starting 28 December 1966. The principal members of the Convair project team were Mr. J. C. Ballinger, Project Leader; Mr. G. B. Wood; and Mr. J. R. Burnett. The authors acknowledge the valuable assistance of Mr. G. L. Drake, Chief of Life Support Engineering, Convair.

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SUMMARY

A study was conducted to define a program for determining the zero gravity capabilities of the life support components and processes contained in the Langley Research Center Integrated Life Support System (ILSS). The study included three major tasks: the identification, and analytical evaluation of gravity-sensitivities inherent in the performance of the ILSS components and processes; the investigation of methods for experimentally evaluating those critical items for which zero-gravity performance could not be adequately determined by analytical techniques; and the formulation of generalized criteria for assessing the gravity-sensitivity of alternate life support system processes as well as those originally incorporated in the ILSS.

The identification and analysis of ILSS gravity sensitivities was directed toward the selection of components and processes which would require experimentation for verification of their zero-gravity performance. From an initial 92 processes associated with the ILSS, 69 gravity-sensitive processes were identified. Analysis showed that for 28 of these, the gravity sensitivity was such that a negligible effect on component performance could be expected due to gravity variations between one and zero gravity. These 28 processes were thus eliminated from further consideration as test candidates.

Additional process screening was performed to eliminate other items whose gravity sensitivities and zero-gravity performance could be adequately determined by analytical methods, or whose testing was considered inappropriate due to the nature of the process. Items whose testing was considered inappropriate included man-machine interface processes such as equipment servicing and personal hygiene tasks, and components in an early developmental phase which were expected to undergo significant re-design. This additional screening resulted in the elimination of all but four of the original processes; but it also revealed that certain premises upon which the analyses were based should be tested to assure adequacy of the analytical screening treatments. The four remaining ILSS processes represent liquid-mixing and flame propagation phenomena, while the analytical problem areas involve heat transfer and liquid transport by gas drag. These items represented potential test candidates.

The investigation of experimental methods included a detailed review of actual low gravity and gravity related techniques; a survey of available facilities for experimentation; and an evaluation of the methods, as they might apply to the test candidates, including consideration of expected costs and facility availability.

The utility of analytical techniques in assessing gravity effects on performance became apparent in the screening studies. Consequently, the development of these techniques was expanded beyond the immediate needs of the ILSS analyses into generalized analytical approaches applicable to those basic processes which may be expected to be common to most foreseeable life support systems. These approaches are intended to provide techniques for predicting gravity-sensitivity of existing systems and components, as well as to provide design criteria for future systems. Processes considered in this phase of the study include heat transfer between fluids and solids; liquid behavior control

be gas flow, capillarity, and centrifugation; solids control by gas flow; fluid mixing; mechanical device operation; and flame propagation.

From consideration of the ultimate value of a possible test program it was concluded that greatest benefit could be realized from experimentation to validate and support the analytical problem areas of heat transfer and liquid transport. Testing of the ILSS processes of liquid-mixing and flame propagation was felt to be of less value as future life support system designs are expected to appreciably reduce or eliminate the importance of their gravity-sensitivities.

A particularly pertinent conclusion which may be drawn from this program is that the majority of processes in the ILSS, and probably within life support systems in general, are of such a nature that their gravity sensitivities can be satisfactorily assessed by analyses; reducing the need for special component testing. In view of this it is recommended that the prediction criteria be further developed and expanded into a "Handbook" which could eventually include essentially all processes common to anticipated future space systems. Performance of experimentation to verify the analytical premises is one step in this direction.

INTRODUCTION

Life support system problems associated with reduced or zero gravity have received varying degrees of attention for several years. During design and development of the Langley Research Center Integrated Life Support System (ILSS), performance insensitivity to gravity was a major consideration. It was recognized, however, that some degree of g-sensitivity (gravity-sensitivity) could exist in the various subsystems and further study should be undertaken to evaluate the performance of these subsystems under zero-g conditions. It was further recognized that the ILSS, though itself not a flight article, could be considered as a progenitor of eventual flight hardware with many of the elementary processes in the ILSS being common to most foreseeable life support systems. Thus, the identification and understanding of g-sensitivities within the ILSS could preclude the introduction of undesireable g-sensitivity in future life support systems. Consequently, this study was initiated with the objective of defining a program that would determine zero-g capabilities of the ILSS components and processes. The study included three major tasks: the identification and analysis of g-sensitivities inherent in the performance of the ILSS components and processes; the investigation of methods for experimentally evaluating those critical items for which zero-g performance could not be adequately determined by analytical techniques; and the formulation of generalized criteria for assessing the g-sensitivity of alternate or future life support systems having basic or elementary processes related to those of the ILSS.

The identification and analysis of ILSS g-sensitivities was basically a screening process for selection of critically g-sensitive components and processes requiring testing for verification of their zero-g performance. The screening process was to eliminate from test consideration those items whose g-sensitivity was not significant to subsystem performance, or could adequately be determined by analytical techniques; and those items whose testing was considered to be beyond the scope of the program, such as man-machine interface processes. The investigation of experimental methods was directed toward the selection of test techniques best suited for studying the critical g-sensitive processes and phenomena. The g-sensitivity prediction criteria were intended to provide the basic analytical tools and techniques for assessing g-sensitivities in existing processes and for pre-determing g-sensitivities of future systems while in the design stage. Conceivably this criteria study could be profitably expanded beyond the processes and ranges of variables significant to the ILSS, into a "Handbook" of broad applicability and utility to the life support system designer.

For convenience, the work performed is categorized in this report into a review of the basic physical principles to be considered in studying process g-sensitivity; the analyses and screening procedures used for selection of processes as test candidates; a review of g-related test methods including their evaluation and selection; and the generalized g-sensitivity prediction criteria.

BASIC PHYSICAL PRINCIPLES

The differences in system behavioral characteristics between the normal and low gravity conditions are not caused by the introduction of any new phenomenon. They are caused, rather by the drastic reduction of a commonly accepted and often over-riding force which is strongly entrenched in the mental and physical make-up of man. In the normal environment many other forces exist, are recognized and understood, and are normally neglected in our routine prediction of how things will behave because these forces are so weak that they are overridden by the force of gravity. With gravity removed or drastically reduced, these "weak" forces can produce significant motions of large, as well as small, systems, and the motions are unfamiliar. Extending this just a bit farther, the unfamiliar motions produce unfamiliar configurations. As an example, it was observed during the early "zero-g" (null-gravity) airplane maneuvers that globs of liquid drifted out of an open top container and floated about the cabin. The shape of these globs tended toward the spherical but oscillated in a more or less regular way with the small drops oscillating more rapidly than the large ones. The liquid came out of the container because it was boiling (LN_2) and because of the random gentle variation of the aircraft acceleration vector, and even the larger liquid masses were rounded by the influence of surface tension.

The experience pointed out that the performance of systems in the absence of gravity must be analyzed with some care and with an understanding of basic physical principles. The general guidelines for such analysis are described in this section. Also, since those early flights, an appreciable background of low gravity experience has been accumulated which will assist to guide the analysis.

Physical Background

Essentially the behavior of matter is the combined result of its properties and its environment and may, in a very basic analysis, be reduced to the interaction of gravity, inertia, and intermolecular forces. For example, the characteristics of matter that permit its categorization into gas, liquid, or solid and thus determine its behavior may be attributed to these forces. Here we are dealing with the interplay of inertia and intermolecular forces (probably electrostatic) and the resultant of this interplay shows discontinuous changes at very closely defined levels of molecular activity and spacing. Molecular activity, or temperature, has such a controlling effect on the characteristics of matter that thermal effects should perhaps be included as a basic behavior determinant along with the gravity, inertia and intermolecular forces. While the properties of materials can all be attributed to these basic determinants, they normally represent combination effects without specific reference to basics. The engineer, however, in performing environmental and system studies frequently must consider both the basics and the combination properties or characteristics.

Engineering methods and procedures by which devices and systems are created and evaluated are derived from various sources. The equations and other relationships used for problem analysis are grounded on mathematical and empirical evidence of their accuracy. The fundamental considerations of the preceding paragraph are among the sources, but others are also used. Classical studies of fluid mechanics and thermodynamics deal largely with the characteristics of continuous media. Modern treatments take the particulate nature of matter into consideration and use it to improve the relationships, as for instance in highly compressed gases where P V/T is not constant. For our analyses here, no general attempt is made to trace the methods to their source.

Methods are outlined below by which the g-sensitivity (gravity-sensitivity) of the ILSS can be analyzed. They are general guidelines, some leading toward a numerical solution. The more important criteria for g-sensitivity are presented in what was felt to be the most generally convenient form.

Solid mechanics.- Assessment of the effect of gravity (and its removal) on solid structures is usually straight forward. Non-moving structural elements will normally undergo very little if any change in shape or configuration due to the removal of gravity, and any slight change that might occur should be amenable to direct computation. Moving elements are generally designed in such a manner that controlling or actuating forces will effectively over-ride the gravitational force, thus eliminating any significant g-sensitivity. However, these gravity effects can again be analyzed in a straightforward manner. In general, control and measurement devices, such as relays or instrument movements have to be reviewed with some care to ensure that the motion of any unbalanced elements is adequately controlled by desired forces.

Interface statics.- The symmetry of the intermolecular forces which pervade the body of a liquid is lost at a liquid-gas interface. As a result, the interface has a measurable surface tension, expressed in units of force per unit length. Surface tension is evident in bubble and droplet shapes. Both tend to be spherical with the surface behaving something like the skin of a balloon which compresses the inner fluid according to the Young-Laplace equation.

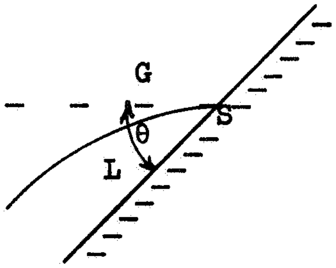
$$\Delta P = \sigma \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

where: ΔP = pressure difference inside and outside the surface.

σ = surface tension

R_1, R_2 = surface radii (Orthogonal)

The surface tension may also be thought of as a surface energy in units of work per unit surface area and applied to solid-gas and solid-liquid interfaces. Then, where liquid, solid and gas meet, a contact angle θ (measured through the liquid) is defined as shown below.



$$\sigma_{LG} \cos\theta = \sigma_{SG} - \sigma_{SL}$$

The tendency for the liquid to wet the solid surface is then greater where θ is small, which is promoted by small values of σ_{LG}.

Capillary effects (the tendency for liquids to rise or fall in small tubes) are directly influenced by gravity. In low gravity, capillarity is evident in tubes some inches or more in diameter. The interplay of the opposing forces is expressed by the Bond Number (Bo).

$$Bo = \frac{\text{Gravity Force}}{\text{Surface Force}} = \frac{\rho\, g\, L^3}{L\,\sigma} = \rho\, g\, L^2/\sigma$$

where: ρ = mass density of the liquid (assuming the gas density is negligible).

g = acceleration of gravity

This dimensionless ratio forms a useful tool to determine whether the behavior of a system is dominated by gravity or capillarity, and, conveniently, the transition is in the region of unity.

Where $Bo \ll 1$, capillary forces dominate, and

where $Bo \gg 1$, gravity (or other acceleration) dominates.

Fluid drag and lift.- Moving fluids exert forces on solid objects by reason of inertia and viscous effects.

The dimensions of viscosity are derived from Newton's law of viscosity.

$$\tau = \mu \frac{dV}{dy},$$

where: τ = shear stress (FL^{-2})

V = fluid velocity (LT^{-1})

y = distance (normal to velocity) (L),

thus: μ = viscosity $(FL^{-2} \cdot L \cdot L^{-1}T) = (FTL^{-2})$

This relation is useful also for computing the fluid shear rate produced by a known shear stress level and vice versa. With viscous fluids, small objects, and low velocities the viscous effects predominate, leading to the Stokes equation for the viscous drag on a sphere.

$$F = 3 \pi \mu V D$$

where: F = drag force

μ = viscosity of the fluid

V = stream velocity remote from the sphere

D = diameter of the sphere

This equation is, however, of limited utility, and at higher velocities (also low viscosity and large size), the dynamic pressure is assessed in terms of the inertia effects.

$$q = \tfrac{1}{2} \rho V^2$$

q = dynamic pressure

A dimensionless ratio was evolved by Osborne Reynolds to distinguish between the viscosity dominated and inertia dominated regions.

$$Re = \frac{\text{Inertia Force}}{\text{Viscous Force}} = \frac{V^2 L^2 \rho}{VL \mu} = \rho \, VL/\mu \; ,$$

This Reynolds Number has had extremely broad use in characterizing flow regimes, with the results usually expressed as a coefficient (C_L, C_f, etc.--used to multiply q) plotted against Re. The major break over from laminar (viscous) flow to turbulent (inertia dominated) flow occurs at Reynolds Numbers between ten and a million. This might seem like a uselessly wide range, but for any given configuration, such as for a circular cylinder in transverse flow, the data has been tied down quite closely. It is indeed true of all the dimensionless ratios (Bo, Re, etc) that they can be rigorously applied only when the hardware configuration in question is geometrically similar to the configuration of another system whose behavior is known. Similarity of the dimensionless parameter then provides assurance of similarity of flow between the system and the model. This, however, requires or implies that other pertinent parameters are likewise generally sufficient to assure similarity of behavioral regime rather than identity of parameter.

Interface dynamics.- Under dynamic loading, the liquid/gas interface may be distorted, agitated and torn. Normally, gravity and surface tension act to stabilize the interface, while inertia acts to break it up. The interplay of gravity and inertia effects, as in the case of water disturbed by the passage of a ship, are related to each other by the Froude Number.

$$Fr = \frac{\text{Inertia Force}}{\text{Gravity Force}} = \frac{\rho \, V^2 L^2}{\rho \, g \, L^3} = V^2/Lg$$

Similarly, the Weber Number relates inertia and surface tension effects.

$$We = \frac{\text{Inertia Force}}{\text{Surface Force}} = \frac{\rho \, V^2 L^2}{\sigma \, L} = \rho \, V^2 \, L/\sigma$$

The relative importance of gravity, inertia and surface tension can then be assessed on one diagram (figure 1).

Inspecting this diagram in search of information on the effect of gravity on the behavior of the liquid/gas interface leads to certain conclusions. Fr and Bo measure this effect, and from the structure of these dimensionless ratios it is apparent that a low "gravity" in a large system can have as much effect as normal gravity in a small one. At zero gravity, Bo becomes zero and Fr becomes infinite.

Zero gravity, meaning no residual acceleration forces on the structure, can happen only momentarily, if at all, and Bo and Fr serve to measure the hydrodynamic importance of the remnant g level. It is apparent that at very low g, the Weber Number forms a useful measure of what might be considered the fluid mechanical violence of the conditions in a reasonably normal plumbing system.

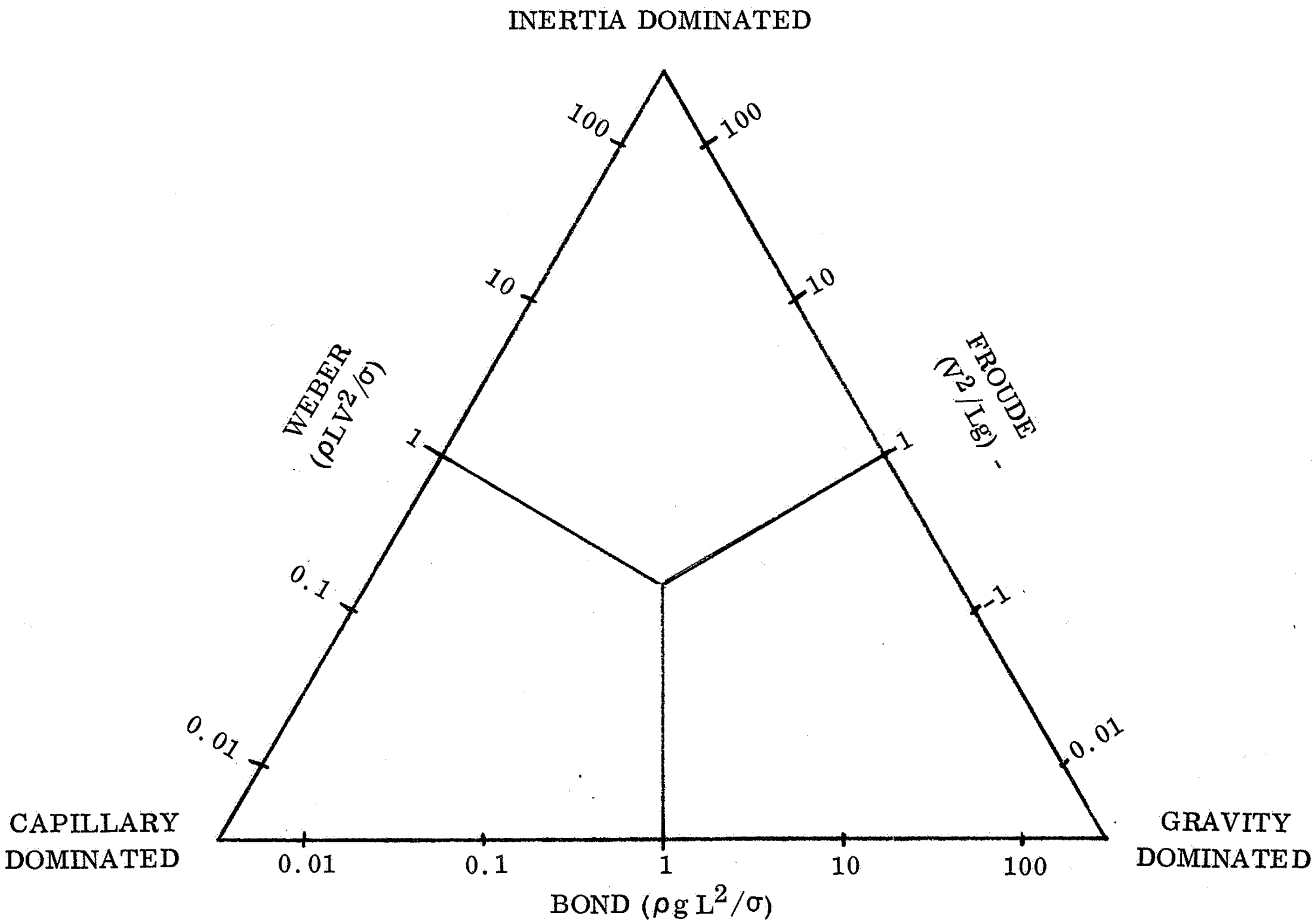


Figure 1. - Regimes of Liquid/Gas Interface Behavior

The ability of a gas stream to move or support liquids or solid particles comes into question in several phases of the life support system study. Equating, therefore, the drag force on a particle to its weight, we may derive the gas velocity required to support the particle against the influence of gravity or any other acceleration field. The results of such a calculation are shown in figure 2 for water droplets falling through air at normal temperature and pressure. The terminal drop velocities are shown for three different g-levels, together with lines of constant Re and We. For the smaller drops at the lower velocities, the drag is mostly viscous friction but the inertia effects start to become effective where Re rises above 10 to 100. It will be noted that the velocity curves extend only slightly beyond a Weber Number of unity. In this region the aero-dynamic forces have an increasing effect on the shape of the drop, with the pressure on the bottom tending to flatten it, and the low pressure at sides of the drop spreading it out. In the region of We = 3 (1/4 inch drops at normal gravity), the drops are torn up by the air stream and larger drops cannot exist.

Gas flow may be expected not only to move liquid or solid particles in the stream but also to drag along any liquid film on the walls of the passage. This effect is very weak at low gas velocity (small Re, Fr and We) because the liquid/gas interface remains smooth, but will increase rapidly above some critical condition, progressing to the point where the liquid is torn from the walls and carried as droplets. An analysis of the relative effects of inertia, viscous and capillary forces has led to the curve shown in figure 3, (ref. 1).

The Re and We of this figure are based on the characteristics of the fluids in question, on the thickness of the liquid film and the velocity of the liquid/gas interface.

In order to utilize this data, and assess the g-sensitivity of the process, the computations could proceed somewhat as shown below, and in reference to the sketch of figure 4.

(1) Determine Re for the driving stream of gas, based on passage size and mean gas velocity.

(2) Estimate C_f (surface friction coefficient).

(3) Compute liquid shear stress ($\tau = C_f \rho V^2/2$).

(4) Compute interface velocity ($U = \tau H/\mu$). A reasonable H may be assumed to do this. The validity of the assumption can be tested later.

(5) Compute Re and We based on H and U to assess film stability.

If reference to figure 3 does not indicate that the film is definitely stable, it may be necessary to re-estimate C_f because roughening of the interface greatly increases the drag force. With the shear stress (τ) established we may now equate drag force to film weight. This provides a guide to the g-sensitivity of the process.

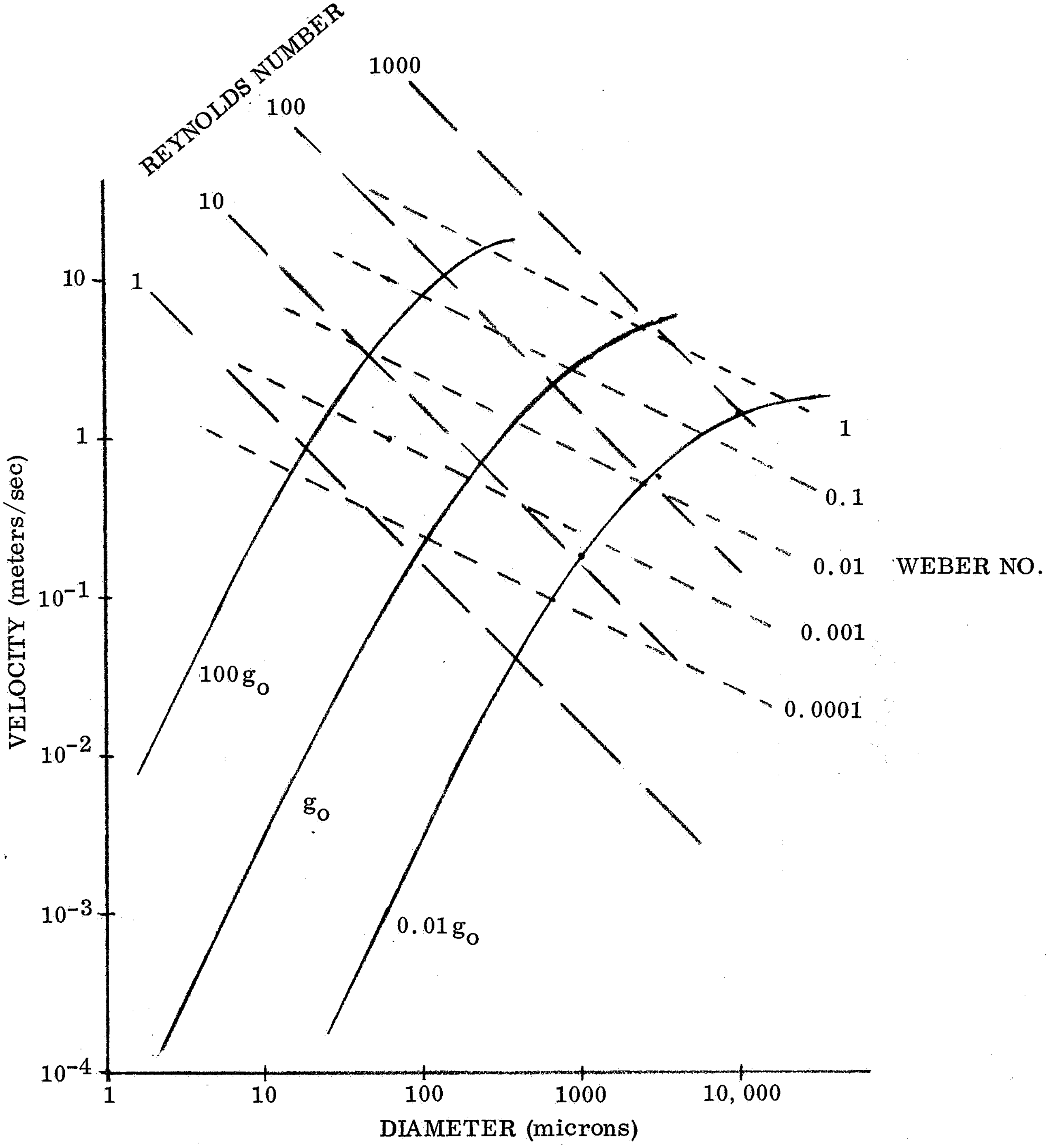


Figure 2. - Rain Speed (Terminal Velocity)

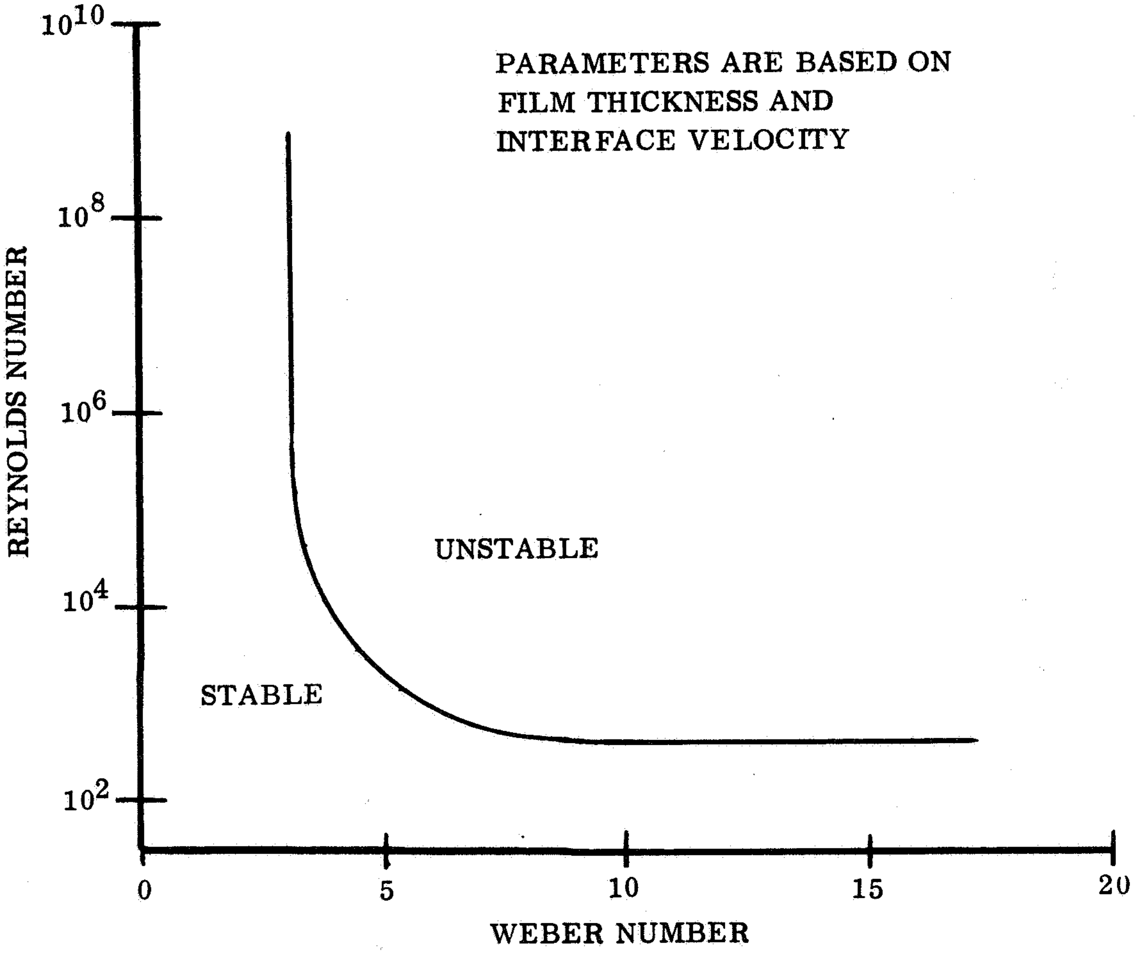


Figure 3. - Film Stability Criteria

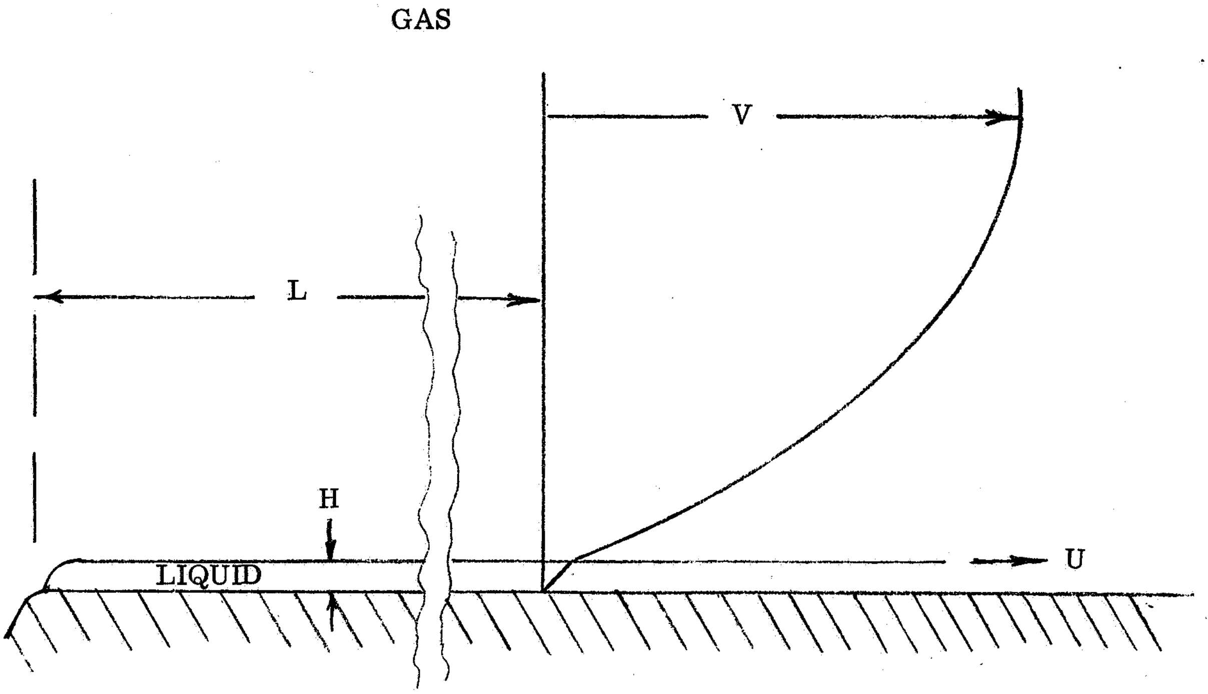


Figure 4. - Liquid Film Drag by Gas Flow

Transient effects.- The time (T) required for a system to respond to a disturbance is often vital to the analysis of the performance of that system. The dynamic analyses of the earlier paragraphs have been presented on a steady state basis, but some of the relations are interestingly parallel to those required for the evaluation of characteristic times. The definition of Weber's Number, for instance, may be rearranged $V^2 L = We\ \sigma$, which is equivalent to $T^2 = L^3/\sigma\ We$. Looking deeper into the matter, the period of the simplest oscillation of a spherical liquid drop in the absence of gravitation may be computed from the following equation (ref. 2)

$$T = .785 \sqrt{D^3 \rho/\sigma}\ , \quad \text{and} \quad \text{for a bubble} \quad T = .64 \sqrt{D^3 \rho/\sigma}\ .$$

Similarly the equations concerning the damping of such oscillations are dimensionally similar to Reynold's Number. Where gravity, or some equivalent tangible force on the container, is present the relations governing liquid sloshing periods take a rather different form. For the simplest (and therefore, as above, the slowest) oscillation of liquid in a deep round basin, the following equation applies (ref. 2) $T = 3.9 \sqrt{D/g}$. Comparing this normal gravity equation (whose derivation neglects surface tension) with the zero-g equations above, evokes the Bond Number, which may be used to determine how the effect of the pertinent parameters on the system time constant can be estimated. Where $Bo \gg 1$, $T \propto \sqrt{D/g}$. Where $Bo \ll 1$, $T \propto \sqrt{D^3 \rho/\sigma}$. Where $B = 1$, the situation is more complex. W. C. Reynolds has presented considerable data on this problem, but it is not felt that the matter must be developed here. The response times lie between the short normal-g and the longer zero-g periods. The liquid/gas interface problems of the ILSS are involved with air/water mixtures moving with some velocity. The pertinent interface dimensions are small and the characteristic times, even in zero-g range downward by orders of magnitude from a tenth of a second.

A rather different sort of response time estimate is pertinent to disconnected masses of liquid or solid. They will in most cases have some velocity relative to the surrounding gas. Estimates of the terminal velocity in various g-fields were presented in figure 2. The gas velocity, however, changes in magnitude and direction and it is probably here valuable to note that some time is required for the droplets to approach the new gas velocity. For small droplets, where Stokes Equation applies, a simple integration indicates that this time (in seconds) is of the order of three times the square of the droplet diameter (millimeters). The proportionality constant will be reduced for larger, higher velocity drops.

Fluid mixing.- Considering the mixing of single phase fluids, either liquid or gas, the effect of gravity on the process is qualitatively clear almost immediately. The variations in density throughout the system are small on an absolute basis. The gravity induced pressure differences are small, and from this it follows that only weak forces are required to counteract the gravitational effects. Stratification can persist for some time if stirring is rigorously avoided, but diffusion still continues. When any two substances are in contact there is always a tendency for the molecules of each to penetrate the other. This is essentially independent of gravity, and is probably the final process of any complete mixing operation. Diffusion is, however, slow, especially in liquids, and where any attempt is made to promote the mixing practically all of it results from the mass motions of the fluid.

One criterion of flow conditions seems particularly pertinent to the mixing of fluids. The Reynolds Number can be used to distinguish laminar from turbulent flow and it was the process of fluid mixing which Reynolds used to demonstrate the significance of a critical value of $LV \rho/\mu$. A stream of dye was injected into the mouth of a tube through which water was flowing. At low water velocities, the dye stream maintained its integrity over very long distances. At high velocities it was quickly broken up and the liquid became uniformly colored.

It may be concluded that reasonable mixing rates involve turbulence and that gravity will generally have little effect if turbulence is present.

Heat transfer.- The exchange of heat into, out of, or through a single phase fluid involves rather small density differences. It might therefore be thought to be insensitive to gravity, but the situation is different from that of composition mixing, for in heat transfer the same fluid may be used over and over again and weak persistent forces may create appreciable velocities.

Heat is transferred by the processes of radiation, conduction and convection, this last being further categorized as forced or free depending on whether it is artificially produced or produced by the action of gravity on the thermally induced changes in fluid density. The relative magnitudes of the different processes depend on the situation, and numerical estimates of the order of magnitude of each can be made to assess their relative importance. Convection is often dominant and some notes on the pertinent criteria are presented here. Several dimensionless criteria are used. The Reynolds Number differentiates between laminar and turbulent flow, as for fluid mixing. Heat transfer is enhanced by turbulence. The Prandtl Number relates flow boundary layer thickness to thermal boundary layer thickness.

$$Pr = Cp\, \mu/k$$

where: Cp = specific heat at constant pressure
k = thermal conductivity

The Grasshof Number relates the effects of bouyancy, inertia and viscosity.

$$Gr = D^3 \rho^2\, g\, \beta\, \Delta t/\mu^2$$

where: β = coefficient of thermal expansion
t = temperature difference

The Nusselt Number is a convenient dimensionless heat transfer parameter and is often used as a measure of the effect of variations in the other parameters.

$$Nu = hl/k$$

where:
h = heat transfer coefficient

The only g-sensitive heat transfer process is free convection. Gr is often used to associate the effects of its several variables on free convective heat transfer and appears (often multiplied by Re) as the independent variable in the representation of much correlated data.

Boiling and condensation.- Very high convective heat flux to or from a fluid can be maintained when that fluid is changing from liquid to gas or vice versa. The microscopic characteristics of the change of state may be considered to be gravity insensitive because of the low Bond Number. On a system basis, however, the large difference in density between liquid and gas indicates that the gravitational acceleration is an important parameter. It is particularly important to note, therefore, that experimental studies of boiling heat transfer at reduced gravity have shown little g-sensitivity, at least in the nucleate boiling region of heat flux. The basic reason for this is that the formation of bubbles is a violent process which so agitates the liquid in the region of the hot surface that the gravity induced general motion of the liquid is relatively unimportant. Low to medium forced convection velocity also has little effect. At very low heat flux there does seem to be some effect and at high heat flux the quiescent zero-g condition probably promotes the break over into film boiling. These fringe effects are probably not particularly pertinent to the Life Support System.

There is little reason to believe that any similar g-insensitivity will be found in condensation. This is essentially a quiescent process and the problem of getting the released heat away from the point of condensation seems to be directly fluid mechanical. The liquid formed must be gotten out of the way. The condensation problem reduces to liquid film transport in two phase flow.

Combustion.- Characteristically, combustion involves the rapid release of heat in a narrow zone. This heat is transferred in a flame front from the burned to the unburned gas, bringing the latter up to its ignition temperature. The heat transfer rate is normally high, is driven by a large temperature difference and insofar as the question of flame front behavior is concerned, it is transmitted over a short distance. The flame front velocity relative to the gas can range from slow (inches per second), smooth and controlled to rapid (thousands of feet per second), violent and explosive. Radiation and conduction play important roles in the heat transfer process, especially in the slow smooth burning. Convective effects can greatly increase the effective flame speed by turbulent tearing of the flame front and/or mass movement of the burning zone. These are, in general, a matter of forced convection rather than free convection, the forcing being caused either by some outside agency such as a pump or by the dynamic effects of the combustion itself. The action of gravity on small systems is too gentle to appreciably increase the speed at which a zone of combustion moves through a combustible gas mixture.

The absence of gravity, however, can inhibit combustion. In most fires no large zone of mixed fuel and oxidant exists, but rather these necessary elements are brought together at the flame by the free convective pumping produced by the heat of the flame. Combustion products are purged from the combustion zone by this same mechanism. Without gravity the flame can die because the fuel and oxidant are separated by a zone of combustion products. This must not be interpreted to mean that zero-g does inhibit combustion. It may or it may not.

Flames can progress quite nicely through gas/oxidant mixtures in the absence of gravity and this is probably also true of conditions where the fuel and oxidant are not actually mixed but are closely associated. The granular structure of fabrics could support what might be called a diffusion flame, and forced convective supply of oxidant can be readily supplied by an air conditioning system or by moving the burning object.

GRAVITY SENSITIVITY IN ILSS COMPONENTS AND PROCESSES

The investigation of gravity sensitivities within the ILSS components and processes was carried out in a stepwise manner, with the steps representing various screening operations terminating in the selection of processes which require experimental testing for verification of their zero-g performance. The screening steps consisted of varying depths of analysis into the possible g-sensitive aspects of the individual ILSS processes, consideration of the importance of the individual processes to the ILSS and future life support systems, and evaluation of the appropriateness of selection of a process for possible test under this program in view of other existing and planned NASA test programs. The principle objective of the screening procedure was to select those critical ILSS processes whose performances may be significantly affected by reduced gravity but whose gravity sensitivities are not assessable by available analytical techniques or by other currently planned or anticipated programs. Achievement of the objective required considerable variation in the depth of analysis applied to various processes, and in one instance an elementary laboratory experiment.

Review of ILSS Subsystems for Gravity Sensitivity

The first step in identification of gravity sensitivity among the ILSS subsystems was a detailed review of the various components and processes, (ref. 3). Tabulation of these components and processes and of the elements of which they are composed, provides an insight into the type of g-sensitive phenomena which must be considered; and establishes a basic list for selecting those items which may show g-sensitivity and hence should be retained for further study. Such a list was prepared and is shown in table 1. For convenience the components and processes are organized into general functional areas, and a number of items which are obviously independent of gravity have been omitted.

Consideration of the individual items of table 1 leads to the identification of a set of more basic processes which are g-sensitive and which can account for any g-sensitivity that may be exhibited by the various subsystems. The basic processes may represent actual subsystem process elements or may be only associated phenomena which can affect subsystem performance. These processes may be somewhat arbitrarily defined depending upon the depth to which it is desired to carry the analysis. For example, it is conceivable to identify the processes very broadly as simply fluid behavior and solid behavior; or to make a very fine distinction involving a large number of more elementary processes such as film boiling, centrifugal phase separation, porous membrane phase separation, ---etc. For initial study of the ILSS, a compromise set of

Table 1. - ILSS Components and Processes

FUNCTION	PROCESS	COMPONENT
Thermal Control	Atmosphere Heating	Controls
	(Component Convective Cooling)	Instruments
		Lights
		Water Pumps
		Fans and Blowers
		Food Freezer
		Waste Processing
		CO_2 Reactor
		Water Recovery Units
		Electronics
		Cabin Walls
		Metabolic
	Atmosphere Cooling	HX "A" Condensing
		HX "B" Non-Condensing
Ventilation	Thermal Mixing	Fans and Blowers
	Composition Mixing	Fans and Blowers
Humidity Control	Gas/Water Separation	Liquid Gas Separator
	Separator Start-up and Shut-down	Liquid Gas Separator
Process Fluid	Fluid Heating	Process Fluid HX
	Fluid Storage	Reservoir
	Fluid Circulation	Pumps and Controls
	System Maintenance	
	(fill, bleed, service)	
Coolant Fluid	Fluid Cooling	Space Radiator
	Fluid Storage	Reservoir
	Fluid Circulation	Pumps and Controls
	System Maintenance	
	(fill, bleed, service)	
Atmospheric Control		
CO_2 Concentration	Gas Drying	Silica gel bed
	Gas Cooling	Gas/Coolant HX
	CO_2 Adsorption	Zeolite Bed
	Gas Heating	Gas/DC-331 HX
	Silica gel desorption	Silica gel bed
	Zeolite Heating	Bed/DC-331 HX
	Zeolite Desorption	Zeolite Bed
	Zeolite Cooling	Bed/DC-331/Coolant HXs
	CO_2 Cooling	CO_2/Coolant HX
	CO_2 Storage	Accumulator
	Gas Circulation	Blower
CO_2 Reduction	Bosch Reaction	Reactor
	Carbon Collection	Reactor
	System Maintenance	Collection Bag
	Water Separation	Condenser (Gas/Coolant HX)
		Gas/Liquid Separator
		Water Trap (1g)
	Water Storage	Expulsion Tank
	Recycle Compression	Compressor
	Gas Cooling	Gas/Coolant HX
	Sabatier Reaction	Reactor
	Desulfurization	Chamber
Water Electrolysis	Gas Removal	Inlet Gas Trap
	Water/Electrolyte Mixing	Electrolyte Cells
	Electrolyte/Gas Separation	Gas/Liquid Separator
	Dehumidification	Liquid Traps
	Electrolysis	Cells
Contaminant Control	Air Filtering	Charcoal
	Filter Maintenance	Particulate, and
	(Replacement and Cleaning)	Absolute filters
	Thermo-Chemical reaction	Catalytic burner
		Air/Air Regenerative HX
O_2, N_2 Resupply	Liquid Storage	Cryogenic Tanks
	Gas Generation	Boil-off HX
Water Management		
Waste Fluid Feed	Acid Pre-Treatment	Chem. Storage Tank
	(Mixing)	Dilution Tank
	Treated Fluid Storage	Collection Tank
		Supply Tank
	Feed Control	Batch Feed Tank
Air Evaporation	Wicking and Evaporation	Wick
	Odor Removal	Charcoal Filter
	Water Condensation	Gas/Coolant HX
	Water Separation	Gas/Water Separator
	Circulation	Fan
	Gas Heating	Gas/DC-331 HX
	Maintenance	
	(Purge Pumping)	Utility Pump
	(Wick Replacement	

Table 1. - ILSS Components and Processes (Cont.)

FUNCTION	PROCESS	COMPONENT
	Purity Measurement	Conductivity Chamber
	Filtering	Charcoal Filter
Emergency Purification	Multifiltering	Metering Pump
		Carbon Filter
		Resin Canister
		Bacterial Filter
Water Output	Storage	Electrolysis Accumulator
		Potable Water Tank
		Emergency Water Tank
		Wash Water Tank
	Wash Water Treatment (Mixing)	Chemical Storage Tank
		Wash Water Tank
Waste Management		
Collection	Waste Collection	Gas Draft Feces Collector
	Urine Collection	Gas Draft Urine Collector
	Filtration	Urine Filter
		Air Stream Filter
	Urine Collection Flush	BAC Treated Water Supply
	Urine/Gas Separation	Liquid/Gas Separator
Drying	Vacuum Heating	Dryer Cans
	Filtering	Bacteriological Filter
Storage	Waste Storage	Storage Containers
	Expendables Storage	Supply Cabinet
Personal Hygiene		
Washing	Water Heating	Water/DC-331 HX
	Heater Gas Purge	Heater Tank
	Wash Water/Gas Separation	Gas/Water Separator
	Strainer Servicing	"Y" Strainer
	Sponge Operation	Sponge and Squeezer
Shaving	Debris Collection and Disposal	Shaver
Food Management		
	Water Heating	Water/DC-331 HX
	Water Chilling	Water/Coolant HX
	Water Dispensing	Water Meter Gage
		Water Dispenser
	Food Storage	Storage Racks
	Food Handling	Manual
Instrumentation and Control		
	Temperature Sensing and Control	
	Pressure Sensing and Control	
	Flow Sensing and Control	
	Humidity Measurement	
	Liquid/Gas Discrimination	
	Gas Analysis	
	Bacteria Analysis	
Special Conditions		
	Gas Leakage	
	Fluid Release to Atmosphere	
	Solid Particle Release to Atmosphere	
	Flame Propagation and Control	
	Spillage Recovery	
Mechanical Operation		
	Lubrication	Various Mechanical Devices
	Performance	

Note: HX - Heat Exchanger

basic processes was selected which give a meaningful categorization of the g-sensitive phenomena without involving unnecessary detail. These g-sensitive processes are discussed below:

Phase separation - This is intended to include the separation of any combination of liquid, solid, or gas phases of any substance or combination of substances.

Condensation heat transfer - This refers to the heat transfer which takes place at a surface upon which a liquid is condensing or has condensed. It includes drop-wise and film condensation.

Convection heat transfer - This refers to fluid heat transfer by virtue of the fluid motion and may be the result of forced or natural convection. In general natural convection relies upon the presence of a gravitational field and density gradients.

Boiling heat transfer - This is the fluid heat transfer which takes place as a liquid is evaporated. In general it involves either a nucleate or film boiling process, depending upon the tendency for the liquid to wet the heated surface.

Fluids retention; Solids retention - These processes or conditions refer to the holding of a liquid, gas or solid within a specified volume or system.

Fluids transport; Solids transport - These refer to the carrying or transfer of fluids or solids either within or outside of the various subsystems.

Composition mixing - This includes the processes of diffusion and convection as they relate to gas or liquid mixing and the dissolution of substances in liquids thus reducing or eliminating concentration gradients.

Thermal mixing - Thermal mixing refers to the processes which lead to uniform temperature distribution. These include convection, conduction, and radiation.

Based on the selection of this set of gravity sensitive processes, the subsystem items of table 1 may be screened for potential gravity sensitivity and the appropriate process or processes identified. A matrix of process relationships obtained in this way is shown in table 2. The rationale behind the selection of these subsystem items and their relations to specific gravity sensitive processes are described in the following:

Thermal control.- Included in this function are the control of cabin atmosphere temperature, humidity, and ventilation; and the liquid thermal systems.

Table 2. - Identification of Gravity Sensitive Process Within The ILSS

ILSS SUBSYSTEM			GRAVITY SENSITIVE PROCESSES									
Functions	Processes		Phase Separation	Condensation HT	Convection HT	Boiling HT	Fluids Retention	Solids Retention	Fluid Transport	Solid Transport	Composition Mixing	Thermal Mixing
Thermal Control	Atmosphere Heating				X							
	Atmosphere Cooling			X	X							
	Atmosphere Mixing										X	X
	Humidity Control		X	X			Ⓧ		X			
	Thermal Fluids Control		Ⓧ				Ⓧ		Ⓧ			
Atmosphere Control	CO_2 System	Bosch Reaction								X		
		Carbon Collection						X				
		Water Removal	X	X			Ⓧ					
	Electrolysis System	Gas Removal	Ⓧ									
		Cell Operation	X								X	X
		H_2 Dehumidification	X	X								
		N_2 Purge									Ⓧ	
	Contaminant Control									Ⓧ		
	Cryogenic O_2, N_2 Supply		X			X						
Water Management	Dilution Tank Chemical Treatment										X	
	Gas Evaporation	Fluid Wicking							X			
		Water Removal	X						Ⓧ			
		Wick Replacement					Ⓧ					
		Purity Measuring									X	
	Wash Water Chemical Treatment										X	
	Fluid Storage						Ⓧ					
Waste Management	Waste Handling									X		
	Collection and Flush								X	X		
	Urine-Gas Separator		X									
	Vacuum Drying				X			X				
	Waste Storage							X				
Personal Hygiene	Water Heating				X							X
	Sponge Operation						X					
	Water Air Separator		X									
	Debris Collection and Storage									X		
Food Management	Water Heating and Cooling				X							X
	Water Dispensing								X			
	Food Handling						X	X				
Instrumentation	Liquid-Gas Discrimination						X					
	Gas Analysis										X	
	Bacteria Analysis										X	X
	Temperature Measurement											X
	Humidity Measurement										X	
Mechanical Devices	Lubrication						X					
	Mechanism Performance									X		
Special Conditions	Gas Leakage										X	
	Fluid Release								X			
	Solids Release									X		
	Flame Propogation								X	X	X	X
	Flame Control				Ⓧ						Ⓧ	
	Spillage Recovery						Ⓧ	Ⓧ	Ⓧ	Ⓧ		

HT - Heat Transfer

Ⓧ - Indicates a relationship due to start-up, shut-down, and servicing operations

X - Indicates a relationship due to normal operation or a special incident

Atmosphere heating and cooling:- Control of atmosphere temperature is accomplished by maintaining a balance between heat input from various heat dissipating components; and heat output to the main cabin heat exchangers and other low temperature surfaces. In the case of heat input, the process involved is primarily convective heat transfer. Heat transfer by conduction, though it is independent of gravity, is not nearly adequate to accomplish the task. Convective heat transfer may be forced, or free, or both. If a significant portion of the heat input is by free convection, performance change may be expected due to its g-sensitivity. Adequate forced convection, on the other hand, being gravity independent, would eliminate any gravity effect on performance.

Heat output, or cooling of the atmosphere is accomplished primarily in the cabin heat exchangers where forced convection is fully established. Two types of cooling processes exist within the ILSS, however, one in the "B" exchanger which is intended to involve gas cooling only, and the other in the "A" exchanger which involves condensation of moisture as well as gas cooling. Thus the "B" exchanger performance may be considered independent of gravity while the "A" exchanger performance could well be influenced by it, depending on the behavior of the condensed water. If the behavior of the water film or droplets which form on the heat exchanger walls is determined solely by the gas convection, or velocity, exchanger performance will not change with gravity. However, if flow of the liquid on the walls is influenced by gravity, performance may be expected to be, also. Secondary atmosphere cooling, due to heat output to other low temperature surfaces involves the same heat transfer processes and considerations as the heat input case.

Atmosphere mixing (Ventilation):- Mixing of the gases within the atmosphere serves two purposes. It establishes uniform gas composition and temperature distribution, both of which are necessary for satisfactory performance of the crew and many of the subsystems. Where mixing involves density gradients, it may be expected to be influenced by gravity, a form of natural convection. The degree to which this natural mixing may be involved in the total mixing process will determine the gravity dependence of this process.

Atmospheric humidity:- Control of atmospheric humidity entails condensation of the water and its separation from the gas stream. Condensation takes place in the cabin heat exchanger "A". The rate of condensation is a function of the heat transfer rate which was discussed in terms of heat exchanger performance under "Atmosphere Cooling," and was found to be potentially g-sensitive. Before separation can take place, the liquid must be transported from the heat exchanger to the gas/water separator. As the density of the water droplets and surface film is very much greater than that of the atmosphere, the transport process may be expected to show pronounced dependence on gravity unless sufficient drag force is presented by the gas stream.

Separation of the liquid/gas phases through use of a porous wall subjected to a small pressure drop may be influenced by gravity in a number of ways. First, the liquid droplets must be brought into contact with the porous wall. Whether this is accomplished or not depends upon the relative magnitudes and directions of the gas stream drag, the droplet inertial forces, and gravity. Second, the liquid, once in contact with the wall, must remain in the wall long enough to be transferred through. This condition is dependent upon pressure, capillary, and gravity forces, assuming a stationary wall. Third, the wall must remain fully wetted to prevent gas break-through, which also requires consideration of gravity forces.

The additional relationship shown in table 2, involving fluid retention, is concerned with maintenance operations during which it may be necessary to shutdown the system and possibly open the liquid side of the separator. As separator performance is dependent upon a fully wetted porous wall, retention of water in the wall until the system is again in operation needs consideration. Gravity sensitivity in this regard cannot be critically assessed until maintenance procedures are detailed. Consequently, at this stage of analysis the process will be assumed to be potentially g-sensitive.

Liquid thermal system:- The process and coolant fluids are in closed, single phase systems with fluid velocities sufficiently high to eliminate gravity effects in considering their normal operation. Gravity effects may require consideration, however, in the performance of servicing and maintenance operations which can in turn, have an effect on system performance. During these operations three potentially g-sensitive processes need consideration. If the servicing can be performed without removal of the fluid, then its retention within the plumbing, assuming the system must be opened, must be considered. If the fluid must be removed, its transfer out of, and replacement into the system must be accomplished. In either case, the entrapment of gas bubbles within the system is a possibility, and requires consideration of phase separation and gas removal.

Atmosphere control.- This function includes the processes involved in the carbon dioxide system, the electrolysis units, contaminant control, and the cryogenic oxygen/nitrogen supply.

Carbon dioxide system:- The carbon dioxide system consists of the CO_2 concentration, and the CO_2 reduction units. Processes within the concentration unit include the forced circulation and convection of gases through constraining passages, chemical adsorption and desorption from packed beds and forced convective heat transfer. Study of the unit does not indicate any sensitivity to gravity. The reduction unit, however, shows a number of potentially sensitive processes. Removal of carbon from between the reactor plates is accomplished by the circulating gas stream. The performance of this process thus depends upon the relative magnitudes and directions of the gas drag forces and gravity. Collection of the carbon involves its retention within the collection bag. While actual separation effectiveness is determined primarily by flow conditions and bag system design, the retention of carbon within the bag may be directly g-sensitive as the bag is open to the gas stream during use. Removal of water from the system is accomplished through condensation to liquid form in a heat exchanger, transport from the heat exchanger to a porous plate separator, and transfer through the porous wall. The condensation process is similar to that described under "Atmospheric Cooling" and the same considerations apply. Transport to the surface of the porous wall is determined by drag forces of the gas, gravitational effects, and wicking or droplet scattering by the fibrous material on the gas side of the wall. Transfer through the wall is under the influence of capillarity, a small pressure differential, and existing gravity forces. Problems with respect to maintenance of a fully wetted wall during operation, and retention of water in the wall for start-up, involve essentially the same considerations as those discussed under "Atmospheric Humidity," and may be g-sensitive.

Electrolysis system:- The electrolysis units produce oxygen and hydrogen gases from input water. Performance may be considered to be dependent upon cell efficiency and the quality of the output gases. Uniformity of the electric current throughout the cells, which implies a homogenous electrolyte free of gas bubbles, is a requisite for high cell efficiency. Preclusion of gas from the cell at start-up following a servicing operation and gas free maintenance of the electrolyte during normal operation may be considered as potentially g-sensitive processes though specific procedures have not yet been developed. Homogeneity of the electrolyte, which in this case includes both chemical and thermal uniformity requires continuous mixing as fresh water is continuously introduced to replace that which is electrolyzed. This mixing may be expected to involve diffusion, convection due to gravity forces, convection due to local thermal expansion and contraction, conduction, and possibly electrical forces.

Separation of hydrogen and oxygen gases from the electrolyte is also required for efficient cell operation. This process may be relegated to the semi-permeable membrane only, in which case it may be found to be sensitive to gravity induced pressure gradients. Or it may require an additional separator. As no satisfactory separator for this purpose is yet available, it will be assumed that such a separator is potentially g-sensitive.

Humidity of the output gases, particularly hydrogen, may require reduction depending upon its effect on other processes (e.g., the Bosch reaction). Presently, no specific separator is assigned to this function. Therefore, as in the case of the gas-electrolyte separator, potential g-sensitivity is assumed.

Gas purge of the electrolysis system during servicing or maintenance may affect cell performance by contaminating the output gases. As the purge involves mixing of gases of different densities, it may be assumed to be at least a potentially g-sensitive process.

Contaminant control:- Normal control of contaminants is accomplished by filtration and thermo-chemical reaction. Filtration removes particulate matter and, through chemical adsorption, many undesireable gases. Thermo-chemical reaction, in the catalytic burner, destroys the remaining harmful gases. Assuming satisfactory atmosphere mixing, the only significant g-sensitivity of the processes may be expected to occur during servicing of the filters. Since the particulate matter may be held very loosely, the possibility of its release from the filters may be g-sensitive.

Cryogenic oxygen/nitrogen supply:- Storage of oxygen and nitrogen as cryogenic liquids is anticipated with their release, upon demand, being in the gaseous phase following controlled boiling. This subsystem does not yet exist in the ILSS, however, by definition, it will entail boiling heat transfer and separation of the liquid and gas phases. Specific g-sensitivity cannot be assessed until a particular subsystem approach is defined, however, it appears reasonable at this time to assume potential g-sensitivity to exist.

Water management.- Included in the water management function are water purification by evaporation, and chemical treatment; and water storage.

Evaporation purification:- Purification by evaporation involves cyclical saturation of a porous wicking material by waste fluids; evaporation of water from the wick into a warm gas stream; condensation of the water in a heat exchanger; and its transport to, and removal by, a gas/water separator. The gas remains in the evaporation loop and is reheated for another pass. Fluid wicking has been demonstrated in a direction opposing a gravitational force, however, the rate and degree of saturation may be sensitive to gravity. Evaporation and the possible release of waste chemicals from the wick to the gas stream, though they profoundly affect performance, do not appear to be gravity related. Condensation in the heat exchanger is a function of the heat transfer rate, a potentially g-sensitive phenomenon, and has been discussed under "Thermal Control," as has the process of liquid transport from heat exchanger to separator. Separation in this system is accomplished by a centrifuge, driven by the gas stream. Water droplets adhere to a spinning screen through which the gas flows and are accelerated radially by centrifugal force to a peripheral trap from which the collected liquid is removed. Factors which may affect this separation include drag of the gas stream, wetting and liquid agglomeration on the screen, centrifugal (inertial) forces, and gravity.

In addition to the normal operation processes, performance of the evaporation units may be influenced by maintenance procedures. Removal of the wick requires system shut down which implies the retention of liquid water which has not yet been removed. Accumulation of this liquid in critical locations, which may be determined by gravity forces, can impair performance at start-up.

A measure of output water purity is obtained from an electrical conductivity measurement of the liquid. Reliability of the measurement is, in part, dependent upon homogeneity and representative sampling. These result from mixing which, in turn, may be gravity sensitive, if density gradients are involved.

Chemical treatment:- Chemical pre-treatment for purification purposes is employed automatically in the dilution tank; and chemical post-treatment in the wash water storage tank is performed manually. Composition mixing which is to be accomplished by convection and/or diffusion may be g-sensitive if significant density gradients exist.

Water storage:- As the name implies, water storage is concerned with receiving water into a variety of tanks and its retention there until needed. A potentially g-sensitive aspect of this is the retention of water in the event that maintenance, requiring opening of the tank is required. As maintenance procedures are not yet specified, possible gravity dependence may be assumed.

Waste management.- Waste management is considered to include the collection of urine and feces; the drying, handling, and storage of the feces; and separation of urine from the gas stream.

Waste collection:- Collection of both urine and feces is a transport process depending on gas stream drag to direct the wastes into their appropriate containers. Clearly, inertia forces are involved; and adverse gravitational forces, if they exist, must be counteracted. The degree to which this is accomplished establishes the gravity dependence.

Urine/Gas separation:- An electrically-powered, centrifugal separator is used to remove the liquid from the gas stream. The fluid mixture is caused to rotate by being ejected into a spinning cup. This generates inertial forces which, in turn, drive the liquid outward. A tube, with its entrance located close to the outer surface of the cup provides an exit for the liquid while the gases leave through a second tube located centrally. Gravity, if present, will influence the position or orientation of the spinning liquid and may affect the rate of droplet travel to the wall. Performance may also depend on behavior of residual fluid during periods when the separator is not running. Possible leakage or mechanical damage due to this behavior may thus be considered g-sensitive.

Feces drying:- Following collection of the feces, the waste material is dried by exposure to vacuum while in a heated container. Two aspects of this drying may be considered as potentially g-sensitive. The rate of drying depends upon the heat transfer rate from the container wall to the waste material. This heating rate may be affected by gravity if the gas pressures are sufficiently high within the container to permit natural convection. The drying rate is also sensitive to the compaction of the waste material. Gravity forces may have an affect on this condition.

Feces handling:- Transfer of the feces from the collector case to the drier and then to the storage container is a manual process involving closing and manipulating the collector bag. Gravity forces are significant as they control the weight of the bag and contents and thus may influence the performance of these manipulative maneuvers.

Waste storage:- Dried wastes are stored in cans which must be repeatedly opened to admit additional material. In the absence of gravity force, loss of stored material when the container is open may be expected to be a potential problem.

Personal hygiene.- Gravity sensitivity may be evinced in the personal hygiene function in the processes of water heating, sponge operation, wash water/air separation and debris control.

Water heating:- Water for washing is heated in a closed container by high temperature process fluid circulating through an externally attached coil. Temperature, for thermal control, is monitored by a sensor attached to the container. Performance of the heating process is concerned with establishing a uniform, predetermined temperature throughout the water. This implies adequate heat transfer between the water and container, and thermal mixing within the body of liquid. In the absence of forced convection, these processes rely on conduction and natural or gravity induced convection.

Sponge operation:- The particular phase of sponge operation which indicates significant g-sensitivity is the wiping process. Behavior of water when squeezed to the surface of the sponge will be affected by its intrinsic properties of adhesion, cohesion and inertia; and by gravity forces if present.

Water/Gas separation:- Separation of used wash water from the atmospheric gases is accomplished in an electrically powered separator similar to the one found in the waste management system and its g-sensitivity has been described in that section.

Debris collection and storage:- This is concerned with the collection and storage of small solid particles such as hair and nail clippings, and involves manual manipulation of clippers and small containers such as plastic bags. As in the case of handling of the feces container, gravity forces are significant to the extent that they influence the performance of the manipulations by controlling weight of the items.

Food management.- This function is concerned with food storage, preparation and consumption. Gravity sensitivity may be expected in the processes of water heating, cooling, and dispensing, and in the handling of the food itself.

Water heating and cooling:- The water heating process is similar to that described for the wash water under Personal Hygiene. Water cooling is much the same with the substitution of coolant for the process fluid and the deletion of the temperature control sensor. Gravity sensitivity for both heating and cooling may become significant through the processes of convection heat transfer and thermal mixing.

Water dispensing:- This is a manual operation and entails the transfer of water, without loss, from the dispenser to the food packets. To the extent that the transfer may be affected by weight differences resulting from different gravity levels, the process may be considered to be g-sensitive.

Food handling:- The manipulating of food and fluids in the food packets and handling of the packets themselves must be done without loss. Gravity is again involved as it determines weight, and changes in weight may affect this activity.

Instrumentation.- The list of instrumentation processes shown in tables 1 and 2, while including more types of measurements than those currently employed in the ILSS, is not necessarily considered to be complete. It is, instead, intended to include those foreseeable processes which may reasonably be expected to be encountered in life support systems in general. For each of the measurements listed there are a variety of available methods, one or more of which are basically insensitive to gravity. However, gravity sensitivity may be expected to become a problem in the sampling area, with respect to the quality of the sample used or the contact which is made with the sample.

Liquid/Gas discrimination:- The primary problem with low or zero-g liquid/gas detectors (other than those which simply provide visual observation of the fluid) has been the clearing of liquid from the detector when its gross environment changes from liquid to gas. Reduction of gravity, and hence weight of the liquid, permits adhesive and cohesive forces to predominate resulting in a liquid retention problem.

Gas and bacterial analysis; Temperature and humidity measurement:- These measurements have the common problem of representative sampling. In all cases, samples, rather than the entire mass, are used and adequate mixing within the mass of the material sampled is necessary. Gravity effects will be involved in the mixing of fluids to the extent that density gradients exist.

An additional problem, particularly with respect to temperature measurement of liquids or solids (such as wick temperature in the water recovery unit) is the assurance that the sensor makes satisfactory contact with the material to be monitored. If the weight of the sensor or of the material is involved in the contact, the measurement may be expected to g-sensitive.

Mechanical devices.- Two areas of interest with regards to g-sensitivity of mechanical devices in general, may be identified. These are lubrication with fluids, and unbalanced mechanism movement. Lubrication with fluids is accomplished primarily through adhesive and cohesive forces. In some cases, the weight of the fluid may assume some importance, and where this is the case, g-sensitivity will exist. Movement of mechanisms such as relays, valves or doors, which in any way is influenced by the weight of the mechanism or its components, will exhibit g-sensitivity.

Special conditions.- In addition to the normal support processes which have been discussed, it is to be expected that special conditions will occur due to causes such as accidents or component failures. It is not possible to anticipate all such conditions and associated or corrective processes, however, some of the more common ones, which are clearly g-sensitive and should receive consideration in life support system design, are listed in tables 1 and 2. They involve basically the release of material to the atmosphere, and its recovery; and the problem of fire. Gravity sensitivity, with regard to materials release, will be manifested in the transport behavior of the material. Spillage recovery will involve retention as well as transport, both being potentially g-sensitive processes. The propagation and control of fires assumes g-sensitivity due to the thermal and hence, density gradients established in the atmosphere and combustion products. Density gradients may result in natural convection, in the presence of a gravity field, which in turn can effect the combustion process by controlling both heat transfer and the rate of oxygen supplied to the flame front.

Performance Effects Due to Gravity-Sensitivity

Identification of the g-sensitivities of the ILSS components and processes discussed in the previous sections represents a first screening of items to be eventually considered as candidates for test. Further screening of these items based on the importance of their g-sensitivities to the performance of the various life support system functions is the next necessary step. This task is documented in this section of the report and includes: a subdivision of the somewhat gross ILSS processes into their more elemental g-sensitive (based on the matrix of table 2) processes; identification of the significant engineering phenomena associated with each elemental process (significant as regards g-sensitivity); and an analysis of each process to determine the importance of its g-sensitive character.

The g-sensitive, elementary, ILSS processes referred to in a general manner in table 2 are specifically identified and listed in table 3.

For purposes of analysis it is necessary to identify also the particular engineering phenomena or parameters, which are involved in the elemental processes, and which are significant in determining g-sensitivity. These engineering parameters are included in table 3 opposite the appropriate process.

Performance effects are considered first from an individual process standpoint. Appropriate analysis is performed to assess the degree of g-sensitivity of the process and from this the expected performance effects are appraised. Following the individual analysis, performance changes which may result from interrelationships among various processes are reviewed. The results are summarized as a list of significantly g-sensitive processes to be considered as candidates for testing.

For convenience, the numbering applied to the following processes corresponds to that used in table 3.

Thermal control.-

Atmospheric heating:

1. Solid-to-gas heating is dependent upon natural convection, forced convection, and conduction. (Radiation can be neglected, as oxygen and nitrogen are essentially transparent in the spectral region corresponding to room temperature). The dominant factor is normally convection. If forced convective currents are maintained in a zero-g environment, heating efficiency is maintained. The vertical natural convective film coefficient (h) is about 0.8 Btu/hr-ft^2-$^\circ$F at one atmosphere in air for a typical aircraft-type compartment. The forced convective coefficient is a function of velocity and equal to 0.23V where V is the velocity in feet per second. This yields an overall film coefficient equal to $h = (0.8 + 0.23V)\sqrt{z}$ where z is the density ratio of the atmosphere in question to the standard atmosphere. If the natural convective element is absent but the

Table 3. - Engineering Phenome Affecting Performance

			SIGNIFICANT ENGINEERING PHENOMENA												
SUBSYSTEM	FUNCTION	G-SENSITIVE LSS PROCESS	Natural Convection	Forced Convection	Diffusion	Conduction	Gas Drag	Weight	Inertia	Capillary Force	Electrical Forces	Manual Forces	Mechanical Forces	Radiation	Notes:
Thermal Control	Atmosphere Heating	1. Solid-to-Gas Heat Transfer	X	X		X									
	Atmosphere Cooling	2. Gas-to-Solid Heat Transfer	X	X		X									
		3. Condensing Heat Transfer					X	X							1
	Atmosphere Mixing	4. Thermal Mixing-Gas	X	X		X									
		5. Composition Mixing-Gas	X	X	X										
	Humidity Control	6. Liquid Condensation in Heat Exchange					X	X							1
		7. Liquid Transport in Gas					X	X	X						1
		8. Porous Plate Separation of Liquid from Gas						X		X					1
		9. Liquid Retention in Porous Plate						X		X					1,2
	Thermal Fluid Control	10. Gas Separation from Liquid						X		X					2,3
		11. Liquid Transport													2,4
		12. Liquid Retention in Plumbing													2,4
Atmospheric Control	Carbon Dioxide Reduction System														
	Bosch Reaction	13. Carbon Transport, Plates to Collection Bag					X	X							
	Carbon Collection	14. Carbon Retention					X	X							
		15. Carbon Bag Servicing						X				X			2
	Water Removal	16. Liquid Condensation Rate in Heat Exchange					X	X							1
		17. Liquid Transport in Gas					X	X		X					1
		18. Porous Plate Separation of Liquid from Gas						X		X					1
		19. Liquid Retention in Porous Plate						X		X					1,2

Table 3. - Engineering Phenomena Affecting Performance (Cont.)

SUBSYSTEM	FUNCTION	G-SENSITIVE ILSS PROCESS	Natural Convection	Forced Convection	Diffusion	Conduction	Gas Drag	Weight	Inertia	Capillary Force	Electrical Forces	Manual Forces	Mechanical Forces	Radiation	Notes:
			SIGNIFICANT ENGINEERING PHENOMENA												
	Electrolysis System														5
	Gas Removal	20. Gas Separation from Inlet Water						X		X					3
		21. Initial Gas-Free Cell													2,4
	Cell Operation	22. Thermal Mixing	X	X		X					X				
		23. Composition Mixing	X	X	X						X				
		24. Semi-Permeable Membrane Separation of Gas from Liquid						X		X					
	Hydrogen Dehumidification	25. Liquid Condensation and Separation from Gas													1,4
	Nitrogen Purge	26. Composition Mixing of Gases	X	X	X										2
	Contaminant Control	27. Particle Retention						X				X			2
	Cryogenic Supplies	28. Boiling Heat Transfer													4
		29. Gas Separation from Liquid													4
Water Management	Chemical Treatment	30. Composition Mixing	X	X	X										
	Gas Evaporation														
	Fluid Wicking	31. Liquid Transport in Wick						X		X					
	Water Removal	32. Liquid Condensation Rate in Heat Exchange					X	X							1
		33. Liquid Transport in Gas					X	X							1
		34. Centrifugal Liquid Separation from Gas					X	X	X	X					1
	Wick Replacement	35. Liquid Retention in Centrifugal Separator						X		X					1,2
	Purity Measurement	36. Liquid Composition Mixing	X	X	X										
	Chemical Treatment	37. Liquid Composition Mixing	X	X	X										
	Fluid Storage	38. Liquid Retention in Plumbing													2,4
		39. Gas-Free Water Maintenance													3

Table 3. - Engineering Phenomena Affecting Performance (Cont.)

SUBSYSTEM	FUNCTION	G-SENSITIVE ILSS PROCESS	SIGNIFICANT ENGINEERING PHENOMENA												
			Natural Convection	Forced Convection	Diffusion	Conduction	Gas Drag	Weight	Inertia	Capillary Force	Electrical Forces	Manual Forces	Mechanical Forces	Radiation	Notes:
Waste Management	Waste Handling	40. Feces Transport						X				X			
	Collection and Flushing	41. Liquid and Solid Transport in Gas					X	X	X						
	Urine-Gas Separation	42. Centrifugal Liquid Separation from Gas					X	X	X	X					
		43. Liquid Retention in the Separator						X		X					2
	Vacuum Drying	44. Solid-to-gas-to-solid Heat Transfer	X	X		X								X	
	Waste Storage	45. Solids Retention in Storage Container					X	X				X			
Personal Hygiene	Water Heating	46. Solid-to-liquid Heat Transfer	X	X		X									
		47. Thermal Mixing	X	X		X									
	Sponge Operation	48. Liquid Retention in Sponge						X		X		X			
	Water-Air Separation	49. Centrifugal Separation of Liquid from Gas					X	X	X	X					
		50. Liquid Retention in the Separator						X		X					2
	Debris Collection-Storage	51. Solids Transport					X	X				X			
Food Management	Water Heating and Cooling														
		52. Solid-to-liquid Heat Transfer	X	X		X									
		53. Thermal Mixing	X	X		X									
	Water Dispensing	54. Liquid Transport						X		X		X			
	Food Handling	55. Liquids and Solids Manipulation						X		X		X			
Instrumentation	Liquid-Gas Discrimination														
		56. Process Not Specified					X			X					4
	Gas Analysis	57. Mixed Sampling	X	X	X										
	Bacteria Analysis	58. Mixed Sampling	X	X	X										
	Temperature Measurement	59. Mixed Sampling	X	X		X									

Table 3. - Engineering Phenomena Affecting Performance (Cont.)

			SIGNIFICANT ENGINEERING PHENOMENA												
SUBSYSTEM	FUNCTION	G-SENSITIVE ILSS PROCESS	Natural Convection	Forced Convection	Diffusion	Conduction	Gas Drag	Weight	Inertia	Capillary Force	Electrical Forces	Manual Forces	Mechanical Forces	Radiation	Notes:
	Humidity Measurement	60. Mixed Sampling	X	X	X										
Mechanical Devices	Lubrication	61. Liquid Retention						X		X					
	Performance	62. Solids Motion						X				X	X		
Special Conditions	Gas Leakage	63. Gas Mixing	X	X	X										
	Fluids Release	64. Liquids Transport					X	X							
	Solids Release	65. Solids Transport					X	X	X						
	Flame Propagation	66. Fluids Combustion	X	X	X			X							
		67. Solids Combustion	X	X	X										
	Flame Control	68. Composition Mixing and Heat Transfer	X	X	X										4
	Spillage Recovery	69. Process Not Specified													

Notes:

1. Liquid-Gas Separator Alternate (Frank Booth, Porous Condensing Plate)
2. Servicing Process
3. Gas Eliminator Alternate (Frank Booth, Wetting/non-wetting Porous Plates)
4. Process Not Specified
5. Potassium Hydroxide Electrolysis Alternate

equivalent film coefficient provided by forced velocity, then $h = 0.23V = 0.8$; $V = 0.8/0.23 = 3.48$ ft/sec. Consequently if forced velocities are maintained significantly above 209 ft/min, (3.5 ft/sec) atmospheric heating is practically insensitive to gravity.

Failure to provide adequate forced convection in zero-g will cause increased temperature differences between exposed surfaces and the atmosphere and may result in critical temperature excursions of thermally sensitive items.

Atmosphere cooling:

2. The conditions described in No. 1 are analogous to atmospheric cooling. Forced convection can provide cooling requirements, and essentially eliminate g-sensitivity.

3. Condensing heat exchanger efficiency is dependent upon maintaining a satisfactory film coefficient throughout its operation. If the effects of gas drag and liquid weight vary with g-variations, then relative sensitivity must be analyzed. How liquid droplets are carried in the gas stream and liquid film thicknesses are maintained by gas drag, are the pertinent factors.

   A rain drop has an average diameter of approximately 1000 microns. From empirical data, the sinking rate, in standard air at one-g, is about 6 ft/sec. This velocity is also the minimum upward gas velocity required to permanently suspend the drop. The velocity is the result of drag forces acting against gravitational acceleration to produce a uniform speed (no net acceleration). As drop size decreases, the sinking rate decreases (2 ft/min for 20 micron fog). For a given droplet size, sinking rate also decreases with gravity.

   Flow velocities within the heat exchanger are about 3 to 4 ft/sec. This velocity range, working against one-g would suspend a 250 to 400 micron drop. Droplets formed by condensation within the gas stream are sufficiently small that they can easily be carried in the heat exchanger against one-g. With decreasing gravity, progressively larger droplets may be carried. Zero gravity operation will be at least as efficient as in one-g in this configuration. This is also true when drag forces act perpendicular to or at some angle against gravity. For cases in which drag forces and gravity are in the same direction, a decrease in efficiency in going from 1 to zero-g may be expected.

   Condensation may also take place on the heat exchanger surface. Assuming dropwise condensation, the drops may be carried away by the gas stream, or may collect to form an effective film. Since filmwise condensation may also occur, fluid build-up is likely. The phenomena involved in fluid build-up include gas drag at the film surface, liquid condensation rate and liquid weight. From an analysis following the approach discussed under Interface Dynamics in the previous section, it appears that gravity effects are not significant during initial film build-up (to perhaps 10-20 microns). However as gas drag during this early build-up period is insufficient to give any appreciable motion to the film, the film remains within the heat exchanger and continues to build in thickness. The film is eventually removed in one of two ways: it either "runs off" due to gravity; or surface instabilities induced by gas drag occur causing it to break up into droplets which then may be carried away by the gas stream. It appears that the trade-off point is in the region of 50 to 100 ft/sec gas velocity. Below 50 ft/sec the process may be considered to be g-sensitive.

Consequently, in the range of 3 to 4 ft/sec currently considered, both the heat exchanger film coefficient and the liquid transport are significantly g-sensitive. Appreciable performance variations may therefore be expected. If gravity forces are in a direction favoring normal flow, a decrease in performance from 1 to zero-g may be expected. The reverse may be expected if gravity forces are in the opposite direction.

Atmosphere mixing:

4. Thermal mixing of the atmosphere in one-g is dependent upon conduction and natural convection where there is no forced circulation. Natural convection, resulting from density gradients, is the dominant factor. In zero-g, forced convection must be provided to equal one-g convective currents for equivalent 1 to zero-g mixing conditions. Standard one-g airconditioning tests indicate that a velocity of 50 ft/min is adequate for this thermal mixing. Assuming that velocities within the ILSS atmosphere will be sufficient for atmospheric heating and cooling (processes 1 and 2), they will then be more than adequate for thermal mixing.

   On the other hand, failure to provide the necessary circulation will result in pronounced temperature gradients throughout the atmosphere (for the zero-g condition). This, in turn can seriously upset the cabin temperature control depending upon location of the thermostat.

5. Composition mixing depends upon diffusion and convection. In one-g, density and thermal gradients produce natural convection which promotes composition mixing at satisfactory levels for the gases of the earth environment. The same analysis as in No. 4 applies here.

   The consequence of inadequate composition mixing can become severe over extended periods as hazardous gaseous products may accumulate locally above acceptable levels.

Humidity control:

6. Liquid condensation in the heat exchanger is related to the heat transfer rate discussed in process 3, and the same analysis applies.

7. Transporting the condensed liquid by a gas stream from condenser to separator is an extension of the phenomena described in process 3. A "channeled" transport is involved in which the liquid is carried with the gas stream to bring it in position to be deposited on the separator surfaces. This is essentially covered in 3. Following this, inertial or centrifugal forces are utilized to "throw" the liquid out of the gas stream and into contact with the separator surfaces. Gravity sensitivity for this process depends upon the relative directions and magnitudes of the inertial and gravitational forces. Analysis shows that for droplet velocities as low as 4-5 ft/sec, the inertial force magnitudes are several times the droplet weights. Considering also the fact that the inertial forces are continuously changing direction, it can be asserted that, with the exception of the phenomena covered under No. 3, the transport process is essentially gravity independent.

8. Once the liquid is in contact with the porous plates of the separator it may progress through, or collect in some manner and be carried off again. The behavior depends upon the relative magnitudes of gravitational, capillary and pressure forces. Assuming sufficient pressure differential across the plates to off-set any hydrostatic pressure head, the significant parameters to be compared for determining g-sensitivity are gravitational or weight forces and capillary or surface tension forces.

   The most unfavorable orientation for this comparison is a vertically mounted plate, having its longest dimension aligned with the gravity force vector. Thus, if L is the long plate dimension, and R is pore radius:

$$\text{gravitational force} = \rho\, g\, L\,; \quad \text{and}$$

$$\text{capillary force} = 2\ \sigma/R$$

   For an L of 1 ft. and an R of 5 microns, the capillary force is found to be approximately 10 times the gravitational. This would indicate g-insensitivity, especially since the actual ILSS porous plates are felt to have effective pore sizes somewhat smaller than 5 microns.

   This is further supported by testing at NASA Langley in which a water saturated porous plate, of the ILSS material, was exposed to a pressure differential of 7 psi with no indication of gas break-through. The high pressure side of the plate was exposed to air, while the opposite side was in contact with water; the plate forming one wall of a water filled chamber.

9. When not in normal operation or when servicing is required, the effect of gravity on liquid retention in the porous plate separator must be considered. In general, the preceding analysis of process 8 applies, implying g-insensitivity except in the case of high mechanical or manual accelerations.

An alternate design, which will perform all the functions of the processes described under humidity control, has been suggested by the NASA Technical Representative. This design provides for initial condensation to take place on the porous plate and thus eliminates the problems of liquid transport to the separator surfaces. The conditions of liquid behavior in and on the porous plate are similar to those discussed above and the analysis is felt to apply.

It should be noted that wetting surfaces, particularly on the porous plates have been assumed throughout the analyses. In the event the surfaces become non-wetting, such as by the introduction of a small quantity of oil to a dry surface, the separation mechanism will "break-down" and the process will become extremely inefficient or fail entirely. It has been found by experimentation that a thoroughly wetted porous plate is not affected by oil, provided that no drying of the plate is permitted.

Thermal fluid control:

10. Gas-liquid separation; eliminating gas from fluid lines; requires a different approach from that normally used in one-g, where weight differences may be utilized. In many cases, gas removal does not appear feasible without design change. A specific design concept for a gas eliminator has been proposed by the NASA Technical Representative, which utilizes semi-permeable membranes (or porous plates) to selectively discriminate between gas and liquid. While it appears theoretically possible to design such a gas eliminator which is independent of gravity, validity of assumption, primarily concerning wetting behavior, suggests that g-sensitivity be examined experimentally.

11. 12. During servicing of the fluid systems, the fluid itself must be controlled to prevent spillage. It may be possible to perform the service with the fluid retained in the system or it may be necessary to remove, and later replace it. As processes have not been specified for these functions, an adequate analysis cannot be performed. It may be noted, however, that in zero-g, the dominance of capillary forces suggests the retention of fluids as being most promising. For example, at a low gravity level of 10^{-7} g, water is readily retained in an open one-inch tube.

Atmospheric control.-

Carbon dioxide reduction system - Bosch reaction:

13. Carbon transport from the collection plates to the collector bag is dependent upon gas drag, carbon particle weight and possible adhesive forces (such as electrostatic) which may exist. The analysis of process 3 is applicable with respect to gas drag and weight, however knowledge of particle size, configuration and bulk density is needed for a realistic study. From inspection of carbon accumulations on the plates and particles taken from the collector bag, these variables appear random in nature. Consequently, the g-sensitivity of this process is not amenable to satisfactory analysis. Unfortunately, significant g-sensitivity can result in severe degradation of the

process, both from a mechanical and reaction standpoint. As a result, it is felt that further experimentation is both desireable and necessary for a valid determination of g-sensitivity.

Carbon dioxide reduction system - Carbon collection:

14. Carbon retention in the bag is dependent upon weight and gas drag. When carried into the bag, carbon will adhere or rebound at reduced momentum, and eventually be returned to the bag. The same variables and uncertainties enter into the transport of carbon into the bag as discussed in process 13 above. However, if the assumption is made that the initial transport into the bag can be made insensitive to gravity, then its retention within the bag can be considered essentially independent of gravity.

15. Carbon bag servicing is sensitive under any gravity field. Sensitivity will be a function of particle size or weight. Any forces exerted by handling the carbon bag will tend to accelerate particles out of the collector, as a function of particle weight and hence gravity. This should be considered as a particularly critical process as the introduction of finely divided carbon particles into the cabin atmosphere can create a serious explosion hazard.

Carbon dioxide reduction system - Water removal:

16. The condensing heat exchange process in the carbon dioxide system is the same as described in process 3.

17. The process of transporting the liquid from the condenser to the fibrous material in the separator is also the same as described in 3, however, the movement of liquid droplets and film along the fibers to the porous plate involves the additional phenomena of adhesion or capillary force. The question that arises is the balance between capillary and gravity forces. This has been treated under process 8 for small pore sizes. In the present case, however, the effective pores within the fibrous material are very much larger (estimated to be 100 to 1000 microns) and g-sensitivity may be expected.

18. The porous plate water separation analysis presented under process 8 applies here as does the discussion of the alternate, NASA suggested separator.

19. The problem associated with liquid retention in the porous plates during servicing is the same as that discussed under process 9.

Electrolysis system - Gas removal:

20. Gas removal from the inlet water refers to essentially the same situation as discussed for thermal fluids control, process 10. Failure to control the gases, however, and their introduction into the cells can seriously impair cell performance by altering the chemical balance and displacing required electrolyte.

21. The process for removal of gases initially, prior to cell operation, is not specified and consequently cannot be analyzed for g-sensitivity. It is felt, however, that the gas eliminator suggested by NASA and discussed under process 10, could be utilized here.

Electrolysis system - Cell operation:

22. Thermal mixing of the electrolyte depends upon convection, conduction, and possibly electrical field forces. In a gravitational field, some natural convection may occur though, at best, it will be quite small due to the restrictive dimensions of the cell liquid volume. The unit lends itself readily, however, to conductive heat transfer and this effect can be expected to be significantly greater than that due to natural convection. Consequently it is felt that the cells are not significantly affected by gravity in this respect.

23. Composition mixing involves similar processes with the exception of conduction. (From a thermal standpoint, diffusion is considered as an inherent part of conduction). In this case, g-sensitivity is measured by the relative significance of natural convection versus forced convection, diffusion and possible electrical forces. Again, natural convection effects will be practically negligible due to the cell dimensions. Some forced convection will occur due to water flow into the cell and possibly due to action of the electric fields. The dominant mixing influence, however, may be expected to be diffusion, and no significant g-sensitivity is felt to exist.

24. The process of gas separation from liquid at the semi-permeable membrane is not clearly understood. It has been demonstrated, though, that a properly designed and assembled unit will effectively separate the two under one-g conditions with the gravity force vector in the most unfavorable orientation. Since any reduction in g-level will only tend to enhance the separation process, it may be safely assumed that this process, under proper hardware conditions, is not sensitive to gravity.

Electrolysis system - Hydrogen dehumidification:

25. No process is currently specified for dehumidification of hydrogen leaving the electrolysis units. The alternate separator discussed under process 8 would appear to be a logical candidate and the comments in that section would apply.

Electrolysis system - Nitrogen purge:

26. Nitrogen purge in servicing the electrolysis unit is dependent upon adequate composition mixing of nitrogen with substances in the unit. The configuration of passages and chambers within the unit precludes the use of natural convection to accomplish the purge. Consequently, although some degree of natural convection will occur, it will be incidental to the purge process. Effective purging will be the result of forced convection.

An alternate electrolysis unit design has been suggested by the NASA Technical Representative. This design utilizes a potassium hydroxide electrolyte in an asbestos matrix. It would appear to eliminate some of the problems encountered with the current units, and would not involve the discussions given in processes 21 through 24 above. Its internal design however could lead to liquid entrainment in the exiting gases due to capillary forces. The use of effective non-wetting materials in appropriate areas could possibly prevent this, but experimentation is necessary. Because of this potential problem of capillarity, performance changes between 1 and zero-g may be expected.

Contaminant control:

27. Retention of particulate matter during servicing of contaminant control filters is related to carbon bag servicing discussed as process 15. Loss of particles to the atmosphere will depend on manually applied forces and particle weight, and is thus g-sensitive. As recontamination of the atmosphere may occur, particle loss can effectively degrade the performance of the contaminant control system.

Cryogenic supplies:

28. Subcritical storage of oxygen and nitrogen supplies has been proposed for the ILSS, but the study was not carried to the depth necessary to produce a detail design concept with respect to heaters and heat exchangers. It has been demonstrated experimentally that nucleate boiling rates do not vary measurably between 1 and zero-g, however, thermal stratification and bubble configuration which can interfere with boiling, are definitely g-sensitive. It is felt that a heater design technique essentially independent of gravity is feasible but no valid assessment of g-sensitivity can be made until a specific design is considered.

29. As in the previous case, a specific design technique is needed for a valid g-sensitivity assessment.

Water management.-

Chemical treatment:

30. Composition mixing of chemicals and process water in the dilution tanks depends on diffusion and convection. Injection of the chemicals and water flow through the system will create some degree of forced convection. Natural convection will occur where induced by density gradients. On the other hand, density gradients, appropriately aligned cannot only eliminate natural convection but can appreciably attenuate forced convection. Due to the complex nature of these mixing phenomena it is felt that the process must be considered as g-sensitive. In addition, since failure to achieve adequate mixing could present a serious health hazard, the process should be considered as a test candidate.

Gas evaporation - Fluid wicking:

31. Liquid transport in the evaporation wick is a function of the weight-capillary force balance. Theoretically, a wick of sufficiently small effective pore size would transport water almost as well in one-g as in zero-g. (See the analysis of process 8). Such a wick would present no significant g-sensitivity, and testing has indicated that such wicks are available.

Gas evaporation - Water removal:

32. 33. The condensation of liquid in the heat exchanger and liquid transport to the separator are essentially the same as the processes described under process 3, and the analysis in that section is considered applicable here. (Actual velocities are somewhat higher here, but their effect on the overall process is not significant).

34. Gravity sensitivity within the centrifugal separator is determined primarily by the relationship between centrifugal (or inertial) and gravity forces. Analysis indicates the two to be approximately equal at speeds of 200 to 300 RPM. As anticipated speeds are in the range 1500 to 2000 RPM, the gravitational effect may be considered negligible.

Gas evaporation - Wick replacement:

35. Retention of liquid in the separator during servicing creates a potential problem by impairing start-up performance. The location and configuration of this liquid and consequently its effects may vary between 1 and zero-g depending on the relative significance of capillary and gravity forces. The value of a detailed analysis of this condition is questionable due to the complex geometries involved, and uncertainties in fluid and surface properties. It is felt that the degree of g-sensitivity can best be determined experimentally.

Gas evaporation - Purity measurement:

36. As analysis indicates that no significant density gradients are to be anticipated, this process may be considered insensitive to gravity.

Chemical treatment - Wash water:

37. This process is essentially the same as that described in process 30. The same analysis is therefore applicable.

Fluid storage:

38. No process is specified for fluid control during servicing. The discussion under process 12 applies.

39. Maintenance of the water in a gas-free condition is essentially the same as that described under process 10 for the thermal fluid systems.

Waste management.-

Waste handling:

40. Transport of the feces from the collector case to the drier and then to the storage container is a manual process closely related to that for carbon bag servicing, process 15. It is clearly g-sensitive, and by nature of the waste particles, could present a health hazard. It is felt that experimental verification of the technique is needed.

Collecting and flushing:

41. Gas transport of the liquid and solid wastes can, in general, be treated by the same analysis as given for process 3. In this case however, as they involve manual functions which in large part determining initial motion and orientation of the wastes, they are not readily amenable to a valid analysis. It is felt that experimental study is necessary.

Urine-gas separation:

42. Centrifugal separation of the liquid from the gas is essentially the same from a g-sensitivity standpoint as that discussed under process 34.

43 The discussion of liquid retention during servicing which was given for process 35 is applicable here.

Vacuum drying:

44. Collected wastes, in permeable containers, when placed in the vacuum dryer depend on convection, conduction and radiation for the heat transfer required to permit drying. All these phenomena play a part in a one-g environment. The waste container, due to weight, rests on the heated surface where conduction occurs. Radiation takes place from the heated side walls and evaporated gases provide a degree of convection. In zero-g, conduction is reduced to random contact and no natural convection is present. Only radiation heating remains essentially the same. Analysis of this design for zero-g operation indicates need for redesign rather than zero-g testing. If design is based on radiant heating or a combination of radiation and weight independent conduction, no significant g-sensitivity occurs. The effect of poor thermal performance is to protract the required drying period.

Waste storage:

45. Retention of dried solids in storage containers presents some handling problems which are g-sensitive. Proper storage placement and creation of small drag forces by a vacuum or recirculating gas flow may be adequate to confine dried materials. Uncertainties regarding the magnitude of velocity levels and forces preclude a valid g-sensitivity analysis without further experimentation.

Personal hygiene.-

Water heating:

46. Solid to liquid heating is dependent upon conduction and convection. In zero-g, when water is not being actually drawn from the container, the liquid will be quiescent, relying solely upon conductive heat transfer. With the present design in one-g, heat transfer by natural convection will predominate. Pronounced g-sensitivity exists, with the heat transfer rates being markedly lower in zero-g. It should be noted that a design based on conduction predominance could effectively eliminate g-sensitivity.

47. Thermal mixing is closely related to the above involving the same phenomena and considerations. In one-g relatively uniform temperatures will exist due to natural convection. In zero-g, on the other hand, severe temperature gradients may be expected in which boiling may actually take place. Any steam formation could seriously impair the water heater performance.

Sponge operation:

48. Liquid retention in a sponge is a function of liquid weight, capillarity and manual dexterity regardless of the gravitational fields from 1 to near zero. Capillary forces dominate unless liquid weight becomes excessive for a given g-level. With zero-g, capillary forces predominate. If manual use of the sponge system under one-g is properly done, spillage can be eliminated. Similar use in zero-g may provide easier, non-spill washing. Gravity sensitivity testing of man and machine is required for this process.

Water-Air separation:

49. 50. From a g-sensitivity standpoint, the discussions under processes 34 and 35 apply here.

Debris collection and storage:

51. Transport of debris, as whiskers, hair and nail cuttings to a collector bag and stowage of the bag involve gas drag, weight and manual forces as discussed previously in processes 13, 15 and 45. It is felt that experimentation is necessary to adequately assess g-sensitivity.

Food management.-

Water heating and cooling:

52. 53. These processes are essentially identical with numbers 46 and 47.

Water dispensing:

54. 55. Liquid is transported throughout the water system by pneumatically-actuated pumping. Provisions are made for dispensing directly into food and drinking containers which are sealed, on filling, with the hands. Manual dexterity, improved with practice, is needed to insure containment. Solid food handling is also a manual operation though provisions are made for holding down containers and packages when not in use. Practice in eating procedures and waste collection requires man-machine testing. These processes or procedures have been used on Mercury and Gemini flights, and their g-sensitivities have apparently created no serious problem.

Instrumentation.-

Liquid-gas discrimination:

56. No process has been specified for liquid-gas discrimination.

Gas analysis:

57. Gas analysis requires a representative sample. Composition mixing is the relevant phenomenom and is analyzed under process 5.

Bacteria analysis:

58. As in the above case, representative sampling through composition mixing is required for bacteria analysis. The processes are discussed under processes 5 and 30.

Temperature measurement:

59. Temperature measurement accuracy is dependent upon adequate thermal mixing. The important aspects are discussed under processes 4 and 47 for gases and liquids respectively.

Humidity measurement:

60. This requires representative gas mixing as in the case of gas analysis. Process 5 includes the relevant phenomena.

Mechanical devices.-

Lubrication:

61. Lubrication characteristics, are dependent upon the ability of the lubricant to maintain a film throughout the required area. This is a function of the liquid's adhesive behavior. Gravity in the earth's atmosphere may act against these adhesive forces, however, zero-g may be expected to improve overall lubrication characteristics. No low gravity testing should be required for lubrication.

Performance:

62. The movement of mechanical parts, unless they are appropriately balanced, will involve weight forces in a gravity field which vanish in zero-g. Many situations of this nature have been discussed in connection with the various servicing and handling operations. The problem is more one of proper design and personnel training than of zero-g phenomenological testing.

Special conditions.-

Gas leakage:

63. In the event of gas leakage, the question of g-sensitivity enters into the mixing behavior of the gas with the cabin atmosphere. The discussion of process 5 is pertinent. If forced convection is dominant, no significant performance difference between 1 and zero-g is anticipated.

Fluids release:

64. Released liquids will be carried throughout the cabin by their initial momentum and gas drag. The effect of gas drag may be treated in a manner similar to that used for process 3. Eventually the liquids will adhere to component or cabin surfaces or will be swept by entrainment into one or more of the subsystems. In one-g there will be the tendency for the liquid to collect in pools, minimizing exposure time of the liquid, spillage recovery efforts, and the amount swept into the subsystems. In zero-g the problems presented can obviously be considerably magnified though the process, being random, is not amenable to analytical quantification. It is felt that information of value could be obtained experimentally.

Solids release:

65. Solids released into the cabin atmosphere will be transported as indicated above. Adhesive forces will be less significant than for wetting liquids but in general, the analysis under process 64 applies here as well.

Flame propagation:

66. 67. Research, testing, and analysis have been devoted to flame propagation for many years. Studies of flame and fire characteristics have involved variation of oxygen partial pressure levels, contaminant production, specific material characteristics and flame suppression techniques. For the purposes of this study, only g-sensitivity is a variable. From data accumulated, all have concluded that one-g flame characteristics are altered in zero-g, though the imposition of small force fields may accelerate zero-g burning rates. A zero-g environment does not noticeably change ignition energy. While flame will propagate along a surface, flame shapes in zero-g lack the characteristic peaks which convective currents produce. The spherical corona is predominantly a diffusion-limited, non-convective flame.

The data indicates that, where flame propagation (and control) is concerned, conditions must be examined to determine convective versus diffusion-dominated aspects. If diffusion only were pertinent, the spherical flame of zero-g would be restricted in size. Upon attaining an initial maximum diameter, products of combustion, diffusing from the flame center, would limit oxygen diffusion to the fuel, diminishing the flame size. The fireball will decrease in size until only a limited flame or no noticeable flame exists. The rate of ball formation and quenching will be dependent on fuel, ignition source and atmospheric conditions. Any inert atmospheric constituent should suppress the flame formation as do the products of combustion.

The introduction of convection in zero-g will accelerate and extend the flame. Flame propagation will, under convective forces, react progressively more as it does under one-g. This discussion is necessarily qualitative in nature and it is felt that low and/or zero-g testing is necessary to quantify g-sensitivity for specific materials and conditions.

Flame control:

68. In general, flame control is accomplished by limiting the introduction of combustibles and/or heat removal which forces a reduction of flame temperature. The gravity sensitive processes generally are natural convection, which tends to provide necessary oxygen; and blanketing by a smothering gas or other material. In zero-g, with natural convection absent, control of flame should be enhanced. However, the smothering effectiveness of a heavy gas or blanket may be markedly reduced in zero-g due to weightlessness. This problem is complementary to flame propagation previously discussed and is in need of testing to obtain quantitative results.

Spillage recovery:

69. No provisions have been specified for recovery of spillage in the ILSS. The significant differences in the process between 1 and zero-g is the increased dispersion of the material which may be expected in the zero-g state and the weightless condition of the spillage. These result in manual, manipulative considerations and are not amenable to a quantitative analysis.

Process interrelationships.- Based on the foregoing analyses of individual processes, those processes which showed significant g-sensitivity were investigated to determine what pertinent effects, if any, their g-sensitivities might have on the performance of other processes and subsystems. For example, poor performance, due to g-sensitivity, of an electrolysis unit hydrogen dehumidifier could have a degrading effect on performance of the Bosch reaction in the CO_2 reduction unit. It is not the purpose here to elaborate on the obvious interrelationships among sequential processes within a subsystem, (for example, failure to achieve adequate chemical-water mixing may result in a health hazard due to contaminated water), but to identify interrelationships which may not be immediately obvious and might be considered more as side effects. A listing of the more significant interrelationships is given in table 4.

Predominant among the identified interrelationships are those involving some form of atmosphere contamination. Zero gravity effects within many of the processes can result in release to the atmosphere of liquids, gases, or solid particles. It is significant that, except for special conditions of leakage or fire, the g-sensitivity is involved in a manual process of some kind. The consequence of the contamination is, of course, dependent upon the nature of the contaminant. Solid particle release, in addition to creating a spillage recovery problem, can well result in a health or explosive hazard. Liquids, released in zero-g, can result in performance degradation of a number of subsystems through corrosive action, electrical shorting, and loading of adsorption beds and filters. Gas-water separation by the use of porous plates can be seriously degraded or completely stopped by exposure of the plates to certain oils or other hydrophobic fluids such as the silicones. Gaseous combustion products, which may be affected by the altered combustion process in zero-g, may prove to be significant hazards from a toxicity standpoint by overloading the contaminant control system.

Important interrelationships also occur involving gas contamination or accumulation in liquids. Gases may enter the liquid systems through faulty gas-liquid separators or during servicing operation and may accumulate and become trapped in critical regions. Heat transfer, in processes utilizing the performance of systems requiring water may be impaired. Ths most critical of the latter is probably the electrolysis unit which will likely require a special gas elimination device.

The sensitivity of the Bosch reaction to moisture content of the gas stream makes this unit particularly susceptible to reduced performance due to failure of the "in-line" liquid-gas separator or water introduction in the hydrogen gas. These latter processes are both considered g-sensitive.

The last item listed is that of flame control by blower shut-down. It might be added, that shut-down of the circulation system for any reason will introduce all of the thermal and gaseous mixing problems referred to under processes 1, 2, 4 and 5.

Gravity sensitive phenomena and processes - Candidates for test.- From the foregoing process analyses and study, those items felt to be significantly g-sensitive and requiring a form of testing to investigate possible performance variations at this level of screening have been identified and are listed in table 5. Further study and screening of these test candidates based on the remaining selection considerations are discussed in the following sections.

Table 4. - Interrelated Processes

G-Sensitive Process		Related Effects
Atmosphere contamination with solids		
15	Carbon bag servicing	explosive hazard, filter loading
27	Particulate filter servicing	health hazard, filter loading
40	Feces bag handling	health hazard
41	Waste transport by gas flow	health hazard
45	Stored waste retention	health hazard
51	Debris transport	health hazard
65	Special solids release	physical damage or injury
Atmosphere contamination with liquids		
41	Waste transport by gas flow	health hazard
48	Liquid retention in sponge	health hazard, water damage
64	Fluids release, leakage	water, thermal fluids damage
Atmosphere contamination with gases		
66	Combustion of fluids	contaminant control overloading
67	Combustion of solids	contaminant control overloading
Gas accumulation in liquids		
39	Water system gas eliminator	loss of control over measured water quantities
20	Electrolysis feed gas eliminator	electrolysis cell degradation
10	Thermal fluids gas eliminator	heat exchanger efficiency loss
Special cases		
16	CO_2 reactor L/G separator	Bosch reaction degradation
25	Hydrogen dehumidification	Bosch reaction degradation
68	Flame control blower shut-down	atmosphere thermal and mixing degradation

Table 5. - Gravity Sensitive Phenomena and Processes to be Considered as Candidates for Testing

General Process Category	ILSS Test Candidate Processes
Atmosphere circulation phenomena	1, 2, 4, 5
Condensation: Heat transfer	3, 16, 32
Condensing rate	6, 16, 32
Porous plate liquid-gas separation	10, 20, 21, 25, 39
Liquid retention in plumbing	* 11, 12, 35, 38, 43, 50
Liquid transport by gas drag	7, 17, 33, 41
Solids transport by gas drag	13, 41
Solids transport - Manual	* 15, 27, 40, 41, 45, 51
Liquid - Liquid Mixing	30, 37
Vacuum Drying	44
Liquid pool heat transfer	46, 47, 52, 53
Liquid recovery and sponge operation	* 48, 69
Flame Propagation	66, 67, 68

Note: Numbers refer to g-sensitive processes listed in Table 3.

*Processes involving manual operations

Test Candidate Screening Analyses

In addition to the elimination of processes as potential test candidates due to their lack of significant g-sensitivity, other screening criteria must be applied to ensure that any suggested experimental testing will be both necessary and sufficient, with regard to assessing ILSS g-sensitivity. These criteria, and their application to the test candidates of table 5 are presented in this section. For convenience of presentation, the criteria are categorized as follows:

Testing is determined to be beyond the scope of this program because:

A. There is presently no component or process in the ILSS representing the test candidate. (These items have been identified only because of their pertinence to a satisfactorily operating zero-g system).

B. Further system or component development is felt to be needed prior to consideration for testing.

C. The test candidates involve man-machine interface problems.

D. The components, although g-sensitive in their present state, can be made essentially g-insensitive by rather elementary redesign.

Testing is felt to be unwarranted as detailed studies have shown that the g-sensitivities of the processes involved can be adequately predicted by analytical techniques.

Discussions of the test candidates of table 5 which may be eliminated from further test consideration are given below:

A. No present component or process in ILSS.-

10. 11. 12. These processes are related to servicing or maintenance operations of the thermal fluids systems while in a low or zero-g condition. It is to be expected that due to leakage or other system malfunction, a maintenance operation which involves opening the fluid plumbing will be required. If removal of the fluid is also required, a well defined procedure and necessary servicing equipment should be available. If servicing can be performed without removing the fluid then some scheme must be provided for its retention. In any event gas entrapment within the system as a result of the servicing process is highly probable. Consequently, a procedure or device for "bleeding" this gas from the system needs consideration. At present, neither the devices nor procedures for accomplishing these tasks exist, and hence they cannot be considered further as candidates for validation testing.

20. 21. These processes refer to the exclusion, and initial removal of gases from the electrolyte chambers of the electrolysis cells. In spite of efforts to maintain a gas free water system, inadvertent introduction of gas into the water supply is a distinct possibility and provision should be made, where necessary, for its removal. The inlet to the electrolysis unit is such a location, and a highly efficient device is needed at this point for gas rejection. Gas entrapment within the cells may also occur in the event that electrolyte removal and replacement is necessary for servicing or repair functions. Provision should be made for this gas "bleeding." As provisions are not available for this "gas control" problem, they cannot be considered for test.

25. Due to the use of electrolytic hydrogen in the Bosch reaction, its dehumidification prior to entering the carbon dioxide reduction unit may be required. No component is available specifically for accomplishing this. Dehumidification processes are used in the water management and cabin humidity control systems but neither is considered to be completely acceptable. Consequently there is no component which may be considered as a test candidate for this process.

38. 39. With exception of the fluids involved, the problem of water retention in the plumbing during servicing, and of gas removal from the system, are essentially the same as described under processes 10 and 12 above. The conclusions are also the same in that the absence of necessary components and procedures precludes their further consideration as test candidates.

69. The recovery of spillage of various types can be expected to involve several techniques and/or devices. At present however, these have not received sufficient attention to produce a concept for testing.

B. Areas requiring further development prior to zero-g testing.-

1. 2. 4. 6. The heat transfer and mixing processes of a cabin atmosphere will, in general, require experimental testing to assure that under zero-g, adequate velocities will exist where needed. The testing needed is in regards to specific items; with specific configurations, gas generating characteristics and heat loads; and located in specific areas. Consequently the information to be gained from a test of the ILSS will be directly applicable only to the immediate component arrangement and configuration which are peculiar to the ILSS and will be of little benefit to other cabin configurations. In view of this questionable value of the testing, it is felt that these items, 1. 2. 4. and 6 should be excluded from further consideration as test candidates.

13. The problems involved in removal of carbon particles from the Bosch reaction, and their transport to the collector by air drag have not been sufficiently resolved as of this point in time. Consequently, it is felt that these processes, though likely to be significantly g-sensitive, should not be considered as test candidates under this program. It should be noted, however, that although these problems have not been resolved in their ILSS application, there appears to be nothing basically wrong with considering particle transport by air flow in a zero-g environment.

41. 48. Use of the personal hygiene sponge for washing (Process 48), and the collection of fecal and urine wastes, including the flushing process for the latter (Process 41) are processes in the personal hygiene system which are currently considered by LRC to be inappropriate for extended space flight. Inconvenience, and potential problems with spillage appear to be the primary concerns. Further, development is underway and thus the processes are not now considered candidates for zero-g testing.

C. Processes involving man-machine interface problems.-

A number of g-sensitive processes are intimately associated with man-machine interface, in that the degree of g-sensitivity is a function of manual training or skill. In general, the consideration of such processes for testing is beyond the scope of this program.

11. 12. 35. 38. 43. 50. Liquid retention and behavior in plumbing during manually performed servicing operations are very closely associated with the particular functions performed and techniques used. Consequently it is felt that they should not be further considered as test candidates.

41. The same conclusion holds in general for feces and urine collection since both processes are strongly sensitive to manual functions.

15. 27. 40. 45. 51. The solids transport problems involved in these processes are almost exclusively man dominated and these processes should not be considered for testing in this program.

48. 69. Similarly, sponge operation and spillage recovery are essentially man-controlled operations and should not be further considered as test candidates.

D. Processes amenable to redesign to eliminate g-sensitivity.-

44. As indicated previously, the present vacuum drying facility acquires its g-sensitivity from weight dependent conduction and possibly natural convection. Conduction heat transfer can be effectively eliminated by isolation mounting of the waste container, or it may be made insensitive to weight forces by establishing positive contact through mechanical loading. (e.g., with the use of springs). The latter is preferred as it will result in a higher overall heat transfer rate and may be expected to overshadow the g-sensitive convection effects. It is felt that appropriate redesign, based upon radiative and controlled conductive heat transfer will diminish g-sensitivity sufficiently to eliminate the need for zero-g validation testing.

46. 47. 52. 53. Heat transfer, within the water heating and cooling containers, is due largely to natural convection in a one-g environment, resulting in significant g-sensitivity. Proper thermal design, emphasizing conduction techniques, could effectively eliminate this g-sensitivity without compromising overall heat transfer rate. Consequently it is felt that at this time these units should be redesigned rather than considered for test.

Gravity sensitivity adequately predictable by analytical techniques.-

3. 6. 7. 16. 17. 32. 33. These associated processes, though appearing to be appropriate for actual testing, were considered, after further study, to be amenable to a reasonable depth of analysis. The pertinent questions to be answered were the g-sensitivities of:

Condensation rate

Heat transfer rate

Parallel passage blockage, and

Liquid film drag motion

The condensation and heat transfer rates are intimately related and their g-sensitivities depend upon the water film thickness and surface roughness. Parallel passage blockage depends upon film thickness and the capillary forces presented by a blocked passage. Liquid film drag is a function of the comparative magnitudes of the gas drag coefficient or sheet stress set up on the film surface, and the weight of the film. As these parameters are all closely related, they have been analyzed based on the ILSS Cabin "A" heat exchanger. Since the analytical approach may be of interest in evaluating alternate methods, it is presented in some detail.

Film surface roughness - It was pointed out in the Physical Background under "Interface Dynamics" that a liquid film surface may be expected to remain smooth for low gas velocities, becoming unstable as the velocity increases. A criterion for this region of transition to instability has been given as a Reynolds number of approximately 200, (ref. 1), as is shown in figure 3. Reynolds number for this application is defined as:

$$Re_w = V_{int} \, \delta/\nu_w$$

where: Re_w = Reynolds number for water,

V_{int} = Interface, or surface velocity,

δ = Water film thickness,

and ν_w = Kinematic viscosity for water.

Assuming a linear velocity profile through the water film and considering the downstream end of the heat exchanger:

$$Re_w = 2\, Q_w/L\, \nu_w$$

where: Q_w = Maximum condensation rate (.06 ft^3/hr)

and L = Total fin perimeter (200 ft)

From this a Reynolds number of approximately 0.01 is obtained. As this is many orders of magnitude lower than the Reynolds number criterion, it may be safely assumed that a smooth film surface exists. It should be noted that this Reynolds number criterion is a theoretically derived value and some question exists as to its validity when applied to specific conditions; however for this particular case it would appear to be a safe value to use due to the large difference between it and the actual Reynolds number obtained.

Maximum Film Thickness - The film thickness, and consequently the interface velocity can be obtained through use of the shear stress.

$\tau_w = \mu_w V_{int}/\delta$ by definition, and

$\tau_a = f \rho_a V_a^2/2$ based on gas stream kinetic energy.

τ_w, τ_a = Shear stress for water and air respectively

where: μ_w = Dynamic viscosity of water

f = Friction factor ($\simeq .04$)

V_a = Core air velocity (6 ft/sec. minimum)

ρ_a = Air mass density (.00155 lb sec²/ft⁴)

g = 32.2 ft/sec²

since: $\tau_w = \tau_a$

$$\frac{V_{int}}{\delta} = \frac{f \rho_a V_a^2}{2 \mu}\text{, but}$$

$$V_{int} = 2\, Q_w/L\text{ , therefore}$$

$$\delta = 2\sqrt{\mu\, Q_w/L\, f\, \rho_a V_a^2}$$

From this equation the maximum expected film thickness is found to be approximately 0.00079 inches, and the corresponding interface velocity is 0.0025 ft/sec.

Capillary forces for blocked passage - Assuming that a passage between fins has become closed with water, the capillary force which will exist, and which must be overcome if the passage is to be cleared, is found from the Young-Laplace equation given in the Physical Principles Section. The equation reduces to

$$\Delta P = 2\,\sigma/D$$

where: σ = surface tension of water

and D = fin separation (0.1 in.)

Thus the required pressure head to eliminate passage blockage is approximately 0.24 inches of water. The pressure drop existing across the heat exchanger during normal operation is computed to be 0.505 inches of water using a mass flow rate based on core mean flow area. As this is twice the required pressure to clear a blocked tube it is unlikely that blockage will ever occur. However, since tube blockage, if it should occur, will reduce the flow area and thus increase core pressure drop, the blockage process becomes self defeating and should not present a problem. The likelihood of passage blockage is further diminished by the very thin water film expected

Liquid film drag - Previous analysis, which neglected gravity effects, indicated a film interface velocity of 0.0025 ft/sec. In the presence of a one-g force, which aids the drag force, this velocity may be expected to be slightly higher, however, it should not significantly affect heat exchanger performance. If the one-g force opposes the drag force, the balance between weight and drag must be considered. This can be done conveniently by determining the maximum amount of liquid which can be transported against one-g by the available film surface shear stress τ_a, and comparing this to the actual liquid condensation rate. The maximum amount of liquid which can be transported, Q_w max. = $V_m\,\delta_m\,L$, where V_m and δ_m are average film velocity and thickness respectively for the maximum transport case. Due to the weight of the water film, its velocity profile is no longer linear but assumes a parabolic shape with zero shear stress at the wall.

$$V_m = \frac{W_w}{2\,\mu_w}\,y^2$$

$$V_m = \frac{W_w}{6\,\mu_w}\,\delta_m^{\,2}$$

where: W_w = water weight density (62.4 #/ft^3)

V_m = local water velocity under maximum transport conditions

y = distance through film from fin wall.

For the maximum transport case: $\tau_a = W_w \delta_m$

and hence: $\delta_m = \tau_a / W_w$

therefore: $Q_w \text{ max.} = \tau_a^3 L / 6 \mu_w W_w^2$

The ratio of Q_w max to the actual condensation rate is found to be .025 indicating that the available air drag is totally inadequate to carry the condensed water film against one-g.

Similar analyses have been performed for the other ILSS components in which liquid condensation and transport by gas drag were considered potentially g-sensitive. Results of the analyses are presented in table 6.

In summary, calculated conditions and parameters which determine the g-sensitivity of conduction rate, heat transfer rate, parallel passage blocking and film drag motion, indicate that with one exception, no significant effects on heat exchanger performance will occur between 1 and zero-g provided the g-force is in the direction of the gas flow. The one exception is passage blocking within the CO_2 reduction unit condenser during Sabatier operation. The low gas flow rate does not provide sufficient core pressure drop to keep individual passages clear should they become blocked. (It may be noted that in this case the water film, considering both opposing walls of a core passage, was found to occupy approximately 30% of the design gas flow area; making tube blockage very likely, at least on an individual passage basis). Except for this case the ILSS units may be considered to be essentially g-insensitive. On the other hand, performance of the units may be expected to become seriously degraded if they are inverted. This is due primarily to the low shear stress exerted by the gas stream on the liquid film surfaces. Except in the case of the air evaporation unit, this shear stress is not sufficient to lift the water film against one-g. In the air evaporation case, tube blockage is expected to occur when the flow is against one-g since the core pressure drop is just sufficient to keep the passages clear in zero-g.

Table 6. - Fluid Transport Analysis Results

Component	Flow Under 0-G			Flow Against 1-G
	Film Reynolds Number *	Outlet Film Thickness (inches)	Blocked Passage Condition $\left(\frac{\text{Clearing Pressure}}{\text{Capillary Pressure}}\right)$	Film Drag by Upward Gas Flow $\left(\frac{\text{Maximum Possible Transport}}{\text{Condensation Rate}}\right)$
Cabin Air (A) Heat Exchanger	.011	.00079	2.1	.025
Cabin Air Exit Duct	.60	.0073	250. **	.0001
Air Evap. Condenser	.0084	.00026	1.1	11.3
Air Evap. Exit Duct	.95	.0015	20. **	4.0
CO_2 Reduction Unit Condenser				
Bosch	.057	.00062	2.9	2.8
" Exit Duct	.96	.0022	18. **	.44
Sabatier	.033	.0099	.13	$3. \times 10^{-14}$
" Exit Duct	.55	.035	1.6**	$9. \times 10^{-13}$

*Stability assumed for Reynolds Numbers less than 200.

**Based on Heat Exchanger pressure drop

In view of these analytical results, the following points were considered particularly pertinent in considering these test candidate processes for actual testing.

> There appears to be no general necessity for orienting condensing heat exchangers so that gravity opposes the air drag.
>
> Should an unfavorable orientation become necessary, the conditions at which significant performance degradation occurs are calculable as are the subsystem modifications necessary to prevent the degradation. This, of course, assumes validity of the basic analytical data, and the necessary assumptions made.
>
> Testing of an ILSS heat exchanger would provide data, for the most part, peculiar to that particular unit with little application to alternate or advanced units.

From consideration of the foregoing, g-sensitivity testing of the discussed heat exchanger processes as they occur in the ILSS does not seem warranted. It would seem appropriate, however, to perform certain basic experiments to verify the questionable aspects of the assumptions required for the analyses. This would confirm the analytical results and thus assure the predictability of ILSS process g-sensitivities.

30. 37. Further study of these liquid mixing processes was conducted to provide deeper insight into the specific parameters requiring testing and the type of testing needed. As discussed previously, these processes involve the pretreatment of urine with chromic acid and the treatment of wash water with BAC (Benzalkonium chloride). In both cases, the mixing processes may be influenced by forced convection, natural convection and diffusion. The act of injecting the solute into the solvent will impart some degree of forced convection irrespective of the gravity forces present. The effect of this forced convection is to disperse the solute within the solvent, increasing the surface area of the solvent-solute interface, and reducing the path length through which the solute must further travel to provide complete mixing. Due to the variables, both manual and automatic, involved in the injection, and the complex geometries of the hardware, the mixing effectiveness of this forced convection cannot be completely analyzed. Natural convection which depends on the gravity forces may have much the same effect as forced convection by causing a dispersion due to falling of the more dense portions of the liquid through the less dense. On the other hand, gravity forces may attenuate the dispersion due to forced convection by tending to stratify the liquid into layers according to density. Diffusion of the solute within the solvent, which is essentially independent of gravity, is due to agitation on a molecular level and generally constitutes the final phase of the mixing process resulting in a stable, homogeneous solution.

Convective behavior, since it deals with gross circulation, can dramatically affect mixing rates. Due to viscosity effects, however, this convective behavior may be expected to last a relatively short time. On the other hand, it is accompanied by molecular diffusion which then continues the mixing process after convection has ceased. Consequently, it is of interest to determine the contribution of diffusion to the over-all mixing process. Unfortunately, analytical derivation of the diffusion contribution was not possible due to the lack of coefficient data for the specific liquids and conditions of interest. There was indication from available data on similar materials, however, that the diffusion rates could be sufficiently high that adequate mixing, based on diffusion alone, might be expected to occur in actual ILSS hardware over the rather extensive holding periods available. As this could eliminate the need for more extensive g-sensitivity testing, the most appropriate approach appeared to be an initial experiment to obtain diffusion data, followed by diffusion analysis of the actual system. The results of this analysis would, in turn, determine the need for further g-sensitivity testing.

Therefore to assess the importance of diffusion in the liquid mixing processes, experiments were performed to examine chromic acid diffusion in urine and Roccal (BAC) diffusion in distilled water. In both cases, measured amounts of solute were released at one end of a glass tube containing the solvent, and measurements to detect concentration build-up rates of solute at the opposite ends of the columns were made as functions of time.

For the Roccal diffusion, a column 34 cm long was used and sufficient Roccal was introduced to give a final, completely mixed, concentration of approximately 0.9 cc per quart of water. As Roccal is less dense than water, it was overlaid on top of the column and diffusion down to the column bottom monitored by electrical conductivity changes in the bottom water. Roccal concentration build-up at the bottom was found to reach 75% of its completely mixed value in a period of seven hours, while essentially complete mixing took place in approximately 20 hours.

In the case of chromic acid diffusion, a column of urine approximately 25 cm long was used. The acid was prepared as prescribed for the ILSS pretreatment chemical and was introduced in an amount required to give the specified concentration when fully mixed (.572% by weight). It was underlaid at the column bottom, being considerably heavier than the urine, and the pH of the upper surface of the column was monitored periodically. In addition, a measure of the diffusion rate could be observed visually due to the differences in color and translucency between the urine and acid. The upper surface pH was seen to decrease only very slowly with time, dropping from 6.4 to 4.9 over a period of 92 hours. At this time a distinct translucency gradient was still visible so the solution was thoroughly mixed mechanically, resulting in the pH dropping to 4.1. As a matter of interest, the pH monitoring was continued for an additional 24 hours and a further drop to 3.7 was observed. Consideration of the chemical reactions within the urine itself, and in combination with the acid, cast considerable doubt over the validity of the pH determinations as a measure of acid diffusion and consequently on the degree of mixing which had taken place. As a result, a slightly different approach was taken, the prime purpose being to determine the pH difference from the top to bottom of a diffusing column.

For this experiment, three relatively short tubes (approximately 10 cm each) were filled with urine. One column was underlaid with acid as before; another was thoroughly mixed (mechanically) with an equivalent amount of acid; and the third was not treated. After a 36 hour period the upper and lower halves of the diffusing column were separated, their pH values measured and compared with the pH values for the other two columns. The results were as follows:

Urine Column	pH
Untreated	5.60
Mixed	3.38
Top half of diffusion column	4.95
Bottom half of diffusion column	2.90

These experiments indicate that chromic acid diffusion in urine is a very slow process requiring, under the conditions examined, many days to approach equilibrium.

The following conclusions were drawn from this preliminary liquid mixing experimentation:

Roccal diffusion in water is sufficiently rapid that the effectiveness of the overall mixing process in the ILSS test bed is not significantly influenced by gravity.

Though precise diffusion rates were not obtained for chromic acid, it is clear that diffusion alone will not provide the mixing required for adequate urine pretreatment.

The process of chromic acid mixing with urine should be further considered for g-sensitivity testing.

Due to the very slow diffusion of chromic acid, a balanced density test method (see following section on Test Methods), would be particularly appropriate, as it permits the study of forced versus natural convection (relatively rapid processes) essentially independent of the diffusion process.

As a consequence of this study, process 37 was eliminated from further consideration, while process 30 was retained as a possible test candidate.

The test candidate screening discussed in this section is summarized in table 7, which shows the finally selected processes requiring test for their g-sensitivity assessment.

Table 7. - Final Test Candidate Screening

Process Number (Table 3)	Process Description	A- No Present Component or Processes in ILSS	B- Further Development Required	C- Associated with Man-Machine Interface	D- Process Amenable to Redesign	Calculable Gravity Sensitivity	Final Candidates For Test
1	Solid to Gas Heat Transfer		X				
2	Gas to Solid Heat Transfer		X				
4	Thermal Mixing - Gas		X				
5	Composition Mixing - Gas		X				
3	Condensing Heat Transfer - Atmosphere Cooling					X	
6	Liquid Condensation in Heat Exchanger - Humidity Control					X	
16	Liquid Condensation in Heat Exchanger - CO_2 Reduction					X	
32	Liquid Condensation in Heat Exchanger - Gas Evaporator					X	
10	Gas Separation from Liquid - Thermal Fluids	X					
20	Gas Separation from Liquid - Electrolysis Inlet	X					
21	Gas Free Electrolysis Cell	X					
25	Hydrogen Dehumidification	X					
39	Gas Free Water Maintenance	X					
11	Liquid Transport - Thermal Fluids	X		X			
12	Liquid Retention in Plumbing - Thermal Fluids	X		X			
35	Liquid Retention - Centrifugal Separator			X			
38	Liquid Retention in Plumbing - Gas Evaporator	X		X			
43	Liquid Retention - Centrifugal Separator			X			
50	Liquid Retention - Centrifugal Separator			X			
7	Liquid Transport in Gas - Humidity Control					X	
17	Liquid Transport in Gas - CO_2 Reduction					X	
33	Liquid Transport in Gas - Gas Evaporator					X	
41	Liquid Transport in Gas - Waste Management	X	X				
13	Carbon Particle Transport		X				
41	Semi-Solids Waste Transport		X	X			
15	Carbon Bag Servicing			X			
27	Particle Retention in Filters - Servicing			X			
40	Feces Transport - Manual		X	X			
41	Feces Collection			X			
45	Solids Retention in Storage Container			X			
51	Debris Transport - Manual			X			
30	Chemical - Water Composition Mixing						X
37	Chemical - Water Composition Mixing					X	
44	Vacuum Drying of Semi-Solids				X		
46	Wash Water Heating				X		
47	Wash Water Thermal Mixing				X		
52	Drinking Water Heating and Cooling				X		
53	Drinking Water Thermal Mixing				X		
48	Liquid Retention in Sponge		X	X			
69	Spillage Recovery	X		X			
66	Flame Propagation - Fluids						X
67	Flame Propagation - Solids						X
68	Flame Control						X

Flame Propagation Problem in the ILSS

This subject is treated separately here in some detail because it concerns a special phenomenon rather than an ILSS process and as such did not, in earlier sections, receive the full depth of analysis and screening considerations given the other items. The discussion is organized according to the nature of the fuel and has been arranged so as to present the flame propagation problems in order of increasing complexity. As was pointed out in the Section on Performance Effects, ignition energy requirements are not significantly affected by gravity variations, consequently this discussion will be concerned with post ignition burning behavior. The types of fuels considered are listed below:

Fuel	Examples
Gases	Hydrogen Vapors
Liquids	Propylene glycol DC331 Lubricants
Solids	Metals Plastics
Structured	Textiles Crumpled materials Particles
Composites	Insulated wire Treated textiles

Gas flames.- The background of information on this subject is considerable, but it accepts gravity as a constant and deals with the effects of the total environment. In gas flames, whether laminar or turbulent, the fuel and oxidant ultimately become associated by the diffusion from opposite sides toward the combustion envelope. The diffusion distance, however, is reduced by the convective mixing which results from atmospheric circulation, from the bouyant convective effects of the hot flame and from the forced convection resulting from the initial gas velocity. The qualitative effects of gravity induced and forced convection are readily apparent from the behavior of a burning horizontal gas jet. The jet, particularly its tip, is deflected upward by its bouyancy; but if the jet driving pressure approaches 1 or 2 millimeters of water, the region of the flame next to the nozzle, which may be considered to be a critical zone, becomes essentially symmetrical. This symmetrical zone indicates that the jet draws air in around itself and would burn nicely but without the deflected tip, in the absence of gravity. Zero gravity therefore would have essentially no effect in inhibiting such combustion and consequently g-sensitivity testing of this type of burning would be of little value.

The only gaseous fuels present in significant quantity in the ILSS are the hydrogen in the electrolysis system, and methane in the CO_2 reduction unit. These are contained at 7 psig and approximately 2 psig, and are generated at rates of one pound and .25 pounds per day respectively. Any reasonable openings of the systems to the cabin atmosphere, including the removal of a piece of the quarter-inch connecting tubing, would produce a jet of such velocity that the jet bouyancy would be of little importance.

It is barely conceivable that evaporated lubricating oil or DC331 might, in a general fire, be created in sufficient quantity to burn well separated from the liquids from which they evolved. In such case, however, it seems almost inescapable that the general level of commotion and turbulence would be so high that the absence of gravity would have no significant effect on the propagation of flames. No g-sensitivity testing is felt warranted.

Liquid fuels.- The information in the literature on this subject is contradictory. Much theoretical and experimental work has been done over several years on the combustion of liquid fuels. Droplet combustion received considerable attention after the second world war because of its importance in gas turbine, diesel engine and rocket combustion. In 1954, M. Goldsmith and S. S. Penner (ref. 4) presented theoretical treatments of droplet evaporation and combustion based on a "spherico-symmetric" model. Their relations predicted the characteristics of steady state combustion in such a model, which necessarily implies zero-g. Many tests of burning droplets and sprays have been made, some of these attempting to approach the zero-g condition of the theory by using very small drops, by conducting the test in a free fall chamber, or by supplying varying degress of downward ventilation around burning spheres. The results of such studies and experiments are often presented as "Burning Rate" or "Evaporation Constant" which are associated by the following defining relations:

$$\dot{m} = \rho \frac{d}{dt} \frac{(\pi D^3)}{6} = \frac{\pi \rho D}{4} K$$

where: $\dot{m}$ = mass evaporation rate or burning rate

ρ = droplet liquid density

D = droplet diameter

K = evaporation constant

$$K = \frac{d}{dt} (D^2)$$

$$K = (D_1^2 - D_2^2) / (t_1 - t_2)$$

The evaporation constant (K) is a particularly convenient parameter because it varies with changing environmental conditions in the same manner as the burning rate, but does not change as the drop evaporates, whereas the mass evaporation rate decreases with drop size and area. The constancy of K follows directly from the theoretical treatments of Goldsmith and Penner and has been experimentally verified for evaporating droplets both with and without combustion. The following K values were obtained on or are adjusted to represent ethyl alcohol droplet burning in zero-g with no ventilation.

M. Goldsmith and S. S. Penner (ref. 4) (Theoretical with some reference to experimental data)	$K = 0.8\ \mathrm{mm^2/sec}$
S. Kumagai and H. Isoda (ref. 5) (Drop chamber tests at various g-levels)	$K = 0.5\ \mathrm{mm^2/sec}$
J. A. Bolt and M. A. Saad (ref. 6) (Small falling drop data "corrected" to zero-g)	$K = 1.0\ \mathrm{mm^2/sec}$
G. A. Agoston, H. Wise, W. A. Rosser (ref. 7) (Ventilated porous sphere "corrected" to zero-g)	$K = 0.4\ \mathrm{mm^2/sec}$

The "correction" to zero-g utilized a relation presented by Agoston, Wise and Rosser:

$$K = K_{OG}\ (1 + N\sqrt{Re}),\quad \text{where}$$

N is similar to a Prandtl Number but was determined experimentally as .28 for ethanol drops, .20 for butanol. Re was based on droplet diameter, ventilation velocity, and the kinematic viscosity of air at a temperature corresponding to the arithmetic mean of the adiabatic flame temperature and the ambient air temperature.

This "ventilation equation" is important not only because of its utility in correcting test data to correspond to the spherico-symmetric theory, but even more because of its particular pertinence to the present problem which involves the effects of ventilation on combustion in the absence of gravity.

The subject appears to be reasonably straight-forward, but there are two apparent contradictions. The work of Goldsmith and Penner, and others, are based on or present a picture of droplet combustion in which the diameter of the flame envelope is directly proportioned to the diameter of the drop. C. C. Miesse, in comments on some of this work and in a paper of his own, (ref. 8) shows evidence that the smaller drops have relatively larger flame envelopes. This finding throws some doubt on the validity of the rest of the theoretical and experimental structure. The other contradiction was reported by Kimzey, Downs, Eldred and Norris, (ref. 9), who burned various fuels in a Zero-G airplane test. They observed flame extinction and attributed it to the lack of gravity. There can be some question of the correctness of this attribution, but their evidence and discussions do have some weight.

Highly volatile liquid fuels do not appear in the Life Support System, but propylene glycol, lubricating oils, DC331 and molten plastics are combustible when heated. In particular, the silicone oil, DC331, due to its use as a thermal fluid is found in the ILSS at temperatures approaching its flash point. Consequently, it is felt that g-sensitivity combustion testing of liquids should be further considered.

Solid fuels.- The combustible, or potentially combustible, solids of the life support system may be further categorized as plastics or metals. (These may be considered as "simple" solids in comparison to structured and composite fuels). There are significant differences between the combustion characteristics of these two. Plastics have relatively low melting, decomposition and ignition temperatures; they have relatively low thermal conductivity; and their products of combustion are gaseous, liquid, solid and various intermediate tarry substances, whereas metallic oxides are solid unless extremely hot.

The combustion of plastics in contact with air may be considered to be similar to the combustion of liquid fuels in that the fuel is vaporized by the heat of combustion and burns as a gaseous diffusion flame. The most significant difference between plastic and liquid fuel is that the plastic may be quiescent in an extended form in zero-g (e.g. a vinyl strip), whereas the liquid will not (i.e. and still be exposed fully to the atmosphere). Unburned plastic fuel may, therefore, extend from inside to outside of a zero-g diffusion flame, thus providing a means for the flame to progress without the same barrier of burned gas that is expected to interfere with liquid droplet combustion. The characteristic times of combustion of plastic fuels, however, may be expected to be approximately the same as for liquid fuels.

The combustion of metallic fuels is somewhat similar to that of plastics but there are significant differences. The temperatures involved are so high that an appreciable part of the heat is transferred by radiation. Also, the high conductivity of metals carries the heat rapidly away from the combustion zone into the unburned fuel. Thirdly, and most important, the build-up of solid combustion products does not diffuse away from the flame. These ashes obstruct the flow of oxygen into the combustion zone and obstruct the transfer of heat away from it. This insulation can be extremely effective. For example, in a magnesium fire at normal gravity it was once observed that the fire had apparently been extinguished by the ash build-up. A few minutes later, a worker kicked the structure which had been burning. The ash was disturbed and the fire flared up and burned the man's leg. Such combustion is definitely g-sensitive.

With regards to the ILSS, the only combustible metal to be found is titanium; and a review of its application shows it to be configured in such a manner that its ignition by anything other than a catastrophic fire is not reasonably possible. Consequently, the further consideration of metallic fuels is felt to be unwarranted. Combustible plastics, on the other hand, are to be found in the ILSS, and as their burning can be significantly g-sensitive, they are to be considered as test candidates.

Structured and composite fuels.- The burning of structured material such as textiles is rather different from that of homogeneous solids in that reasonably large masses of fuel are available in fairly compact arrangement but finely divided so that they have large ratios of surface to volume and are interspersed with air. The arrangement so favors combustion that textile flammability is a principle selection parameter and textiles are frequently treated with a variety of retardants for further assurance of safety. The combustion of such materials can definitely be expected to be sensitive to both gravity and ventilation.

Of the composite fuels, wire insulation may be considered to be the most important (from a combustion standpoint) due to the presence of an effective igniter. Aircraft and spacecraft wiring is normally quite resistant to fire, but not necessarily fireproof. It is assumed that the wiring of an operational ILSS will be of this type, although it is not completely true of the present system.

A combustible cloud of solid or liquid particles may be formed in the ILSS by some mishap. Such a cloud, which could be considered as a structured material could be ignited and burn or explode. In this case, however, the combustion would resemble that of a gas/air mixture and would not be significantly sensitive to gravity.

Much information is available on the combustion of structured and composite materials, but very little on combustion at zero-g. For example, Roth (ref. 10) presents a literature review of space cabin fire and blast hazards. This review contains a chapter on the flammability of fabrics and carbonaceous solids, and data are presented giving the effect of various parameters on burning time, but gravity variations are not included. It is felt, therefore, that structured and composite materials, as represented at least by textiles and wiring, should be considered as test candidates.

Test Candidate Selection Summary

The foregoing treatments of g-sensitivity in the ILSS may be summarized as a set of screening or selection processes and the results of their application to the components and processes found in the ILSS. This summary is given in table 8. The screening criteria are explained in the footnotes, and the remaining ILSS processes which are considered potential test candidates are shown to be "liquid mixing" and "flame propagation."

In addition to these actual ILSS processes, certain "analysis verification" experiments warrant consideration as test candidates. These experiments are needed to support the analyses used in assessing gravity sensitivities of the various ILSS components and processes which involve condensation and liquid transport by gas drag. The experiments would verify the basic data and assumptions employed in the analyses. In particular the experiments would include: investigation of the conditions producing heat exchanger passage blocking; study of the influence of gravity on the size of droplets released from the down-stream edge of a condensing fin; and verification of the film stability data presented in figure 3.

Table 8. - ILSS Process Selection For Gravity-Sensitivity Testing

ILSS Function	ILSS Component	ILSS Process	Process Screening No. 1	G-Sensitive ILSS Processes	Process Screening No. 2	Process Screening No. 3	Process Screening No. 4	Final Test Candidates
Thermal Control								
Atmosphere Temperature	Controls Instruments Lights Water Pumps Fans and Blowers Food Freezer Waste Processing CO_2 Reactor Water Recovery Units Electronics Cabin Walls Metabolic	Atmosphere Heating (Component Convective Cooling)		1. Solid-to-Gas Heat Transfer		B		
	HX "A" Condensing HX "B" Non-Condensing	Atmosphere Cooling		2. Gas-to-Solid Heat Transfer		B		
				3. Condensing Heat Transfer			X	
Ventilation	Fans and Blowers	Thermal Mixing		4. Thermal Mixing-Gas		B		
	Fans and Blowers	Composition Mixing		5. Composition Mixing-Gas		B		
Humidity Control	Liquid/Gas Separator	Gas/Water Separation		6. Liquid Condensation in Heat Exchange			X	
				7. Liquid Transport in Gas			X	
				8. Porous Plate Separation of Liquid From Gas	X			
	Liquid/Gas Separator	Separator Start-up and Shut-down		9. Liquid Retention in Porous Plate	X			
Thermal Fluid Control	Process Fluid HX	Fluid Heating	X					
	Space Radiator	Fluid Cooling	X					
	Reservoir	Fluid Storage	X					
	Pumps and Controls	Fluid Circulation	X					
	- - - - - - - - -	System Maintenance		10. Gas Separation from Liquid	A			
				11. Liquid Transport	A	C		
				12. Liquid Retention in Plumbing	A	C		
Atmospheric Control								
CO_2 Concentration	Silica gel bed	Gas Drying	X					
	Gas/Coolant HX	Gas Cooling	X					
	Zeolite Bed	CO_2 Adsorption	X					
	Gas/DC-331 HX	Gas Heating	X					
	Silica gel bed	Silica gel desorption	X					
	Bed/DC-331 HX	Zeolite Heating	X					
	Zeolite Bed	Zeolite Desorption	X					
	Bed/DC-331/Coolant HXs	Zeolite Cooling	X					
	CO_2/Coolant HX	CO_2 Cooling	X					
	Accumulator	CO_2 Storage	X					
	Blower	Gas Circulation	X					

Table 8. - ILSS Process Selection For Gravity-Sensitivity Testing (Cont.)

ILSS Function	ILSS Component	ILSS Process	Process Screening No. 1	G-Sensitive ILSS Processes	Process Screening No. 2	No. 3	No. 4	Final Test Candidates
CO_2 Reduction	Reactor	Bosch Reaction		13. Carbon Transport, Plates to Collection Bag		B		
	Reactor	Carbon Collection		14. Carbon Retention	X			
	Collection Bag	System Maintenance		15. Collection Bag Servicing		C		
	Condenser (Gas/Coolant HX)	Water Separation		16. Liquid Condensation Rate in Heat Exchanger			X	
	Gas/Liquid Separator			17. Liquid Transport in Gas			X	
	Water Trap (1g)			18. Porous Plate Separation of Liquid From Gas	X			
				19. Liquid Retention in Porous Plate	X			
	Expulsion Tank	Water Storage	X					
	Compressor	Recycle Compression	X					
	Gas/Coolant HX	Gas Cooling	X					
	Reactor	Sabatier Reaction	X					
	Chamber	Desulfurization	X					
Water Electrolysis	Inlet Gas Trap	Gas Removal		20. Gas Separation From Inlet Water		A		
				21. Initial Gas-Free Cell		A		
	Electrolyte Cells	Water/Electrolyte Mixing		22. Thermal Mixing	X			
				23. Composition Mixing	X			
	Gas/Liquid Separator	Electrolyte/Gas Separation		24. Semi-Permeable Membrane Separation of Gas From Liquid	X			
	Liquid Traps	Dehumidification		25. Liquid Condensation and Separation From Gas		A		
		System Maintenance		26. Composition Mixing of Gases	X			
	Cells	Electrolysis	X					
Contaminant Control	Charcoal	Air Filtering	X	27. Particle Retention		C		
	Particulate, and Absolute Filters	Filter Maintenance						
	Catalytic Burner	Thermo-Chemical Reaction	X					
	Air/Air Regenerative HX							
O_2, N_2 Resupply	Cryogenic Tanks	Liquid Storage		28. Boiling Heat Transfer	X			
	Boil-off HX	Gas Generation		29. Gas Separation From Liquid	X			
Water Management								
Water Fluid Feed	Chemical Storage Tank	Acid Pre-Treatment		30. Composition Mixing				X Liquid Mixing
	Dilution Tank							
	Collection Tank	Treated Fluid Storage	X					
	Supply Tank							
	Batch Feed Tank	Feed Control	X					
Air Evaporation	Wick	Wicking and Evaporation		31. Liquid Transport in Wick	X			
	Charcoal Filter	Odor Removal	X					
	Gas/Coolant HX	Water Condensation		32. Liquid Condensation Rate in Heat Exchange			X	
	Gas/Water Separator	Water Separation		33. Liquid Transport in Gas			X	
				34. Centrifugal Liquid Separation From Gas	X			
	Fan	Circulation	X					
	Gas/DC-133 HX	Gas Heating	X					
	Utility Pump	Maintenance (Purge Pumping)		35. Liquid Retention in Centrifugal Separator		C		
		(Wick Replacement)		38. Liquid Retention in Plumbing		A C		
	Conductivity Chamber	Purity Measurement		36. Liquid Composition Mixing	X			
	Charcoal Filter	Filtering	X					

Table 8. - ILSS Process Selection For Gravity-Sensitivity Testing (Cont.)

ILSS Function	ILSS Component	ILSS Process	Process Screening No. 1	G-Sensitive ILSS Processes	Process Screening No. 2	Process Screening No. 3	Process Screening No. 4	Final Test Candidates
Emergency Purification	Metering Pump	Multifiltering	X					
	Carbon Filter							
	Resin Canister							
	Bacterial Filter							
Water Output	Holding Tanks	Storage		39. Gas-Free Water Maintenance		A		
	Electrolysis Accumulator							
	Potable Water Tank							
	Emergency Water Tank							
	Wash Water Tank							
	Chemical Storage Tank	Wash Water Treatment (Mixing)		37. Liquid Composition Mixing			X	
	Wash Water Tank							
Waste Management								
Collection	Gas Draft Feces Collector	Waste Collection		40. Feces Transport		C		
	Gas Draft Urine Collector	Urine Collection		41. Liquid and Solid Transport in Gas		B C		
	Urine Filter	Filtration	X					
	Air Stream Filter							
	BAC Treated Water Supply	Urine Collection Flush		41. Liquid Transport in Gas		B		
	Liquid/Gas Separator	Urine/Gas Separation		42. Centrifugal Liquid Separation From Gas	X			
				43. Liquid Retention in the Separator		C		
Drying	Dryer Cans	Vacuum Heating		44. Solid-to-gas-to-solid Heat Transfer		D		
	Bacteriological Filter	Filtering	X					
Storage	Storage Containers	Waste Storage		45. Solids Retention in Storage Container		C		
	Supply Cabinet	Expendables Storage						
Personal Hygiene								
Washing	Water/DC-133 HX	Water Heating		46. Solid-to-liquid Heat Transfer		D		
				47. Thermal Mixing		D		
	Heater Tank	Heater Gas Purge		49. Centrifugal Separation of Liquid From Gas	X			
	Gas/Water Separator	Wash Water/Gas Separation		49. Centrifugal Separation of Liquid From Gas	X			
				50. Liquid Retention in the Separator		C		
	"Y" Strainer	Strainer Servicing		50. Liquid Retention in the Separator		C		
	Sponge and Squeezer	Sponge Operation		48. Liquid Retention in Sponge		B C		
Shaving	Shaver	Debris Collection and Disposal		51. Solids Transport		C		
Food Management								
	Water/DC-133 HX	Water Heating		52. Solid-to-liquid Heat Transfer		D		
	Water/Coolant HX	Water Chilling		53. Thermal Mixing		D		
	Water Meter Gage	Water Dispensing		54. Liquid Transport	X			
	Water Dispenser							
	Storage Racks	Food Storage	X					
	Manual	Food Handling		55. Liquids and Solids Manipulation	X			

Table 8. ILSS Process Selection For Gravity-Sensitivity Testing (Cont.)

ILSS Function	ILSS Component	ILSS Process	Process Screening No. 1	G-Sensitive ILSS Processes	Process Screeni No. 2	No. 3	No. 4	Final Test Candidates
Instrumentation and Control								
		Temperature Sensing and Control		59. Mixed Sampling	X			
		Pressure Sensing and Control	X					
		Flow Sensing and Control	X					
		Humidity Measurement		60. Mixed Sampling	X			
		Liquid/Gas Discrimination		56. Process Not Specified	X			
		Gas Analysis		57. Gas Analysis	X			
		Bacteria Analysis		58. Mixed Sampling	X			
Mechanical Operation								
	Various Mechanical Devices	Lubrication		61. Liquid Retention	X			
		Performance		62. Solids Motion	X			
Special Conditions								
		Gas Leakage		63. Gas Mixing	X			
		Fluid Release to Atmosphere		64. Liquids Transport	X			
		Solid Particle Release to Atmosphere		65. Solids Transport	X			
		Flame Propagation and Control		66. Fluids Combustion				X Flame Propagation
				67. Solids Combustion				X
				68. Composition Mixing and Heat Transfer				X
		Spillage Recovery		69. Process Not Specified	A	C		

NOTE:

Screening Process No. 1 - Processes were removed from further consideration as test candidates as they were judged to be insensitive to gravity force variations.

Screening Process No. 2 - Processes were removed from further consideration as test candidates as analysis showed no significant effect on process or component performance due to gravity-sensitivity.

Process Screening No. 2 - Processes were removed from further consideration as test candidates due to:

A. No present component or process in ILSS.
B. Further system or component development needed prior to consideration for testing.
C. Processes involve man-machine interface problems.
D. Processes amenable to redesign to eliminate g-sensitivity.

Process Screening No. 4 - Processes were removed from further consideration as test candidates as their g-sensitivities were found to be adequately predictable by analytical methods.

HX - Refers to heat exchanger.

GRAVITY SENSITIVITY TEST METHODS AND FACILITIES

To permit selection of appropriate test methods which could be used for evaluation of the test candidates, a review of gravity related test methods and available testing facilities has been made. The methods review has been rather broad in scope to enable an optimum selection based on the yield of critical data, cost, and availability of facilities.

Test Methods

Low gravity or gravity-related test methods which have been used, or considered for use, in studying problems unique to a low or "zero-g" field are described in this section. For purposes of clarity it is appropriate here to discuss the term "gravity" (g), as it will be used in reference to the test methods. Gravity is handled and thought of on a force basis. A package resting on the earth therefore experiences "one-g" whereas a free falling package at the same location experiences "zero-g" even though it is accelerating toward the center of the earth at 32.174 ft/sec^2. (The acceleration nullifies the "g" force). The "g" level is defined as the sum of all tangible external force applied to the package divided by the tangible external force required to support that package against normal earth gravity (at the earth's surface). It is a measure of the tendency for the components or contents of the package to be displaced or deformed. As a further example, consider a 100 pound drop capsule falling at such a velocity that its aerodynamic drag is ten pounds. If no other external forces are applied to that capsule it experiences 10^{-1} g. In normal earth gravity, the package would concurrently be accelerating toward the center of the earth at 28.957 ft/sec^2.

Summary notes on the various test methods are shown below:

Reduced scale - A necessary feature of many low gravity tests.

Centrifuge - Useful to broaden the test spectrum, but results can be misleading.

Free fall - Most common; many facilities; useful data; but size, transient time, and cost problems complicate application.

Flow loop - Conceptual only, no facility exists.

Density balance - Very useful for fluid statics. Limited applicability to dynamic problems.

Re-orient - Considerable utility, especially where analyses indicate the system is probably suitable for use in normal or low gravity.

Solid state - Possibly useful for heat transfer problems but mathematical analyses are generally better.

Two dimension - Very good for the limited range of problems where the third dimension can be neglected.

Magnetic/electric - Probably not useful for the ILSS.

Reduced scale.- This is not really in itself a "Test Method." It is however, included here because it is an invaluable concomitant of many test arrangements. Scale reduction, for instance, can be useful for static and dynamic testing at normal gravity (g) in order to determine the characteristics of large systems at low gravity. It is also useful for "free fall" testing because it reduces the sensitivity of the test system to drag deceleration, and the required test time or duration.

Testing at reduced scale is common engineering practice, particularly in fluid mechanics. Full scale testing of large fluid systems such as hydraulic turbines, airplanes, ships, etc., is so time consuming and expensive that it is normally undertaken only on a final proof basis. Developmental testing is done at reduced scale. Dimensionless scaling parameters, such as Froude Number and Reynolds Number, which categorize certain types or regimes of flow are used to design and control the tests, and interpret the results.

Centrifuge.- In some cases it may be possible to evaluate the g-sensitivity of a system by conducting increased gravity tests on a centrifuge. This method might tie in nicely with the use of reduced scale models because it can thus simulate real system accelerations greater than or less than normal gravity.

General scale reduction must be done with some caution, and probably will not extend below 1/10, or possibly 1/100 of real system size. Also it is difficult to apply high accelerations to large systems. Putting these factors together, the gravity force simulation spectrum reasonably available reaches from perhaps 1/100 to about 100 full scale g. This provides a reasonably broad base for extrapolation, but is still far from the frequently desired 10^{-4} or 10^{-6} g. The results might be markedly optimistic or pessimistic. Early centrifuge data on boiling liquids indicated that boiling heat transfer would be drastically impeded by the absence of gravitational forces. Drop test and airplane test data, however, showed very little change from normal to "Zero-G." Qualitative explanations of "Bubble Pumping," etc., were soon forthcoming, but the quantitative substantion took some years. The lesson is that the prediction was based on an overall synoptic view of the general problem rather than on an understanding of the basic mechanisms.

Free fall.- In a state of free fall, systems can approximate the acceleration conditions of an orbiting vehicle as closely as desired, required, and justified. A close approximation may, however, be expensive and the cost must be weighed against the required size, g-level, test duration, and initial fluid disturbance. The trade-off can be somewhat complex, for the allowable g-level and the required test duration both vary with the size of the test specimen. The prominent characteristics of representative free fall systems are shown categorically in table 9. A common problem is the residual acceleration of the test capsule due to windage, connecting cables or other effects. For a useful test these effects, and the windage or aerodynamic drag may be computed by

Table 9. - Free Fall Test Systems

Type	Secs	g	lbs.*	Comment
Laboratory Drop	1/2	10^{-3}	20	Should be considered for exploratory investigations.
Laboratory Pop-up	1 1/2	10^{-3}	20	Launching acceleration may disturb the experiment.
Tower Drop	2	10^{-3}	200	Streamlined capsule can handle compact experiments.
Tower Drop	2	10^{-6}	100	"Box-in-Box" system provides low residual g.
Ground Facility Drop	4	10^{-7}	300	Driven outer box provides low residual g.
Ground Facility Pop-up	10	10^{-7}	300	Launching acceleration may disturb the experiment.
Sky Drop--Helicopter	6	10^{-4}	100	Pre-release acceleration effects may persist during trajectory.
Sky Drop--Tether Balloon	3	10^{-5}	100	Developmental.
Sky Drop--Free Balloon	20	10^{-3}	200	Developmental
Aircraft Bolt in	32	10^{0}	1000	Random acceleration continues during trajectory.
Aircraft Free Capsule	10	10^{-5}	100	Pre-release acceleration effects may persist during trajectory approximately 10% yield.
Ballistic Vehicle	60	10^{-6}	20	"Small" rocket propulsion required.
Ballistic Vehicle	600	10^{-7}	300	ICBM class vehicle required for boost.
Ballistic Vehicle	6000+	10^{-8}	20	Orbital booster required.

*** Approximate Maximum Weight of Test Specimen**

assuming that the relative (wind) velocity is not changed by the windage. This will be very nearly true if the drag is low enough to provide an acceptably low residual g. The following equation then expresses the aerodynamic drag deceleration of a capsule falling through still air at sea level standard conditions.

$$\text{Deceleration (g's)} = 1.23 \frac{AC_d}{W} t^2$$

where: A = Cross section area of the drop capsule (ft^2)

C_d = Drag coefficient (based on A)

W = Capsule weight (lbs.)

t = Time after release (secs.)

Putting typical numbers into this equation soon reveals that it is difficult to achieve low residual g-levels for more than a very short test period. A reasonable potential level of success in this effort is indicated in the following descriptions.

Laboratory test: A typical half second drop test rig can easily be arranged where seven or more feet of head room is available. The general features are most apparent by reference to a simple schematic such as figure 5. The hoist should be quick and convenient. An electrically operated "Ball Lock Pin" release has been found near perfect for capsules up to about 200 pounds. Catenary instrumentation cables have very small effects on the trajectory if hung so that the loop is narrow. An arresting cable with a pre-set brake at top or bottom has been found quite satisfactory for controlled deceleration of the capsule at the end of the drop. Other capsule decelerators, such as crushing carboard, driving spikes into sand, etc., have been used, but each requires some development effort at the start of the program, and may require appreciable cost or effort for each test drop.

With twelve feet of head room, laboratory free fall tests can be extended to about one and one-half seconds by a simple pop-up test rig (figure 6). In this system the experiment package is launched from near the floor of the test area. It accelerates upward briefly, coasts upward in free fall and then descends -- still in free fall -- until arrested by the launching cable. An interesting feature of this method is that one may stand on a step ladder or staging with one's face positioned at the top of the trajectory. If the experiment capsule is transparent, a surprisingly clear view of the experiment can be obtained by direct observation. On the basis of the deceleration equation, the residual or drag deceleration can be kept

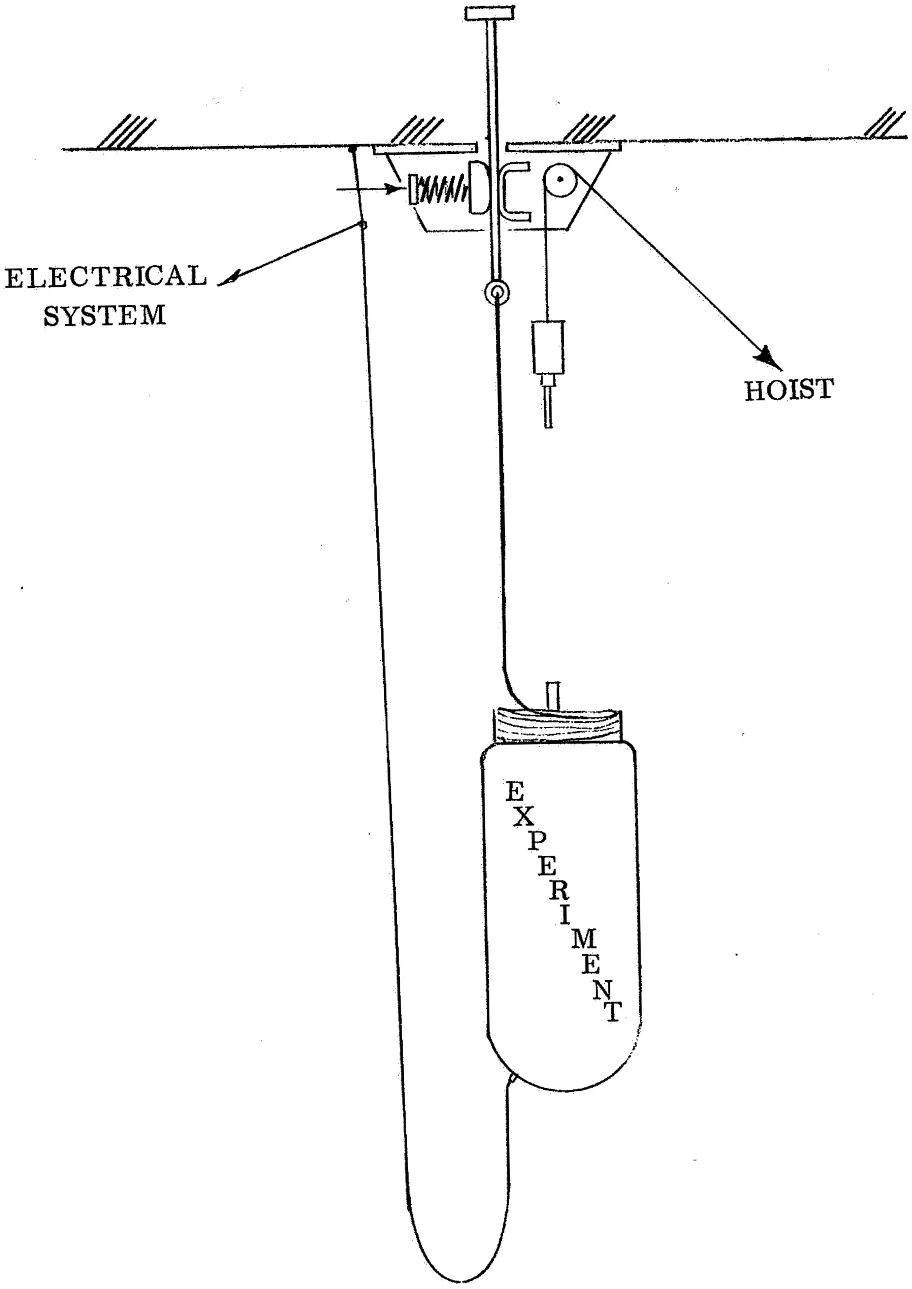


Figure 5. - Laboratory Drop Test Rig

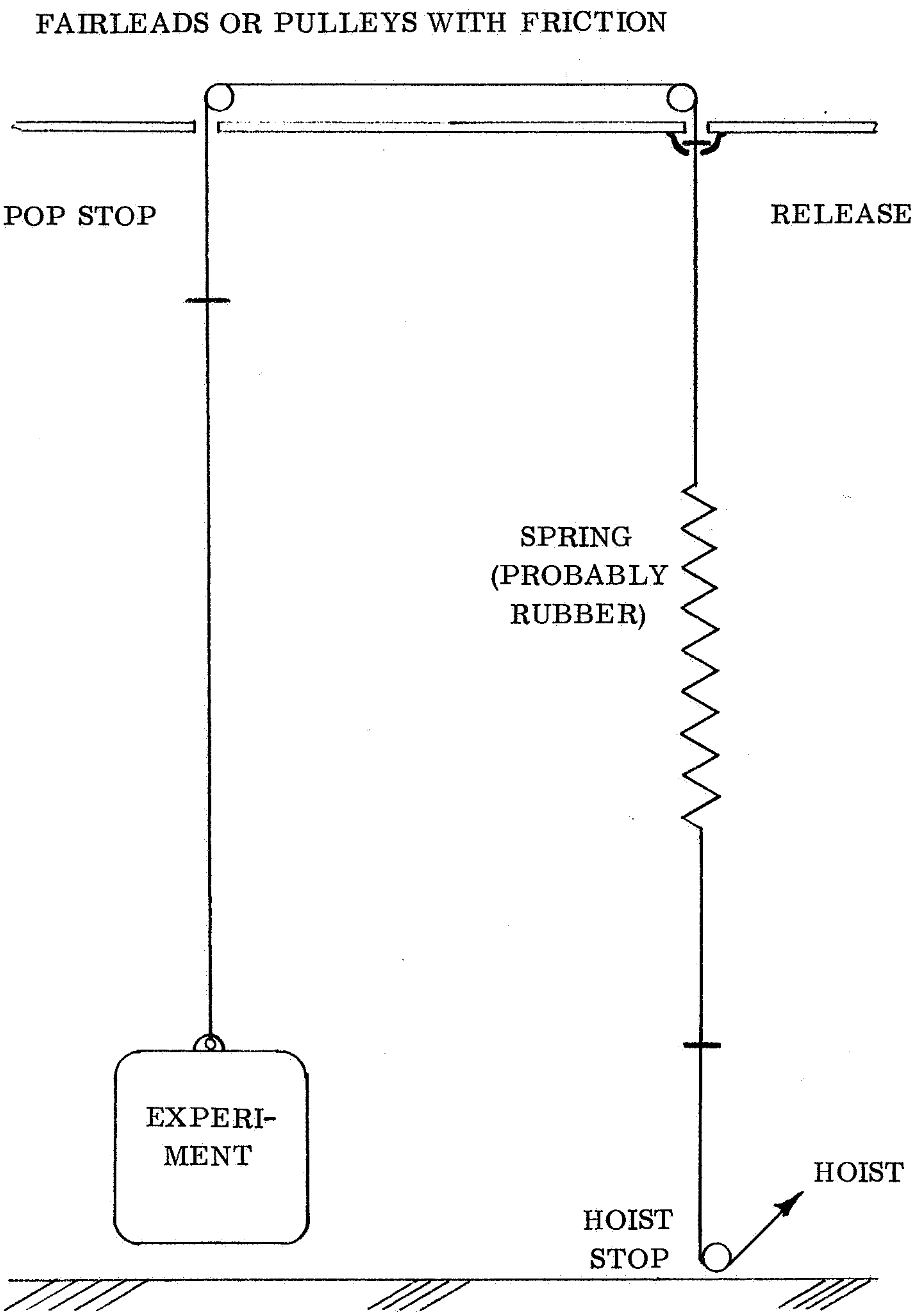


Figure 6. - Pop-up Test Rig

below 10^{-2}g, and is vanishingly small near the top of the trajectory.

There are, however, two potential drawbacks. One is essentially unavoidable but may not be deleterious. The launching acceleration is normally rather severe. It will be very accurately aligned with the gravity vector but will provide a disturbing transient in some types of experiments by violently flattening the capillary rise that existed in normal gravity.

The other disadvantage is that a trailing cable is difficult to arrange satisfactorily. Capsule born instrumentation, e.g., a spring powered camera, can, however, often be provided quite conveniently, and the system is very economical on a dollar per second basis. The laboratory pop-up system can also be converted to a box-in-box system which allows the 10^{-2}g to be reduced to 10^{-4}g or lower.

Tower drop: Drop test rigs have been set-up in or supported by towers which exist and are available. (see figure 7.) The apparatus may be thought of as generally similar to the Laboratory Drop of figure 5 although much more sophisticated systems have been used. Typically, an 80 foot tower can provide about two seconds of free fall, and with a heavy, compact, streamlined capsule, the peak drag forces can be held low enough for about 10^{-3}g drag deceleration. The box-in-box improvement can be added, preferably with a "double pass" arrangement. The outer capsule or box serves essentially as a windshield for the inner box which houses the experiment, this inner box being allowed to float freely within the outer box during the drop. The air drag on the outer box inevitably slows its fall somewhat, the result being that the inner box moves toward the bottom of the outer box during the drop. The inner box may be released from the ceiling or launched from the floor of the outer box at the start of the drop. This latter (double pass) arrangement is recommended because it allows a smaller outer capsule, because the relative velocity (and therefore the air drag on the experiment box) is less, and because it eliminates the possibility of a negative g-transient acceleration of the experiment box at the instant of release. This negative g-transient occurs in systems where the inner box is hung from the tower and the windshield box hangs on the inner one. The elastic energy stored in the framework of both boxes by the influence of gravity is released when the inner capsule is released from the tower. This released energy reacts to propel the inner capsule downward. By inverting the system, and having the inner box initially on the floor of the outer box, a similar energy release propels the inner box upward at the start of the drop, but the launching transient then appears as a slightly delayed decay of the pre-release normal gravity.

Ground based facility: Ground based facilities for free fall testing are considered as different from drop towers because of the amount of study, construction, and money that can be and has been spent on them. Several exist in the United States. Low gravity times up to about ten seconds are available or planned, and drag decelerations range down toward the 10^{-7}g region. Drag reduction means which have appeared in

Figure 7. Tower Drop

the literature include box-in-box, box-in-evacuated-box and evacuated-tower.

Helicopters and balloons: These have been proposed, and used to some extent, as launching platforms for drops from a wide spectrum of altitudes. Helicopter drops have been made, but with some lack of success because of vehicle induced perturbations of the experiment before release. High altitude free balloon drops have been proposed and may offer less than 10^{-3}g deceleration for perhaps twenty seconds. High altitude wind shear may cause transverse lift forces greater than the drag. Some study of this matter is needed. It is anticipated that smoke trail sounding rockets or drop capsules will make possible a realistic assessment of wind shear rates. This technique could feed data into pre-design analyses and later might be used for the selection of suitable test place and time.

Low altitude drops from ground based balloons have also been proposed for economical two to four second free fall periods. In this technique the test capsule would be carried aloft by a balloon tethered close to the ground. The tether would then be allowed to run out freely, and, when the balloon reached a suitable altitude the capsule would be released. The capsule would still be connected to the balloon by a catenary cable and would be arrested when that cable becomes taught. The assembly would then be hauled back down. Little facility money is required for such a system but the cost of repeated use needs further analysis.

Aircraft trajectories: These have been well examined and many trajectories have been flown. The KC-135 airplane has been specially modified for this service and has been very popular. Using a capsule floating in the cabin, free fall times of roughly ten seconds can be obtained in about one trajectory out of ten. Air drag and other forces can range down to about 10^{-5}g. Pre-free fall conditions are characterized by a wandering acceleration vector which distrubs liquid behavior experiments.

At least an appreciable portion of the difficulties with this technique stem from high altitude wind shear. Ground observation of smoke trails or contrails in the flight path may help to resolve the problem.

Ballistic vehicles: Relatively small rockets (e.g. NIKE) have provided up to two minute free fall periods. Ballistic missile vehicles (e.g. ATLAS) can stretch this up toward an hour and carry loads up into hundreds of pounds. Orbital vehicles test times can range into months, but the reasonable package is small.

A combination arrangement has interesting possibilities. A rather large experiment can be conducted in a special upper stage vehicle launched into an orbit about the earth by/from a ballistic missile vehicle. As an example, two OV1 satellites can be carried on one Atlas booster, and each can carry a 220 lb., 8.6 ft^3 experiment into a 400 mile circular orbit. The vehicles may be g-gradient stabilized in their roughly two hour orbits and could have residual acceleration levels less than 10^{-7} g for most of their two to three months in space. The cost of such satellite experiments is quite high. There is a remote possibility of reducing it by riding as a secondary payload on a vehicle having excess payload capacity. Finding such a vehicle which also has a suitable trajectory early enough to get on board is problematical.

Flow loop.- This conceptual laboratory test method could provide low g-conditions for indefinitely prolonged periods. It is a continuously flowing system with the pipe so configured and the flow rate so adjusted that the downward acceleration of the fluid matches the local gravity. The flow rate, component temperatures, and the contour and cross sectional area of the pipe are adjustable in order to obtain the desired cancellation of terrestrial gravity over the full path length. This can be a somewhat involved process if there is appreciable conversion of liquid to gas (or vice versa) in the flow loop. It can be handled by analytical prediction, adjustment of the apparatus according to the prediction, running a test and readjusting as necessary. The method is particularly applicable for the investigation of heat transfer to or from fluids of very low quality (nearly all liquid) because the gas bubbles travel with essentially the liquid velocity, whereas liquid droplets usually lag behind a carrying gas stream. The bubble path can be used to verify the correctness of the flow and contour adjustments, for if the flow velocity is low the bubbles will rise and if the velocity is too high they will descend under the action of the "negative g" field. More exactly, if the velocity is high the bubbles will tend to concentrate near but not at the bottom of the passage because of the velocity profile in the tube. The g-cancellation obviously is not perfect but might range effectively down to the 10^{-1} g or 10^{-2} g region.

Implied in this technique is the requirement that the flow velocity must be rather high in order to allow a usefully long flow loop. Also, the pertinent passage(s) must be relatively thin in order to avoid drastic deformation of the geometry of the system being tested. Conceivably, the technique might be useful in evaluating the performance of low gravity air/water separators -- if these separators operate at a suitable high flow velocity and if they are of a near-planar design which can be distorted into a parabolic arch.

Density balance.- This test method was first demonstrated in 1861 by J. F. A. Plateau when he suspended olive oil globules in a methyl alcohol/water mixture. It is cheap, convenient, and useful for almost any problem in low gravity hydrostatics. Figure 8 is a photograph of a 1/35 scale liquid/liquid model of the Centaur LH_2 tank, showing how the liquid and gas contents of that tank would, without heat transfer to complicate the picture, arrange themselves in a near zero-g orbit. The central bubble, representing gaseous hydrogen, is actually water. The surrounding fluid, representing liquid hydrogen, is a mixture of Freon TF and naphtha. The mixture ratio was adjusted to exactly match the water density by the simple but tedious expedient of drop by drop addition of light or heavy liquid, followed by careful stirring, until the bubble had no tendency to ascend or descend. The method is not generally useful for dynamic problems, for inertia effects on/of the second liquid are

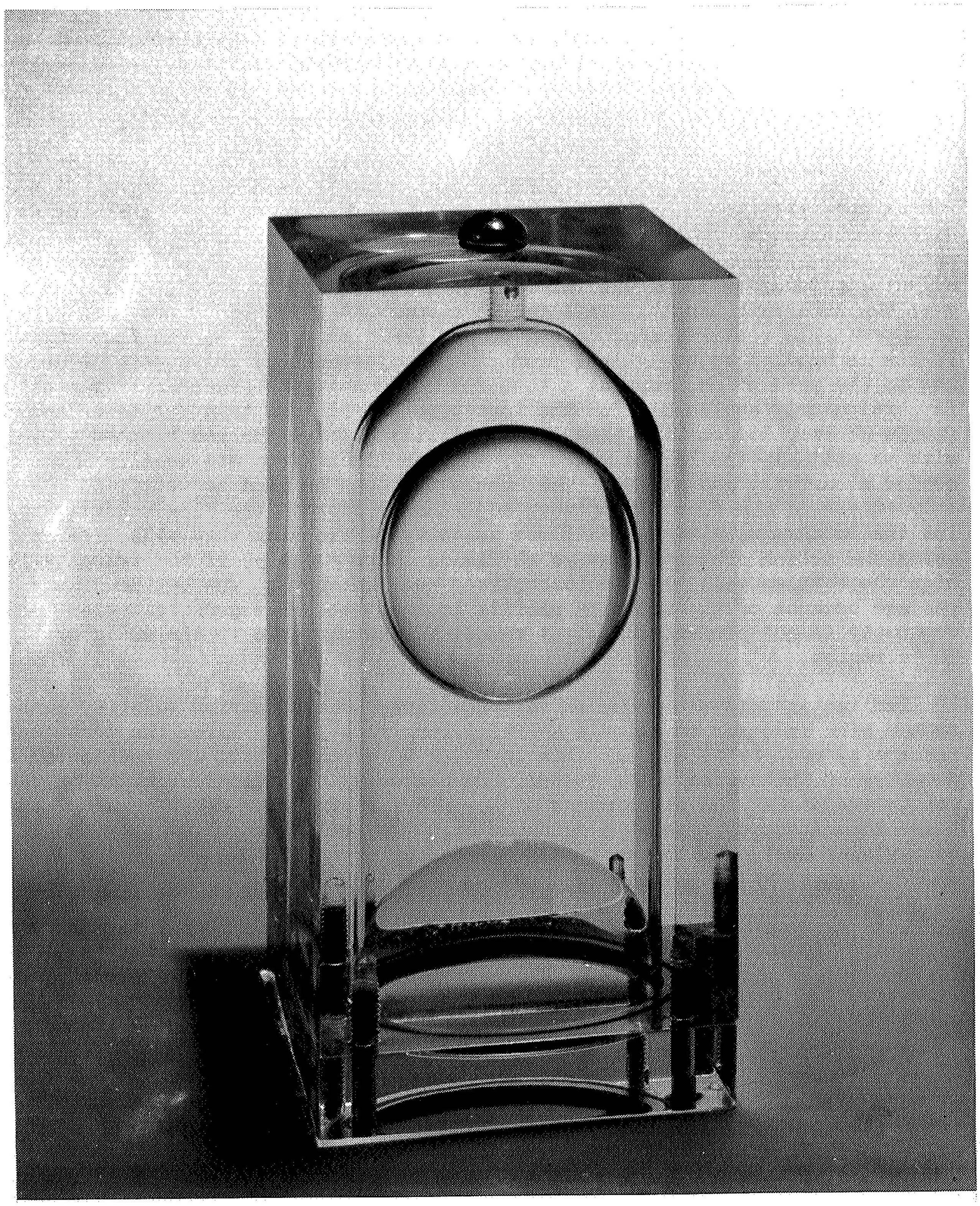


Figure 8. Liquid/Liquid Model

quite different from those on/of the light gas which it simulates. Limited information can be obtained on some dynamic problems, especially where the motion is produced by a force (such as surface tension) which is not derived from the effects of acceleration on the difference in density between gas and liquid. For example, it was conceived at Convair that in a two phase fluid mixture with the liquid strongly wetting, a probe shaped like a pencil point would tend to shed liquid back along its shank, leaving the tip dry. This was checked in an oil/water mixture and later verified in a drop test. The patterns of liquid/gas interface motion were apparently identical and the velocities seem to match reasonably well although no exact comparison was made.

Re-orient.- Some systems are strongly affected by gravity while others are essentially immune. In the misty mid-region, many questions have been settled by re-orienting the system and observing the change in performance (as by tipping a meter to check for pointer unbalance). The very real utility of this technique lies in the not uncommon region where the effect of gravity is slight and perhaps negligible, as for high velocity, two phase flow in small tubes. Being a laboratory bench technique it combines neatly with reduced scale testing and possibly with the flow loop technique.

This technique might be applicable to a boiler, condenser or liquid/gas separator, if the flow velocity is so high or other design features are such that one can have reasonably high analytical assurance that the system will not be affected by gravity nor hampered by its absence. The test technique then would simply be to operate an instrumented model in the various pertinent orientations, as with the fluids flowing up, flowing down, and sideways.

Solid state.- Fluid heat transfer in the absence of phase change and at very low gravity is likely to be essentially conductive. If this can be established analytically, and if the system is too complex for direct analytical solution, solid state simulation may be useful in either of two levels of sophistication. Steady state heat transfer conditions can be matched (model to real system) by copying the geometry and matching the ratios of thermal conductivity. Gas, for example, might be matched by a closed cell foam. For transient tests, it would also be necessary to match the thermal mass ratios. Techniques such as mixing heavy and light materials and adroit distortion of the geometry may be necessary here for good simulation.

Two Dimension.- Gravity effects can be nullified by levelling of systems which can be confined to (or simulated by analagous systems which can be confined to) a plane. This method is useful for many mechanical systems, but not often for fluid behavior problems. A particular field of application is in the development and testing of low gravity apparatus.

This method was applied during the Centaur Zero-G program in order to develop test apparatus for the model drop test simulation of a vehicle maneuver in space. A linkage was constructed which confined the model to a plane but allowed it full freedom to move in that plane. The apparatus was then set up in the laboratory with the constraint plane carefully leveled. An air jet system was constructed and adjusted to give the model the desired trajectory in this constraint plane. The apparatus was then installed in the drop capsule, hoisted up the tower and dropped with the plane of constraint vertical in order to achieve the desired pre-maneuver liquid/gas configuration.

Magnetic/electric.- A magnetic or an electric field can provide counter gravity forces. Conceivably the method may be useful. There is literature which refers to these as "small experiments," "cumbersome" and "expensive." The first two comments seem apt. Stability may be a real problem, and the application of the technique to water/air mixtures is conceptually frustrating. Electric fields have been applied to liquid-liquid models in order to reduce or over-ride the reluctance to coalescence exhibited by water droplets suspended in oil. It has also been used for the collection and dispersion of liquids in low gravity fields. The conceptual difficulties arise from the controlling effect of solid and liquid geometry, dielectric properties, and conductivity on the forces produced.

It is barely conceivable that some useful test data might be obtainable by using electromagnetic force. With a strong horizontal magnetic flux threading the test specimen, an electric current can be passed through it at right angles to the magnetic flux. If a liquid metal such as mercury or molten tin were used, the current density can be high enough to provide about 10g force levels on the liquid. It might seem, therefore, that the current (and magnetic field) could be adjusted to nicely cancel the effect of gravity. Any irregularity in the current density would, however, destroy the balance. The prognosis is not promising. One or more of these techniques may be useful for micro scale corrections of another basic test method.

Test Facilities

Low gravity test facilities useful and available for evaluation of the test candidates are discussed below. The descriptions primarily include only those salient features of the facilities which are of particular interest in considering their application to the present program. Detailed descriptions of most of the facilities, including their applicability to the general problem of low-gravity phenomena may be obtained by contacting the cognizant individuals mentioned. These facilities are all concerned with the free fall type of testing. Reduced scale, re-orientation, density balance, solid state, and two dimension tests can provide useful information, and were considered in the evaluation. No unusual test facilities are, however, required for such experiments.

Ground based.-

NASA-LeRC: The most ambitious ground based free fall test facility in the United States is located at NASA-LeRC in Cleveland, Ohio under the supervision of Ed Otto and Don Petrash. It employs a vacuum chamber, 20 ft. in diameter by 500 ft. high (deep) with launching and arresting gear at the bottom, and allows free fall times of up to ten seconds by using the pop-up technique. Capsules ranging up to 6000 pounds in weight can be handled with maximum drag decelerations down to about 10^{-3}g. Lower drag can be provided by box-in-box techniques, but the presently intended principal use of the facility is for tests in the 10^{-1} to 10^{-2}g region. These accelerations will be provided by a compressed gas propulsion system mounted in the free fall capsule. It is anticipated that the facility will operate at the rate of about one drop test per shift.

An older drop test facility is also located at NASA-LeRC and is more or less typical of such facilities in several locations in the United States. It provides a free fall time of a little over two seconds with the test capsule being dropped inside of and free from an outer box or windshield capsule (Box-in-Box). The capsules are arrested at the bottom of the shaft by inelastic crumpling of expanded material. During the drop, the capsules are completely free, as no catenary cables are used. Data is, by and large, cinematic recording of liquid/gas interface configurations. A capsule born oscillograph has occasionally been used for recording data. The test capsule is a modular aluminum frame about 18 inches wide by 18 inches high by 32 inches long, weighing about 200 pounds. Several test capsules can be (and usually are) under development simultaneously permitting multiple tests during a single shift.

Marshall Space Flight Center: A large drop test facility has been erected and used at NASA/MSFC in Huntsville, Alabama under the supervision of E. N. Stone. It accommodates a 3 ft. cube test package weighing up to 400 pounds. The test package floats freely during the drop inside a 4000 pound drag shield. This outer shield is guided on vertical rails and provided with thrust motors to keep it clear of the test capsule during the 4.3 second drop. A 400 frame per second camera is mounted on the test capsule and six telemetry data channels are available. Test capsule accelerations are reported to be less than 5×10^{-4} g during the drop, with an 18g deceleration at the bottom. Deceleration is achieved by dropping the shield into a pneumatic cylinder. The 16 to 20 man crew normally makes two drop tests per day.

University of Colorado: A proposal to convert an existing 3000 ft. mine shaft into a facility for low-g testing has been made by Professor Frank Kreith of the University of Colorado. The proposal has not received financial support but the mine shaft is still carried on the University of Colorado list of facilities. It is mentioned here because it has the unique potential capability of thirteen seconds drop duration. Realization of this potentiality would be a considerable undertaking.

Martin/Denver: Under the supervision of H. L. Paynter, a 2.1 second drop tower is in regular operation. Two or more drop tests per day can be made with a crew of one engineer and two technicians. The inner or test capsule is 33 inches in diameter by 4-1/2 ft. high and can have about 8 ft. of relative motion within a streamlined outer capsule, or drag shield. The 8 ft. of "headroom" has been employed to allow Negator spring driven acceleration of the test capsule between -.05 and +.05g. For "zero-g" testing the drag shield is evacuated to 3 mm Hg; the residual acceleration is then, by measurement, less than 10^{-3} g (probably 10^{-4} g). Landing deceleration is kept below 25g. A Millikan DBM camera is mounted on the test capsule. The drag shield weighs 2500 pounds with its c.g. at 30 percent of its height.

North American/Downey, California: A facility roughly equivalent to that at Martin is operated at North American under the direction of M. J. Suppanz. It has 2 seconds of drop time with two different box-in-box systems. The larger has a test package 4 ft. long by 2 ft. wide by 2 ft. high. The smaller test package is only 6 inches diameter by 12 inches high, but its outer capsule is evacuated to provide test accelerations down to 10^{-6} g. The camera for this testing is mounted on the outer capsule, and relative motions are compensated by a zoom printing process developed for the purpose.

University of Michigan, Ann Arbor: Professors John C. Clarke and Herman Merte have conducted considerable low gravity investigations of boiling heat transfer by use of a 1.4 second drop facility. The system is equipped with a counter weight which provides the capability for obtaining gravities from near zero to standard gravity with a corresponding increase in test time. They are currently setting up a new 2 second drop tower for extending this work to include liquid hydrogen. The test facilities were developed particularly for the pool boiling experiments.

Douglas/Santa Monica, California: The major hardware for a pop-up test facility with a capability of 3 seconds free fall has been built by Douglas, Missile and Space Systems Division. Use of an evacuated tower will permit g-levels down to 10^{-6} for a test package weighing 200 to 500 pounds. The facility is not currently in operation but the major components are available.

Lockheed/Santa Cruz, California: Hugh Satterlee of the Lockheed, Sunnyvale Thermodynamics Group guides an experimental zero-g program, utilizing a drop facility located on the Santa Cruz Test Base. The test capsule is basically a 2 ft. cube which carries the batteries, lights, and cameras, and is equipped with thrust motors to provide accelerations up to ∓ 1/3 g. It has 13 ft. of vertical free room inside the 1600 pound drag shield which is guided by 1/2 inch wire cables. Free fall drops last 2.95 seconds and the residual accelerations are less than ∓ 5 by 10^{-4} g. Terminal deceleration not exceeding 20g is provided by a nylon net which catches the drag shield. The minimum recycle time is forty-five minutes; two-hours is more normal, with one engineer and two technicians operating the facility.

Aircraft.- Wright-Patterson Air Force Base in Dayton, Ohio operates three "Zero-G" aircraft (One C-131B and two KC-135's) out of Patterson Field under the supervision of Don Griggs. The C-131B can fly 15 second low-g parabolas; the KC-135's can do a little over 30 seconds. These durations include the time required to stabilize the "orbits" so that for exacting tests the useful free fall times are much shorter. The KC-135 flights characteristically provide about 10 seconds of free float (no bumping) in about one parabola out of ten planned. The zero-g aircraft basically serves as a drag shield, and a launch and catch device, for the free fall experimental package. Experimental packages must in general be self contained and portable by one man. Though the aircraft may be used for many types of tests, its prime utility is in the man-machine interface area.

Facility availability.- This is almost everywhere categorized as "a matter of priority." That, however, has a range of meanings, and certain specific information should be useful. At Wright Patterson (Zero-G aircraft) Don Griggs stated that they are fully scheduled at present, that he could not predict 1969, and that priorities and scheduling would have to be arranged through NASA/LeRC. The facilities at NASA/LeRC are now in heavy demand, but it is believed that 6 months to a year advance scheduling would not be too difficult. The MSFC facility in Huntsville can now schedule tests on an "in between" basis. No particular future scheduling difficulties are anticipated.

The smaller company operated facilities at Lockheed, North American and Martin Denver are busy, but their test rate could be considerably increased by a procedural modification. They, in general, conduct repeat testing by readjustments and modifications to the inner capsule (module). Creation of additional inner capsules, plus some minor modification of the outer capsule, could appreciably shorten the time between drops, by allowing quick module switching with adjustments made to the out-of-facility capsule. This method is being followed at NASA/LeRC.

TEST METHODS EVALUATION AND SELECTION

The utility and applicability of the zero-g test methods have been assessed for each of the selected test candidates. The resultant experimental approaches are suggested here. Prime considerations entering into the evaluation are the utility of the results, the cost of the investigation and the availability of the facilities required.

Two particularly critical questions arise at the outset of this type of methods evaluation. First; is testing in a reduced or zero-g (free fall) environment a requirement, or can the g-sensitivities be adequately inferred from simulated low-g conditions? Second, if actual low gravities are required, what are the minimum test durations needed to provide the desired data?

In general, the cost involved in a simulated low-g test would be a small fraction of that involved in actually producing a useable low-g environment. In addition, where actual low-g testing is deemed necessary, the costs have been found to increase extremely rapidly as the test duration increases. These cost relationships become evident from the previous discussions of "Gravity Sensitivity Test Methods and Facilities." Consequently, the first evaluation step is a study of the test requirements and parameters to establish these points.

Flame Propagation

The immediate objectives of a flame propagation test would be to determine the effects of reduced gravity, and its related parameter ventilation, on flame propagation characteristics of the elements of the ILSS. It would be further desired that the testing be sufficiently basic to make the results generally applicable to the elements of life support and other orbital systems beyond the ILSS. With these objectives as a guide, a large number of ILSS materials were obtained, and a set of preliminary experiments devised to determine ignition and flame stabilization times, and whether or not free fall testing would be required. A detailed treatment of the preliminary experiments is given in the appendix, but a summary of the more significant results is included here.

From approximately 57 non-metallic materials used in the ILSS approximately 20 were considered to be possible test candidates. Samples of these were obtained and to them were added propylene glycol, DC331, filter paper, and paper towelling. The latter two were included due to their ubiquity and rapid burning behavior. Ignition characteristics of these materials were observed during their exposure to a gas flame and/or an electric arc ignitor. Required ignition times were measured for the gas flame tests, and electrical ignition energies as well as a general assessment of ease of ignition was made for the arc ignitor tests.

In general the flammabilities of all the ILSS solid materials were very low, or the times required for their satisfactory ignition were quite long. The consequence being that their consideration as candidates for low-g testing would necessarily imply a very costly test program.

The liquid tests showed propylene glycol to be non-flammable in its diluted state on the ILSS. The DC331 was found to burn vigorously when pre-heated near its flash point but to produce a smoky flame containing large amounts of soot. Lubricating oil was not tested as no appreciable quantity is used on the ILSS.

Following the ignition characteristics testing, experimentation and study was performed to investigate the possibility of obtaining low-g combustion characteristics by the use of simulated low-g techniques, and to develop test methods, devices, and procedures which could apply to future test planning.

A small experimental vertical wind tunnel was set-up to provide controlled, low turbulence, downward ventilation for the test specimens. The specimens included various types of paper, insulated wire, thread, ethyl alcohol, and ethyl ether. With the exception of the insulated wire, the specimens were ignited with an electric arc and the flame propagation rates were observed at various downward ventilation rates. Effort was made to reduce or cancel the bouyant ventilation effects of the flame by appropriate adjustment of the down-draft. Combustion data was obtained photographically. Analysis of the data from this experiment indicated that the technique was not a satisfactory simulation of actual reduced gravity. For some specimens the down-draft produced little or no effect on the upward flame propagation, while for others the results become erratic.

Studying the pictorial data, however, provided realistic information on flame propagation rates and their variability. Also, the development of the ventilation apparatus, the arc ignitor and sample retention devices, and the cinematic recording techniques provided considerable insight into the design of low-g flame propagation test systems.

Other methods of simulating low-g flame propagation were studied but not at the experimental level. These centered around the problem of nullifying the flame bouyancy effect, but none were considered to be satisfactory.

As a consequence of these preliminary experiments and studies, a test approach evolved which, though somewhat different from that originally anticipated, could produce essentially the same results but at a minimal test cost. The approach is directed toward the determination of criteria for predicting flame propagation by using materials amenable to the relatively inexpensive drop testing. These materials could then be tested over a wide range of parameters and, by appropriate extrapolation procedures, could then be used to assess the effects of gravity on flame propagation for materials in general including less convenient materials such as those of the ILSS. The approach is illustrated in figure 9, where the inaccessible test region for economical testing corresponds to the sizes, ventilation and gravity levels of concern for most of the ILSS materials.

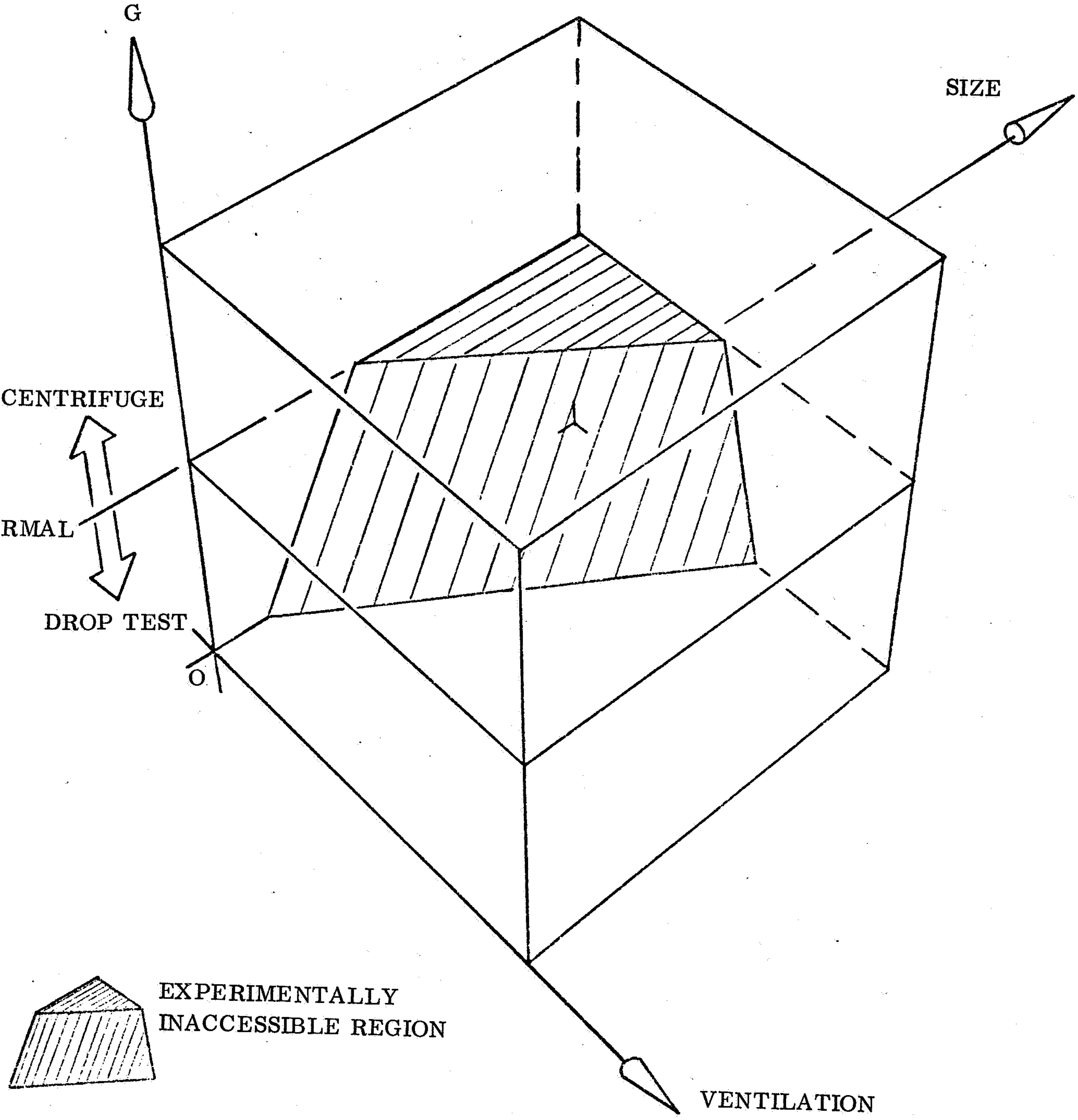


Figure 9. - Flame Propagation Test Regions

The determination of flame propagation prediction criteria involves both analysis and test. Three intermediate or partial objectives can be identified as shown below, and these may also be thought of as phases of the investigation.

Flame Propagation Mechanisms

Flame Propagation Relationships

LSS Element Flame Propagation Characteristics

It is felt that the flame propagation mechanism could be investigated by direct analysis, and that the validity of the analytical results could be assessed through the use of test specimens which are quite small and highly combustible, such as droplets of ethyl ether, fine cotton thread and strips of paper. Their characteristic combustion times are so short that a two second drop test would provide complete coverage of the transient combustion. The simple globular or linear form of the specimen would facilitate analytical investigation of the combustion, and it is expected that the correspondence between theory and practice would in this phase be close and fully verified.

Independent variables for possible investigation in this and the later phases are tabulated below.

Environment:	Acceleration (g)	
	Ventilation	
	Atmosphere:	Temperature
		Pressure
		Composition
	Ignition Source	
System: (Including Specimen)	Size	
	Geometry (Configuration)	
	Material Characteristics	

Establishing "Flame Propagation Relationships," which is in effect an extension of the preceding phase to more complex problems, would make use of larger test specimens with the limit being set by the drop test time available. In addition, the test specimens would be of different configurations and material, such as paper and cloth squares, and it is felt that the direct analytical performance prediction would, at least to some extent, have to be modified toward the creation of a dimensional framework for planning the tests and correlating the results.

Determining "LSS Element Flame Propagation Characteristics" would involve little if any actual zero-g testing. The objectives would be to establish categories of flammability of LSS Elements and to attach g/ventilation sensitivity data to them. The testing in this phase, probably even more than in the other phases, would have to be prepared on a contingent basis. With alternate routes to be followed depending on the preceding analysis and test results.

This phase deals with real time and size effects. Testing would be conducted at normal gravity and possibly on a centrifuge at increased gravity, but there would be no reduced gravity testing. This ties into the representation of figure 9 which illustrates how the flame propagation characteristics in the inaccessible Zero Gravity/Zero Ventilation/Large Size corner can be inferred by at least three independent methods of extrapolation.

In summary, test methods appropriate for flame propagation testing include low-g drop tests, one-g laboratory tests, and high-g centrifuge tests for basic investigation, and for establishing critical flame propagation relationships; and one-g and possibly high-g tests for categorizing full scale flammabilities and extrapolating them into the low-g region.

Specific test facilities include the 4.3 second drop facility at NASA/MSFC; a simplified two-second drop facility having a very short "turn-around" time; a centrifuge having at least a 10g, 500 pound capability; and a laboratory area suitable for one-g burning tests.

The approach to the investigation of flame propagation described above would definitely increase the level of knowledge on this complex subject, but the applicability of the results to the ILSS or near future life support systems is somewhat uncertain. The flammability level of materials used in the environment of the ILSS is almost universally low. In presently anticipated future systems flammability levels will almost certainly be lower, and the reduction of gravity definitely tends to inhibit combustion. Consequently, the practical value of these tests at this time is considered questionable.

Liquid Mixing

As in the preceding discussion on "Flame Propagation," the objective behind liquid mixing testing is not only to assess the g-sensitivity of the specific system and conditions of the ILSS but to perform the testing in such a way as to make the results as generally applicable as possible. Consequently, the evaluation of test methods was directed toward those methods which could provide the most useful data for predicting the g-sensitivity of any liquid mixing process, including the ILSS process, and at the same time be performed at minimum cost.

Consideration of the phenomena of liquid mixing, and a review of available test methods indicated that an actual low-g environment should not be necessary. As g-sensitivity is significant only in the convective component of liquid mixing, and the diffusion component is relatively very slow, satisfactory simulation of the low, or zero-g condition can be obtained by use of the balanced density method. No major facility would therefore be needed. Principle hardware items include a variety of injection devices, and several full scale, clear plastic mixing tanks, two of which should closely approximate the geometry of the ILSS urine dilution and pre-treatment tanks.

Test liquids could be selected having appropriate densities to simulate the desired g-level. These could be colored where necessary to simplify mixing rate determination. Mixing rates would be monitored visually and by cinematography.

Correlation with actual ILSS liquids would be obtained at one-g using chemical analysis techniques to determine concentrations.

It should be noted here that while g-sensitive liquid-mixing conditions may exist within the ILSS and the mixing behavior is not amenable to analysis, it appears highly probable that thorough mixing can, and will, be provided by relatively simple and inexpensive hardware or procedural changes. As this would eliminate any significant g-sensitivity, the above suggested mixing test may be of more academic than practical value.

Verification Testing

The g-sensitivity analyses reported in the Test Candidate Screening section are necessarily based on certain premises. These premises include the guiding assumptions and the physical background data. It is felt that in selected cases experimentation is necessary to verify the adequacy and validity of the assumptions and the accuracy of the basic data. From the previously discussed screening analyses, three g-sensitive areas have been selected for such experimental verification. These areas are: Liquid release from condensing heat exchanger fins; heat exchanger passage plugging; and stability of liquid films exposed to gas drag. The conduct of experiments to verify assumptions made in these areas, and the correlation of the resultant test data with the analytical results should considerably enhance the value of the performance predictions based on the analyses. These predictions could then be accepted with more confidence and would almost necessarily be more accurate; and the experimental support would make the predictive tools which can arise from the analyses more attractive to the designer of life support systems.

Liquid release from fins.- At the downstream end of a condensing heat exchanger, water must often be removed from the fins or passage walls by gravity, gas flow or other means. The size of the droplets shed at the ends of the passages is associated with the thickness of the film built up in the passage and will also be affected by gravity. The drop size may have a reflected upstream effect on the heat exchanger, and it is of considerable importance to the design and operation of downstream devices such as a centrifugal separator. Analytical methods such as those used to assess the liquid transport problems in the heat exchanger could and should be used to estimate the drop sizes, but the physical situation is quite complex, and it is felt advisable to conduct a verification experiment in support of the analyses. The utility of the experimental approach here is not so much to supply or improve the accuracy of the basic physical data needed as a basis for the analytical treatments, but rather to ensure the adequacy of the analytical assumptions.

The apparatus for this test would simulate at least a part of the downstream end of an ILSS heat exchanger, but very probably would not duplicate it. Windows or transparent walls would be provided in the downstream plenum chamber, and care would be exercised in their location and design to allow a clear view of the plenum chamber contents and to prevent their presence from affecting the droplet formation. It is anticipated that three g-sensitivity test methods would be used.

Centrifuge testing would allow the definite evaluation of a droplet size/gravity trend. Reorientation of the test package would allow extrapolation toward zero-g from two different directions; and carefully configured Density balance tests would provide assurance that the extrapolations are applicable in the very low-g regions. Test conditions such as liquid fraction and flow velocities would include values simulating the ILSS environment and would be extended up or down as required to approach or exceed critical conditions, and the results would be correlated with the predictions of the analyses.

Passage plugging.- The previously performed g-sensitivity analyses present analytical treatments of the blockage or plugging of heat exchanger passages. Briefly, these analyses show that if the flow rate through a condensing heat exchanger is sufficiently low, the water films on the passage walls may build up in thickness until they meet in the middle. The meniscus formed by the joined films will then tend to obstruct or block the passage of air. The pressure required to break the meniscus can be calculated directly, as is done in those analyses, but there is a possibility that the situation is not that simple. Possible discrepancies include the effects of random acceleration of the condenser or small irregularities in the passages, which may create multiple obstructive menisci; and the capillary (or surface tension) retention of water at the condenser outlet, which would tend to thicken the water films in that region.

For the experimental evaluation of this problem, a typical condensing heat exchanger (or simulating elements) could be set up and tested to determine whether these or other effects extraneous to the basic analysis do indeed have a significant effect on the passage plugging and clearing. Flow rates and fluid (gas and liquid) conditions, and the orientation of the test set up would be controlled to be near the plugging/clearing threshold. Test results would be compared with the analytical predictions.

Liquid film stability.- The condition of liquid films being dragged along solid surfaces by gas flow occurs in many of the ILSS components. The Basic Physical Principles section gives data on the stability of such films. This data, shown pictorially in figure 3, was taken from a Stanford University Report (ref. 1) by Reynolds, Saad and Satterlee. Reynolds, et al of that reference derived the data from an analytical study by J. E. Miles (ref. 11). Figure 3 shows a stability limit, but there is some question whether this analytically derived data is directly applicable to the specific processes encountered in life support systems. Qualitatively, it is known that as the Reynolds Number and Webers Number increase, (e.g., with increasing velocity) the film becomes wavy, then is increasingly roughened, and at still higher velocities the film is torn into drops and spray.

The g-sensitivity analyses indicate that the water films in the condensing heat exchangers will be smooth and flat. Surface drag coefficients were assigned on the basis of that indication, and it is felt to be valuable to verify experimentally whether the basic smooth and flat datum is true here. Testing could be performed at or near ILSS scale size and conditions, with water films carried along by air current. The test fixture could be fitted with a window for observing the film, and observations made with the fixture positioned at several different orientations to verify the analytical data.

GRAVITY SENSITIVITY PREDICTION CRITERIA

Assessment of the g-sensitivity of a life support process involves identification and comparison of the g-sensitive and g-independent elements which make up the process. From the g-sensitivity studies which have been performed on the ILSS subsystems, a number of processes have been identified as being common to most foreseeable future life support systems, and at least potentially g-sensitive. It is of interest to examine the elements making up these processes and to develop a generalized approach or set of criteria to use for predicting their g-sensitivities. The processes are listed below.

Heat transfer between fluids and solids.

Liquid behavior control by: Gas Flow
Capillarity
Centrifugation

Solids control by gas flow.

Fluid mixing.

Mechanical device operation.

Flame propagation.

It is recognized that these represent very broad fields of study with innumerable possible variations of application. The effort here has thus been directed toward the more basic features of the processes with a great deal of specific application information left undeveloped. It is hoped that this work may serve as a beginning or nucleus from which a comprehensive "design handbook" may be eventually developed, expanding the applicability of prediction criteria for the processes considered here, as well as increasing the scope to include additional processes.

Heat Transfer Between Fluids and Solids

Heat transfer may take place through convection, conduction, and radiation; convection normally being subdivided into natural (free) convection, and forced convection. Gravity-sensitivity is manifested only in natural convection and is the result of gravity induced bouyancy forces. Determination of the g-sensitivity of a heat transfer process thus involves the comparison of natural convection, or potential natural convection, with the other heat transfer modes. This may be accomplished by determining the parameters (preferably design parameters) to which each heat transfer mode to be considered is sensitive, and establishing the relationships between those parameters corresponding to the g-independent modes with the parameter or parameters corresponding to natural convection. This establishes the magnitude of the design parameter for the g-independent mode necessary to produce a heat transfer rate (or heat transfer film coefficient) equivalent to that for natural convection. From these magnitudes, and the relationships between the individual parameters and the heat transfer rates for their corresponding modes, the relative magnitudes of g-dependent and g-independent heat transfer can be determined or established. This leads to an estimation of the effect on over-all heat transfer of the removal or addition of the g-level considered.

In considering the three g-independent heat transfer modes which may be compared to natural convection, the radiation mode appears to be the least important as it is seldom relied upon to provide appreciable heat transfer between a solid and a fluid. Conduction is probably next in importance, with forced convection being the mode most frequently used due to its convenience with fluids and its high heat transfer capability. In view of this, the details of establishing g-sensitivity criteria for a primarily forced convection process are illustrated for several forced convection conditions.

For a vertically oriented flat plate in the laminar flow regime, convective heat transfer may be calculated from the following equations for forced and natural convection respectively:

$$Nu = .664 \; Pr^{1/3} \; Re^{1/2} \quad \text{(ref. 12, p. 149)}$$

$$Nu = .56 \; Gr^{1/4} \; Pr^{1/4} \quad (Gr < 5 \times 10^{8}) \quad \text{(ref. 12, p. 217)}$$

where: Nu = Nusselt Number

Pr = Prandtl Number

Gr = Grashof Number

Re = Reynolds Number

Equating these convection relationships provides the design parameter, velocity (V), for forced convection as a function of the design parameter, wall to fluid temperature difference (Δt), for natural convection; for the case when the forced convection heat transfer coefficient is just equal to that for natural convection.

$$V = .713 \; Pr^{-1/6} \; (\beta g)^{1/2} \; L^{1/2} \; \Delta t^{1/2} \quad (Gr < 5 \times 10^{8})$$

The terms β and g are fluid thermal expansion coefficient and gravitational acceleration respectively. The plate length (L) is a design parameter which can influence both natural and forced convection heat transfer and thus may be associated here with either V or Δt. This relationship is shown graphically in figure 10 for water at average film temperatures of 50° and 100°F and in figure 11 for air at average film temperatures of 70°, 300°, and 1000°F. For convenience, plate length has been grouped with the velocity term. Flow region limits within which the relationships are applicable are specified by the appropriate dimensionless parameter criteria.

Similar calculations have been made for a vertically oriented flat plate in the turbulent flow regime and for tubing or cylinders in cross-flow. For the vertical plate:

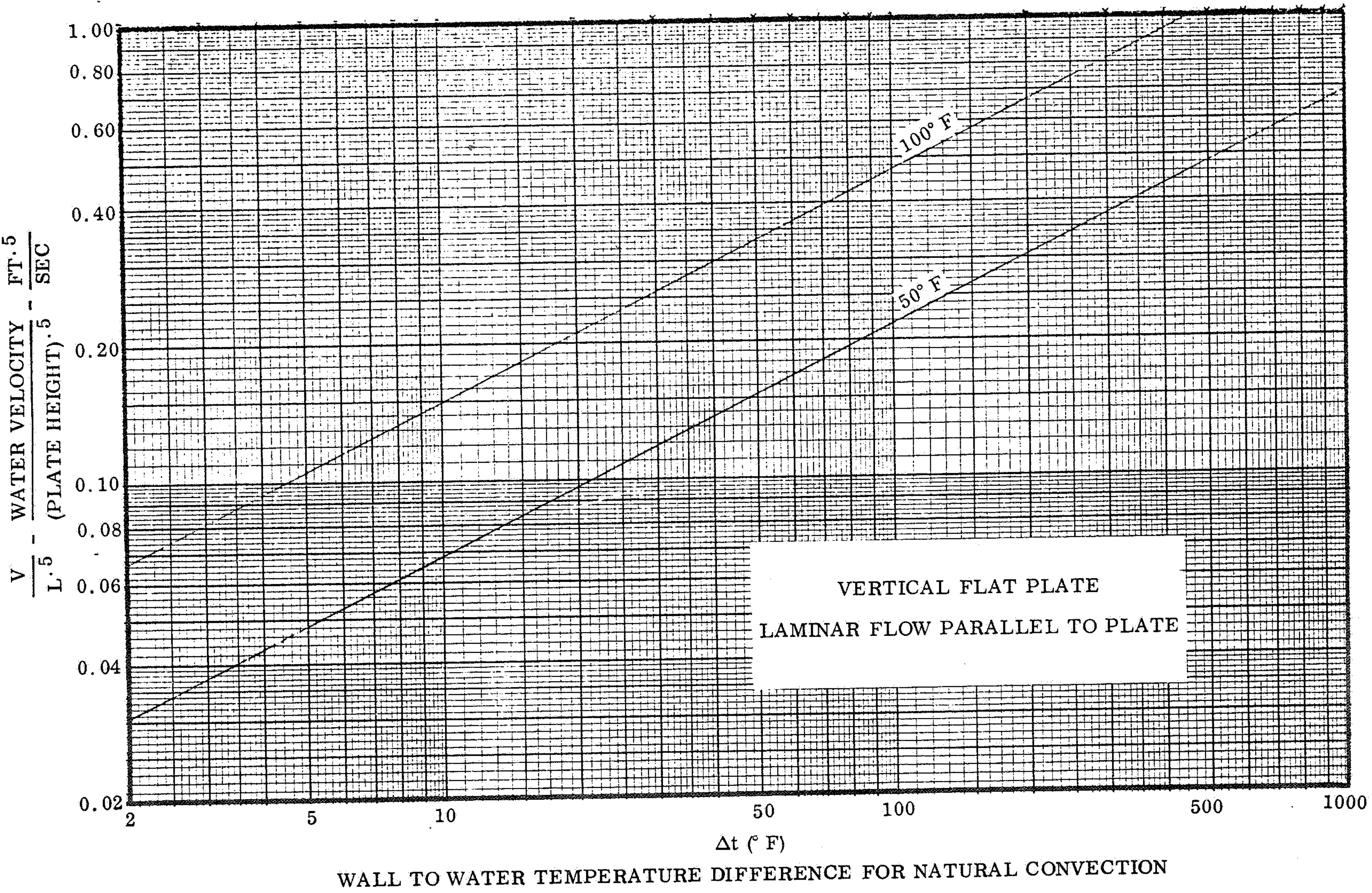


Figure 10.- Water Velocity Parameter Required to Produce Heat Transfer Coefficient Equivalent To That Developed by Natural Convection Resulting from Wall to Liquid Temperature Difference (Δt).

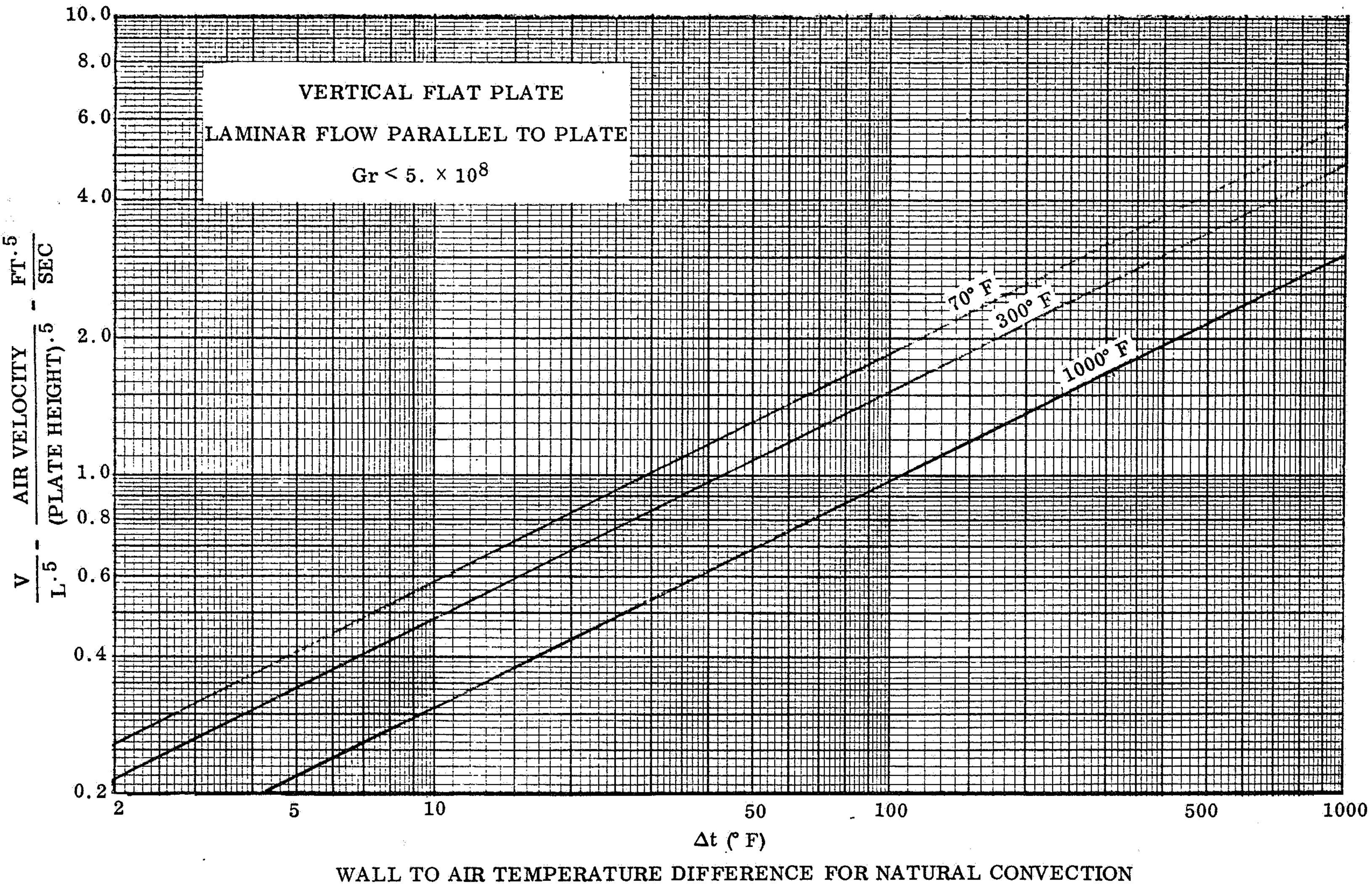


Figure 11.- Air Velocity Parameter (1 Atmos.) Required to Produce a Flat Plate Laminar Heat Transfer Coefficient Equivalent to that Developed by Natural Convection Resulting from Wall to Air Temperature Difference (Δt).

$Nu = .037\ Pr^{1/3}\ Re^{.8}$ (ref. 12, p. 170) for forced convection,

and $Nu = .17\ Gr^{1/3}\ Pr^{1/3}$ $(GrPr > 2 \times 10^{9})$ (ref. 12, p. 217) for natural convection with water

and $Nu = .12\ Gr^{.33}\ Pr^{.33}$ $(GrPr > 10^{8})$ (ref. 1, p. 217) for natural convection with gases.

Equating these gives the velocity, temperature difference relationships:

$V = 6.75 \left(\frac{\mu}{\rho}\right)^{.16} (\beta g)^{.42}\ L^{.25}\ \Delta t^{.42}$ $(GrPr > 2 \text{ by } 10^{9})$ for water,

and $V = 4.3 \left(\frac{\mu}{\rho}\right)^{.16} (\beta g)^{.42}\ L^{.25}\ \Delta t^{.42}$ $(GrPr > 10^{8})$ for gases.

The terms μ and ρ refer to fluid dynamic viscosity and density respectively. For tubing or cylinders in cross-flow:

$Nu = .385\ Re^{.56}\ Pr^{.3}$ $(Re > 100)$ (ref. 13, p. 58) for forced convection,

and $Nu = .525\ Gr^{1/4}\ Pr^{1/4}$ $(GrPr > 1000)$ (ref. 13, p. 59) for natural convection

Equating these gives:

$$V = 1.73\ Pr^{.089} \left(\frac{\mu}{\rho}\right)^{.1} (\beta g)^{.45}\ L^{.35}\ \Delta t^{.45} \quad (Re > 100;\ GrPr > 1000)$$

which is applicable to gases and liquids. These relationships, for flat plate turbulent flow and cylinders in cross-flow, are illustrated in figures 12 and 13 respectively for average air film temperatures of 70°F, 300°F, and 1000°F.

These examples are not intended to include all cases of natural and forced convection but to illustrate the relationships which can be developed between them and which may then be used to assess or specify the g-sensitivity of the over-all heat transfer process. Knowing the forced air velocity which produces a heat transfer rate equivalent to that resulting from natural convection, it is only a matter of referring to the forced convection formula to identify or establish the relative magnitudes of the g-independent and g-dependent heating modes. If, for example, a convective heat transfer process which is designed to produce a heating rate under zero-g of Z times the 1-g natural convective rate for the same temperatures, is brought into a 1-g environment, the heating rate may increase or decrease depending on the orientation of the forced velocity vector and the bouyant forces. In either case, the change in heating

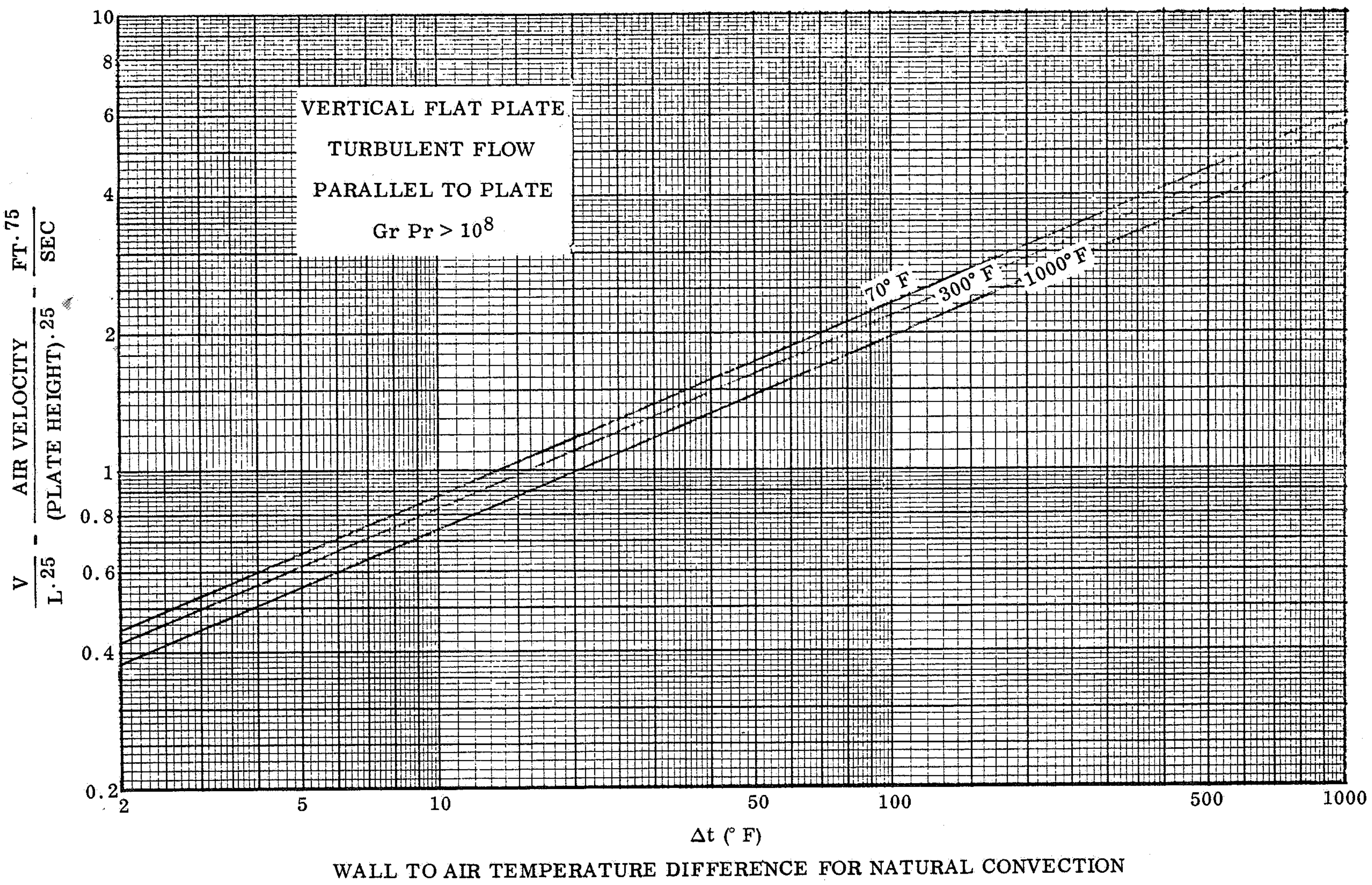


Figure 12.- Air Velocity Parameter (1 Atmos.) Required to Produce a Flat Plate Turbulent Heat Transfer Coefficient Equivalent to that Developed by Natural Convection Resulting from Wall to Air Temperature Difference (Δt).

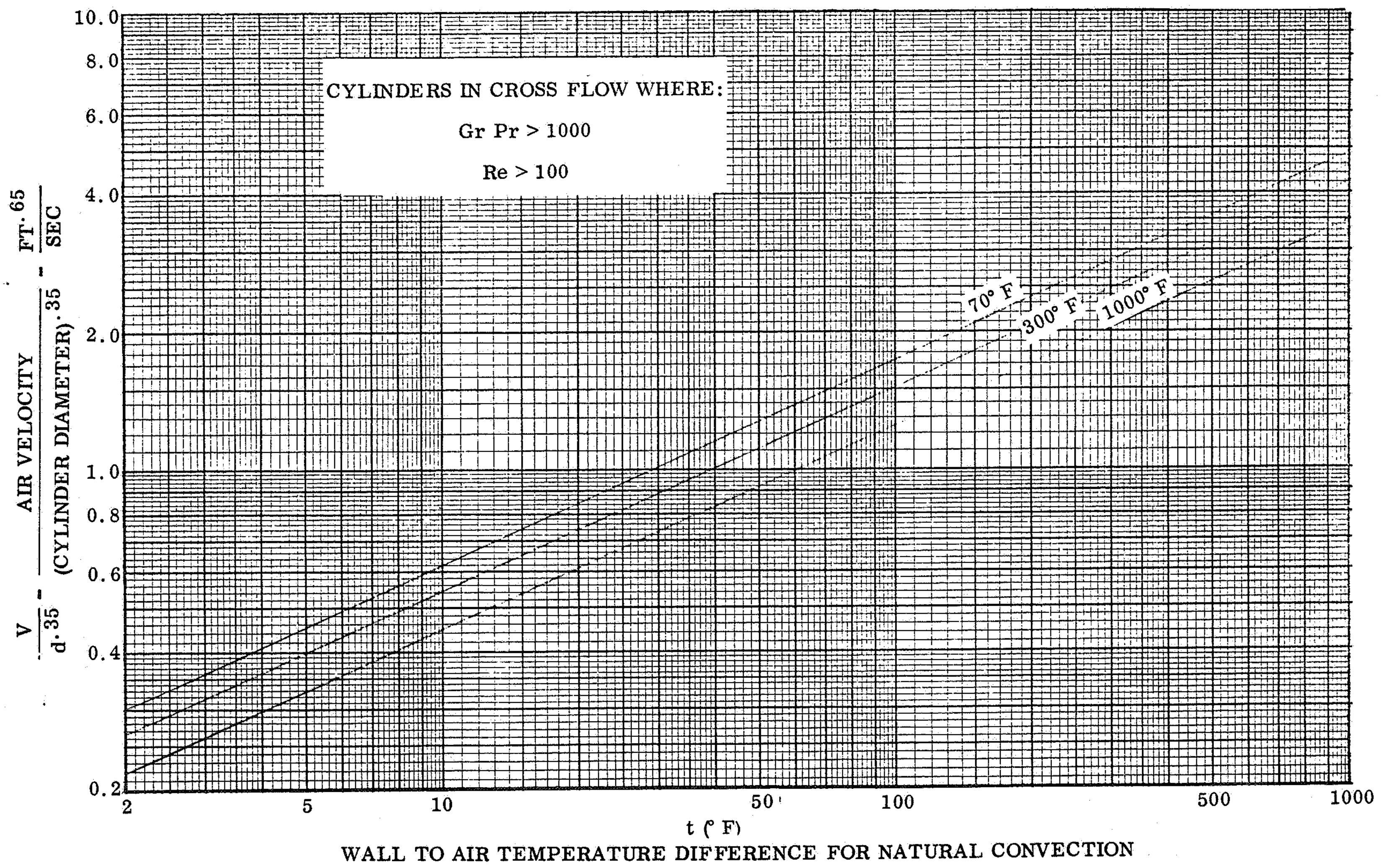


Figure 13. - Air Velocity Parameter (1 Atmos.) for Cylinders in Cross-Flow Required to Produce Heat Transfer Coefficient Equivalent to that Developed by Natural Convection Resulting from Wall to Air Temperature Difference (Δt).

rate may be expected to be no greater than $1/Z$ times the forced convective rate as designed for the zero-g condition. The precise change depends upon the particular relationships assumed and upon the magnitude of Z, but for general engineering purposes is not critical.

Calculations similar to those for forced convection may be made for comparing conduction and natural convection. Again, a large number of relationships are possible depending on the particular conditions of the natural convection and the resultant selected formula for the natural convective heat transfer. As an example, the conduction design parameter, conduction path (X), required to give a heat transfer rate just equivalent to that produced by natural convection on a vertical flat plate (for laminar flow) is found by equating the heat transfer equations:

$$q/A = \frac{k}{X} \Delta t \text{ for conduction, and}$$

$$q/A = h \ \Delta t \text{ for convection where the film coefficient (h) is obtained}$$

$$\text{from: } Nu = .56 \, Gr^{1/4} \, Pr^{1/4}$$

$$Nu = \frac{hL}{k}$$

q = heat transfer rate

A = plate area

k = fluid thermal conductivity

Equating the heat transfer equations and substituting the terms of the dimensionless parameters, the conduction path is found in terms of the plate length and temperature differences associated with the natural convection.

$$X = \frac{\mu^{\frac{1}{2}}}{.56 Pr^{\frac{1}{4}} \, \beta^{\frac{1}{4}} \, g^{\frac{1}{4}} \, \rho^{\frac{1}{2}}} \, L^{\frac{1}{4}} \, t^{-\frac{1}{4}}$$

From the basic concept of the convective heat transfer coefficient, it is clear that this conduction path length is related to the convective thermal boundary layer thickness, and in the case of laminar flow, may be a close approximation to it. For the cases of air and water at room temperature and Δt greater than a few degress, this path length is in the order of a tenth inch or less. Consequently, for small conduction path lengths, as would be used where significant conduction is desired, the common natural convection relationships begin to lose their applicability. This is due principally to to the restriction of fluid motion. As a result, g-sensitivity of a primarily conductive process decreases markedly as the conduction path length is reduced to the value given by the above equation, and for engineering purposes can be considered insignificant at values less than this.

Comparison of radiant heat exchange to natural convection by the type of approach used for conduction and forced convection becomes very complex due to the nature of thermal radiation. Thermal radiation exchange; being a function of fourth power temperatures, emissivities, adsorptivities, and geometry; has no common parameters with natural convection. A common temperature difference (Δt) can be developed in a somewhat artificial manner but its use involves the generation of sets of parametric data which themselves are computed values of radiation heat exchange under specific conditions, (ref. 14) Consequently, it is felt that, for the cases where solid-fluid radiation is significant, the relative magnitudes of radiant heat and natural convected heat should be computed from the basic heat transfer relationships. As has been pointed out, these cases may be expected to be quite rare as the nature of thermal radiation makes it an unlikely candidate for the solid-fluid heat transfer process.

Liquid Behavior Control by Gas Flow

For the assessment of g-sensitivity of processes in which use is made of gas flow to control liquid behavior, three conditions particularly need consideration: (1) drag of a stable liquid film along a solid surface due to shear stress at the liquid-gas interface; (2) instability of the liquid film surface which can result in liquid breakaway from the surface; and (3) transport of free liquid droplets by gas drag.

Drag of a liquid film along a solid surface is dependent essentially upon the surface shear forces, the pressure drop along the surface, and the liquid weight. Gravity sensitivity of the process depends upon the relative influence of liquid weight on the film motion. This influence may be determined from an analysis of the forces involved.

Considering an element of a liquid film subject to drag, weight and pressure forces along a plane solid wall, figure 14, a force balance may be written as follows:

$$(\tau_1 - \tau_2)\,\Delta x\,\Delta z + (P_1 - P_2)\,\Delta x\,\Delta y = \rho\,g\,\Delta x\,\Delta y\,\Delta z$$

Where:

τ = Shear stress

P = Fluid pressure

ρ = Liquid mass density

g = Acceleration due to gravity

In differential form: $\frac{\partial \tau}{\partial y} = \rho\,g - \frac{\partial P}{\partial z}$

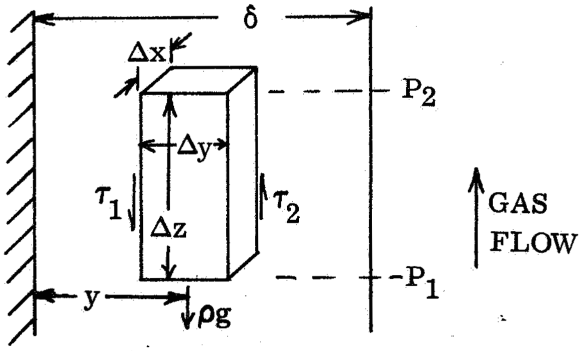


Figure 14.-Liquid Film Forces

Integrating and inserting the boundary condition: $\tau = \tau_i$ at $y = \delta$ where (i) refers to liquid-gas interface, gives:

$$\tau = \tau_i + \rho\ g\ (\ y - \delta\ ) - \frac{\partial P}{\partial z}\ (\ y - \delta\ )$$

By definition $\tau = \mu\ \frac{\partial V}{\partial y}$ where μ is liquid dynamic viscosity and V is liquid velocity, consequently:

$$\frac{\partial V}{\partial y} = \frac{1}{\mu}\left[\ \tau_i - \rho\ g\ (\ \delta - y\ ) + \frac{\partial P}{\partial z}\ (\ \delta - y\ )\right]$$

By integrating and evaluating the constant at $y = o$, $V = 0$, the liquid velocity is found to be:

$$V = \frac{1}{\mu}\left[\ \tau_i - \rho\ g\ (\ \delta - \frac{y}{2}\ ) + \frac{\partial P}{\partial z}\ (\ \delta - \frac{y}{2}\ )\right] y$$

From this, the liquid volume flow rate Q may be found since

$$Q = x \int_o^{\delta} V\ d\ y$$

$$(1) \qquad Q = \frac{x}{\mu}\left[\ \frac{\tau_i}{2}\ \delta^2 + \frac{1}{3}\ (\ \frac{\partial P}{\partial z} - \rho\ g\ )\ \delta^3\ \right]$$

It may be seen from this equation, that the liquid flow rate in the direction of gas flow can be expected to increase with film thickness to a maximum value

(assuming $\rho\ g > \frac{\partial P}{\partial z}$), and then decrease, eventually becoming negative, as

liquid weight becomes more significant. It is of interest to determine this maximum flow rate and the film thickness which corresponds to it, in terms of the gas flow parameters which are directly established by design. Maximum flow rate corresponds to the condition

$$\frac{\partial Q}{\partial \delta} = 0, \text{ or } \tau_i\ \delta - \rho\ g\ \delta^2 + \frac{\partial P}{\partial z}\ \delta^2 = 0$$

from which:

$$\delta = \frac{\tau_i}{\rho\ g - \frac{\partial P}{\partial z}}$$

Substituting this into the relationship for Q, gives:

$$Q_{max} = \frac{x\,\tau_i^{3}}{6\,\mu\,(\rho\,g - \frac{\partial P}{\partial z})^2}$$

Since $\tau_i = f\,\frac{\rho_g}{2}\,V_g^{2}$ where:

f = Friction factor

V_g = Gas flow velocity

ρ_g = Gas mass density

it is possible from gas flow conditions to determine the maximum liquid flow which can be transported against a gravity force.

Assuming a desired liquid transport rate can be achieved in a gravity field, a quantitative measure of g-sensitivity may be assessed in terms of film thickness for specific gas flow conditions. This may be done by computing δ from equation (1) for the desired g-conditions, where ρ is the g-sensitive parameter. Thus, for the zero-g condition, equation (1) becomes:

$$Q_{(o-g)} = \frac{x}{\mu}\left[\frac{\tau_i}{2}\,\delta^2 + 1/3\,\frac{\partial P}{\partial z}\,\delta^3\right]$$

Comparison of the film thicknesses under different gravity levels can be of importance from a flow standpoint if the thicknesses represent a significant portion of the available flow channel. The comparison may also be of importance in the event that heat transfer through the film is a consideration.

It may be found that for many applications the pressure gradient $(\frac{\partial P}{\partial z})$ can be neglected. In this case the equations for Q, Q_{max}, and $Q_{(o-g)}$ reduce to the following:

$$Q = \frac{x}{\mu}\left[\frac{\tau_i}{2}\,\delta^2 + \frac{\rho g}{3}\,\delta^3\right]$$

$$Q_{max} = \frac{x\,\tau_i^{3}}{6\,\mu\,\rho^2\,g^2}$$

$$Q_{(o-g)} = \frac{x\,\tau_i}{2\,\mu}\,\delta^2$$

This liquid film transport analysis has considered the case of a flat plate, which should be applicable to many heat exchangers and to plumbing of rectangular cross section. The case of a cylindrical wall has been treated by I. J. Willis (ref. 15). Converting terms to correspond to those used herein, the equations developed for velocity and flow rate become:

$$V = \frac{1}{\mu}\left[\tau_i - \rho g \left(\delta - \frac{y}{2} \right) + 1/2 \frac{\partial P}{\partial z} \left(\delta - \frac{y}{2} \right) \right] y, \quad \text{and}$$

$$Q = \frac{\pi}{12\,\mu}\left[4\,\tau_i \,(3R - 2\delta) + \left(1/2 \frac{\partial P}{\partial z} - \rho g \right) (8R - 5\delta)\, \delta \right] \delta^2$$

where (R) corresponds to cylinder radius. If film thickness is negligibly small compared to cylinder radius, the flow rate equation may be reduced to:

$$Q = \frac{2\,\pi\,R}{\mu}\left[\frac{\tau_i}{2}\,\delta^2 + 1/3 \left(1/2 \frac{\partial P}{\partial z} - \rho g \right) \delta^3 \right]$$

This is equivalent to the relationship for the flat plate case with a geometry correction factor of 1/2 applied to the pressure gradient term.

If large film thicknesses and/or high gas velocities are to be encountered, the liquid-gas interface may be expected to become unstable resulting in liquid break-away from the surface. An analysis of the relative effects of inertia, viscous and capillary forces has led to the film stability criteria shown in figure 3. Reynolds and Webers numbers, as used in that figure are based on the characteristics of the fluids in question, on the thickness of the liquid film, and on the velocity of the liquid-gas interface.

Transport of free liquid droplets by a gas stream can be analyzed by comparing drag force to droplet weight. With these forces acting in the same direction, the effect of gravity is to accelerate the droplets to a velocity greater than that of the gas stream. With the forces opposing, the effect of gravity is to reduce the droplet velocity to a value less than stream velocity and in the extreme case to make it negative with respect to stream velocity. For engineering considerations, the most critical condition is that occurring when the forces are equal and opposite. This condition corresponds to the point at which the stream velocity just fails to be sufficient to transport the droplets. It is of primary interest, therefore, to determine this critical velocity.

Drag force results from viscous and inertial effects and the relative importance of these is related to Reynolds number. At Reynolds numbers up to 0.1, drag is essentially a viscous phenomenon and may be obtained from Stokes equation. Assuming approximately spherical droplets:

$$F_{\text{viscous}} = 3\,\pi\,\mu_g\,V_g\,D$$

This may be expressed in terms of the drag coefficient C_D, where:

$$F = C_D\,A\,\frac{\rho_g V_g^2}{2} = 3\,\pi\,\mu_g\,V_g\,D \qquad (2)$$

and C_D is found to be:

$$C_D = \frac{24}{Re}$$

F = Drag force

D = Droplet diameter

A = Droplet projected area

subscript $_g$ refers to gas.

In the Reynolds number range 0.1 to 10., inertial or pressure effects become significant, their importance increasing with Reynolds number until they account for about 95 percent of the drag at a Reynolds number of 1000. For practical application, C_D, for spheres, based on extensive empirical data, is readily available in reference literature as a function of Reynolds number, figure 15. In this figure, the transition from viscous to inertial drag can be seen. Equating F to droplet weight for spherical drops gives:

$$\frac{C_D \, \pi \, D^2 \, \rho_g \, V_g^2}{8} = \frac{\pi \, D^3 \, \rho g}{6} \left(\begin{array}{c}\text{Neglecting gas density} \\ \text{in the weight term}\end{array}\right),$$

from which, the critical velocity V_c can be obtained.

$$V_g^2 = \frac{4}{3} \, \frac{\rho}{\rho_g} \, \frac{g}{C_D} \, D = V_c^2$$

For free water droplets in air this relationship is illustrated by the solid lines in figure 16, assuming one atmosphere pressure and 70°F. For small droplets, and moderate velocities, the spherical droplet shape is a realistic assumption. For large drops and high velocities, however, the drops tend to flatten, distorting the spherical shape, and resulting in a change in the true critical velocity. This change is shown in figure 16 by the dashed lines falling away from the lines for spherical drops. The data for the one-g case was obtained from reference 16 and represents distorted drops of mass corresponding to spherical diameters (D). By use of the constant Webers numbers lines, the deviations from the curves for spherical drops can be extrapolated to various g-levels. This results from the fact that droplet shape is dependent upon Webers numbers (the ratio of inertia to surface tension forces), and the C_D ratio for flattened to spherical drops is essentially constant in the Reynolds number range 500 to 10,000, where the deviation occurs.

As drops become larger they tend to become unstable and at high velocities they breakup, setting a limit to drop size. For water at one-g this maximum size is approximately 1/4 inch.

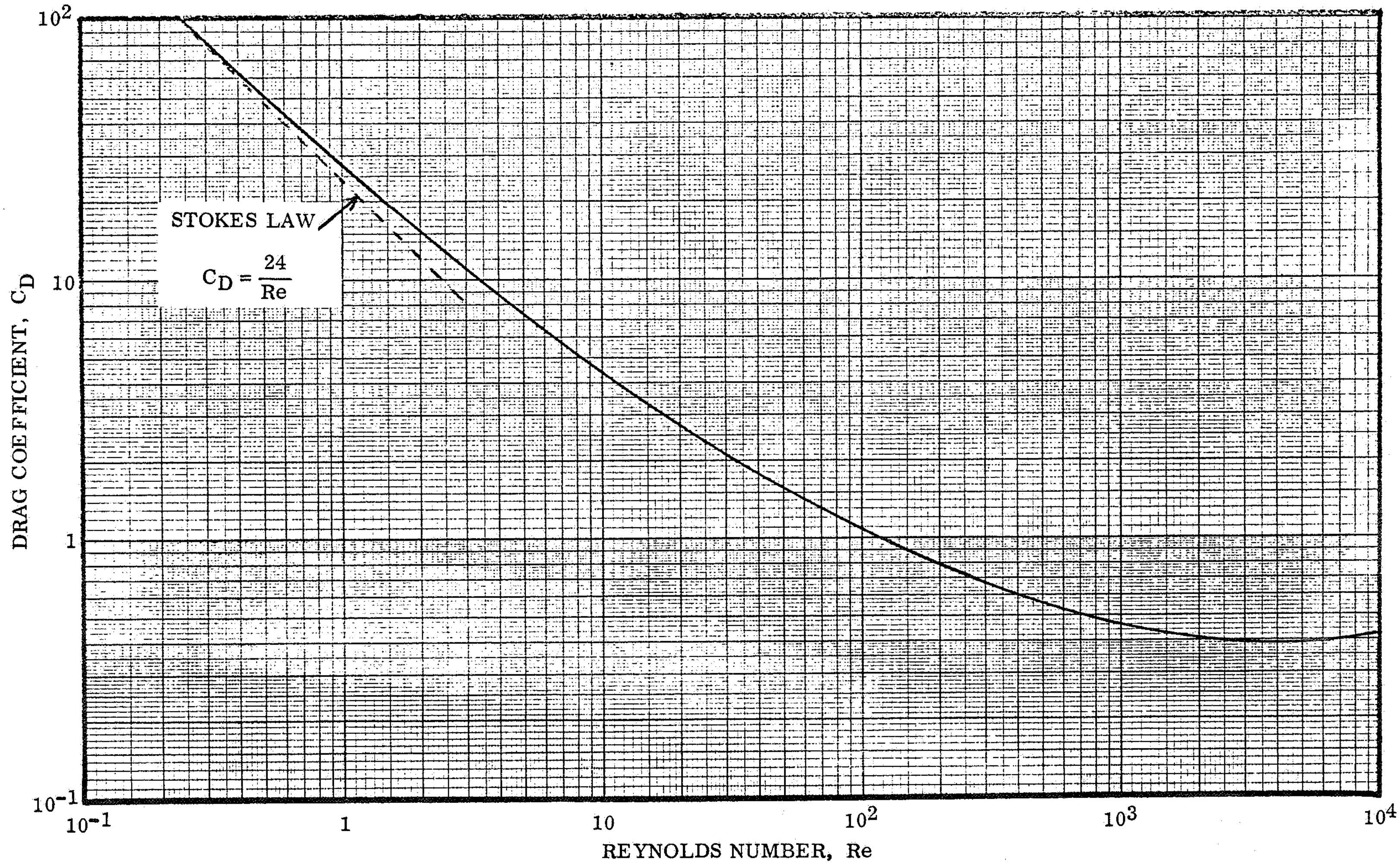


Figure 15. - Drag Coefficient vs. Reynolds Number for Spheres

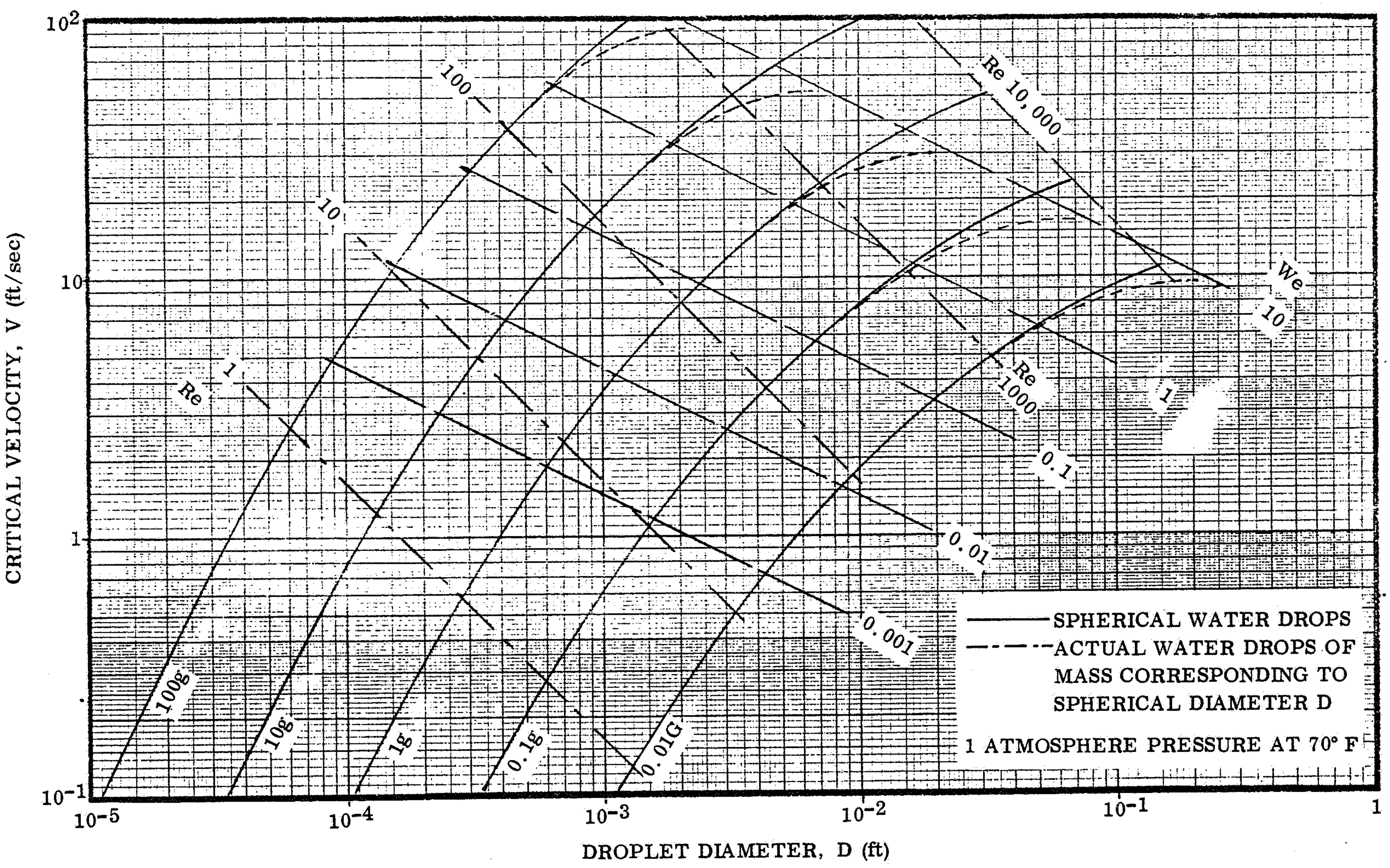


Figure 16.- Critical Air Velocity Required to Support Water Droplets Against Gravity

A related aspect of g-sensitivity is the gravity effect on droplet velocity when the gas velocity exceeds the critical velocity. For the steady state condition, it is clear that the critical velocity will correspond to the relative velocity between droplet and gas stream, hence actual droplet velocity is the difference between stream velocity and critical velocity. Before steady state is reached, however, it is likely that droplet acceleration will take place. This acceleration can be of interest, as steady state may never be reached for short transport paths. Considering upward velocities to be positive, the equation for droplet acceleration may be written:

$$\frac{1}{g}\,\frac{dV_d}{dt} = -\frac{1}{g}\,\frac{dV}{dt} = \frac{A\,\rho_g\,C_D}{2\,v\,\rho\,g}\,V^2 - 1$$

in which

V_d = droplet velocity

V_g = gas stream velocity

V = relative velocity between droplet and gas

$V = V_g - V_d$

v = droplet volume

In terms of droplet transport distance(s), from the point of entry into the gas stream, this may be written:

$$\frac{V_d}{g}\,\frac{dV_d}{ds} = -\frac{(V_g - V)}{g}\,\frac{dV}{ds} = \frac{A\,\rho_g\,C_D}{2\,v\,\rho\,g}\,V^2 - 1$$

The drag coefficient C_D has been shown to be related to Re (figure 15) which in turn is a function of V. Consequently an expression for C_D in terms of Re or V must be obtained in order to perform the integration. The C_D -Re relationship being empirical, appears to involve a rather complex expression for a reasonably good curve fit. The following equation was obtained by curve fitting techniques and is representative of the empirical data over the range Re = 1 to Re = 4000.

$$C_D = .39\,e^{0.1015\left(\log\frac{4000}{Re}\right)^{1.76}}$$

For Re < 1, the Stokes equation $C_D = 24/Re$ may be used, while Re > 4000 exceeds the likely range of concern. Substituting the curve fitted relationship for C_D into the equation for dV/ds, the following is obtained:

$$-\frac{(V_g - V)}{g}\,\frac{dV}{ds} = \frac{.39\,A\,\rho_g\,V^2}{2\,v\,\rho\,g}\,e^{0.1015\left(\log\frac{4000\,\mu}{\rho_g\,D\,V}\right)^{1.76}}$$

While this general expression is unfortunately not amenable to solution in closed form, it may be solved numerically for specific cases where needed.

Approximate solutions can be obtained however by direct integration for cases of $C_D = M/Re$ and $C_D = K$, where M and K are constants. The first of these ($C_D = M/Re$) gives results of increasing accuracy as Re decreases, being exact for the Stokes law region; while the second ($C_D = K$) gives results increasing in accuracy as Re increases to $Re = 4000$. For the case $C_D = K$, the expression

$$\frac{A\ \rho_g\ C_D}{2\ v\ \rho g} = \frac{1}{V_c^2} \quad \text{where} \quad V_c = \text{critical gas velocity}$$

while for $C_D = M/Re$,

$$\frac{A\ \rho_g\ C_D}{2\ v\ \rho g} = \frac{A\ M\ \mu}{2\ v\ \rho g\ D}\ \frac{1}{V} = \frac{1}{V_c\ V}$$

$$\left(\text{since:} \quad \frac{1}{V_c^2} = \frac{A\ \rho_g\ C_D}{2\ v\ \rho g} = \frac{A\ M\ \mu}{2\ v\ \rho\ Dg\ V_c}\right).$$

Substituting these expressions for C_D into the dV/dt and dV/ds equations gives the following:

for $C_D = K$

$$\frac{1}{g}\ \frac{dV}{1 - \frac{V^2}{V_c^2}} = dt$$

$$\text{and} \quad \frac{1}{g}\ \frac{(V_g - V)\ dV}{1 - \frac{V^2}{V_c^2}} = ds$$

for $C_D = M/Re$

$$\frac{1}{g}\ \frac{dV}{1 - \frac{V}{V_c}} = dt$$

$$\text{and} \quad \frac{1}{g}\ \frac{(V_g - V)\ dV}{1 - \frac{V}{V_c}} = ds$$

Integrating and inserting the condition $s = o$ at $t = o$ and $V = V_g$, gives the following expressions for time as a function of droplet velocity, distance as a function of droplet velocity, and distance as a function of time:

for the case $C_D = M/Re$

$$t = \frac{V_c}{g} \log \frac{V_g - V_c}{V_g - V_c - V_d}$$

$$s = \frac{V_c}{g} \left[(V_g - V_c) \log \frac{V_g - V_c}{V_g - V_c - V_d} - V_d \right]$$

$$s = (V_g - V_c) \left[t - \frac{V_c}{g} \left(1 - e^{-\frac{g}{V_c} t}\right) \right]$$

for the case $C_D = K$

$$t = \frac{V_c}{2g} \log \frac{(V_g^2 - V_c^2) - V_d (V_g - V_c)}{(V_g^2 - V_c^2) - V_d (V_g + V_c)}$$

$$s = \frac{V_g V_c}{2g} \log \frac{(V_g^2 - V_c^2) - V_d (V_g - V_c)}{(V_g^2 - V_c^2) - V_d (V_g + V_c)} - \frac{V_c^2}{2g} \log \frac{V_g^2 - V_c^2}{V_g^2 - V_c^2 - V_d (2 V_g - V_d)}$$

$$s = (V_g + V_c) t - \frac{V_c^2}{2g} \log \frac{(V_g + V_c)^2 e^{\frac{4g}{V_c} t} - (V_g^2 - V_c^2) 2e^{\frac{2g}{V_c} t} + (V_g - V_c)^2}{4 V_c^2}$$

As pointed out, these relationships are exact only at the limits of the pertinent Reynolds number range. At intermediate values of Re, the better approximation may be obtained by selecting the equation based on the C_D -Re relationship which more nearly approaches the actual curve. Approximately equal error may be expected at $Re = 100$; the $C_D = K$ equation being preferred for $Re > 100$; while the $C_D = M/Re$ equation is preferred for $Re < 100$. To illustrate the results given by the two equations for the distance versus velocity (which are probably the most useful for a droplet transport design problem) the most unfavorable condition of $Re = 100$, the case of a droplet diameter of 0.00117 ft. and a gas velocity of 44.5 ft/sec. has been selected. The Reynolds number range is thus 32 to 320 with $Re = 100$ being the mean log Re, and $C_D = 1.08$ being the corresponding drag coefficient. The critical velocities thus become:

V_c = 4.4 ft/sec. actual

$$V_c = \sqrt{\frac{4 \rho g D}{3 \rho_g C_D}} = 6.21 \text{ ft/sec. for } C_D = K$$

$$V_c = \frac{4 \rho g D^2}{3 \mu M} = 2.78 \text{ ft/sec. for } C_D = M/Re,$$

with M evaluated at Re = 100. Spherical droplets at $g = 32.2$ ft/sec^2 have been assumed. Results are plotted in figure 17 as the ratio of droplet velocity to terminal droplet velocity versus distance of droplet transport. The true droplet transport curve will, of course, lie between those shown.

Due to the nature of the preceding droplet transport equations, the solutions for the limiting condition of zero-g are not immediately obvious. They may be obtained through substitution of the critical velocity expression and series expansion of the log terms, or by re-development of the relationships from the original equations for dV/dt and dV/ds. The latter involves multiplying the differential equations by g and letting g then go to zero. The resulting equations for the zero-g condition are as follows:

for the case $C_D = M/Re$

$$t = T \log \frac{V_g}{V_g - V_d}$$

$$\text{where: } T = \frac{2 v \rho D}{A \mu M}$$

$$s = T \left[V_g \log \frac{V_g}{V_g - V_d} - V_d \right]$$

$$s = V_g \left[t - T \left(1 - e^{-\frac{t}{T}} \right) \right]$$

for the case $C_D = K$

$$t = L \left[\frac{V_d}{V_g^2 - V_d V_g} \right] \quad \text{where: } L = \frac{2 v \rho}{A \rho_g C_D}$$

$$s = L \left[\frac{V_d}{V_g - V_d} - \log \frac{V_g}{V_g - V_d} \right]$$

$$s = V_g t - L \log \frac{L + V_g t}{L}$$

These relationships for the zero-g condition correspond to the previous relationships for the $g > o$.

By use of the equations for distance as a function of velocity, the effect of gravity on droplet transport, for the same flow velocity and droplet diameter used in figure 17, is illustrated in figures 18 and 19.

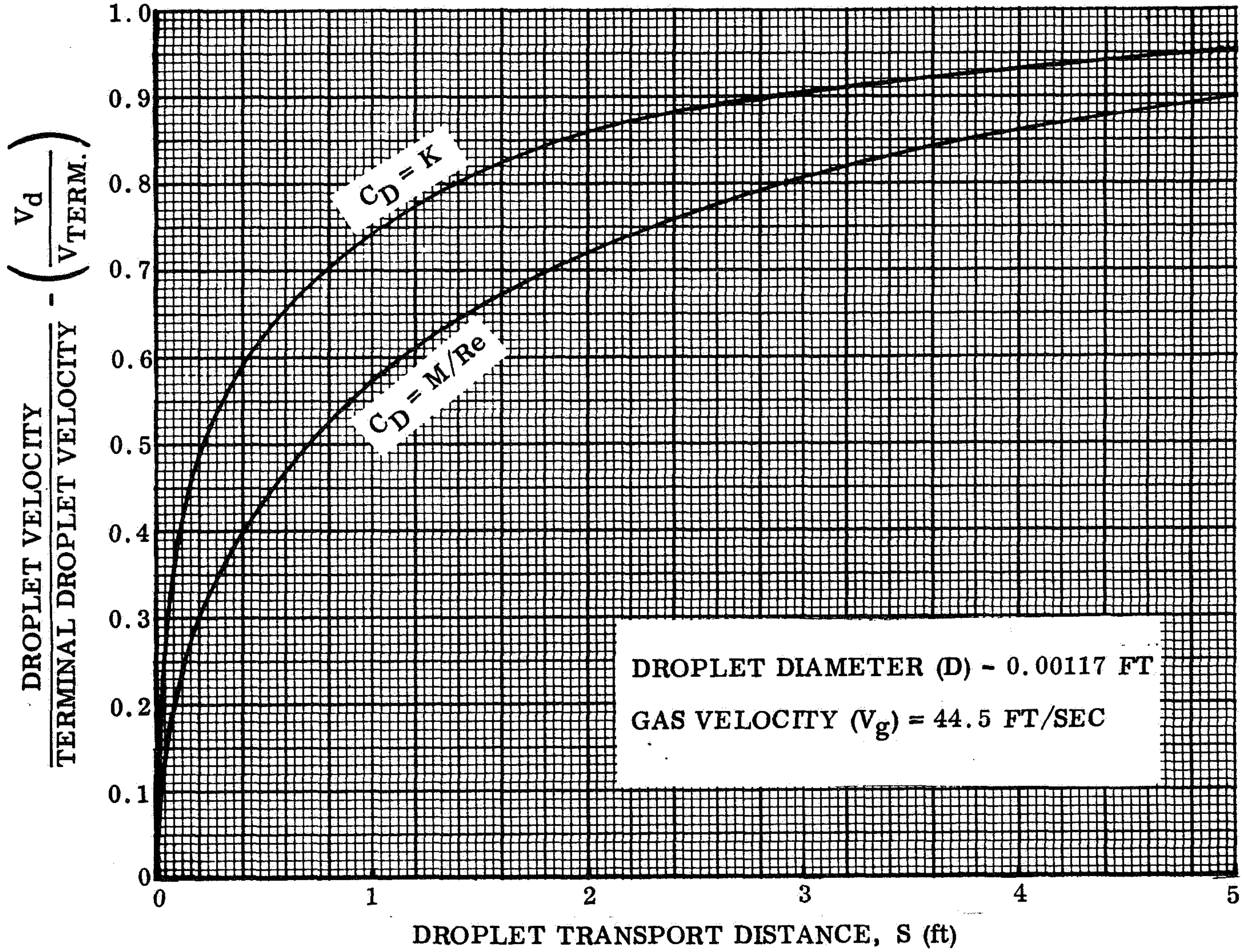


Figure 17.— Comparison of Droplet Transport Relationships

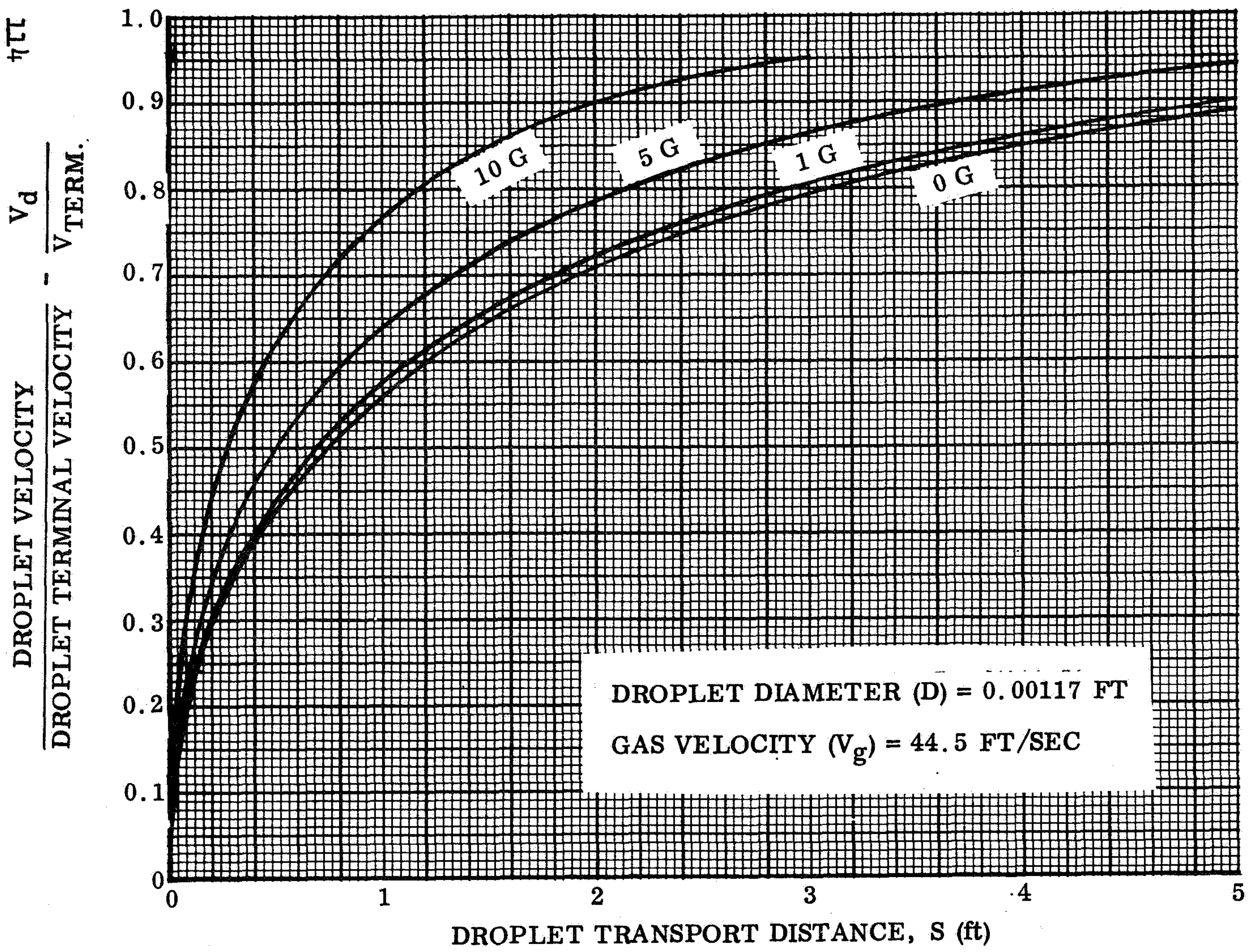


Figure 18.-Gravity Effect on Droplet Transport for C_D = M/Re Case.

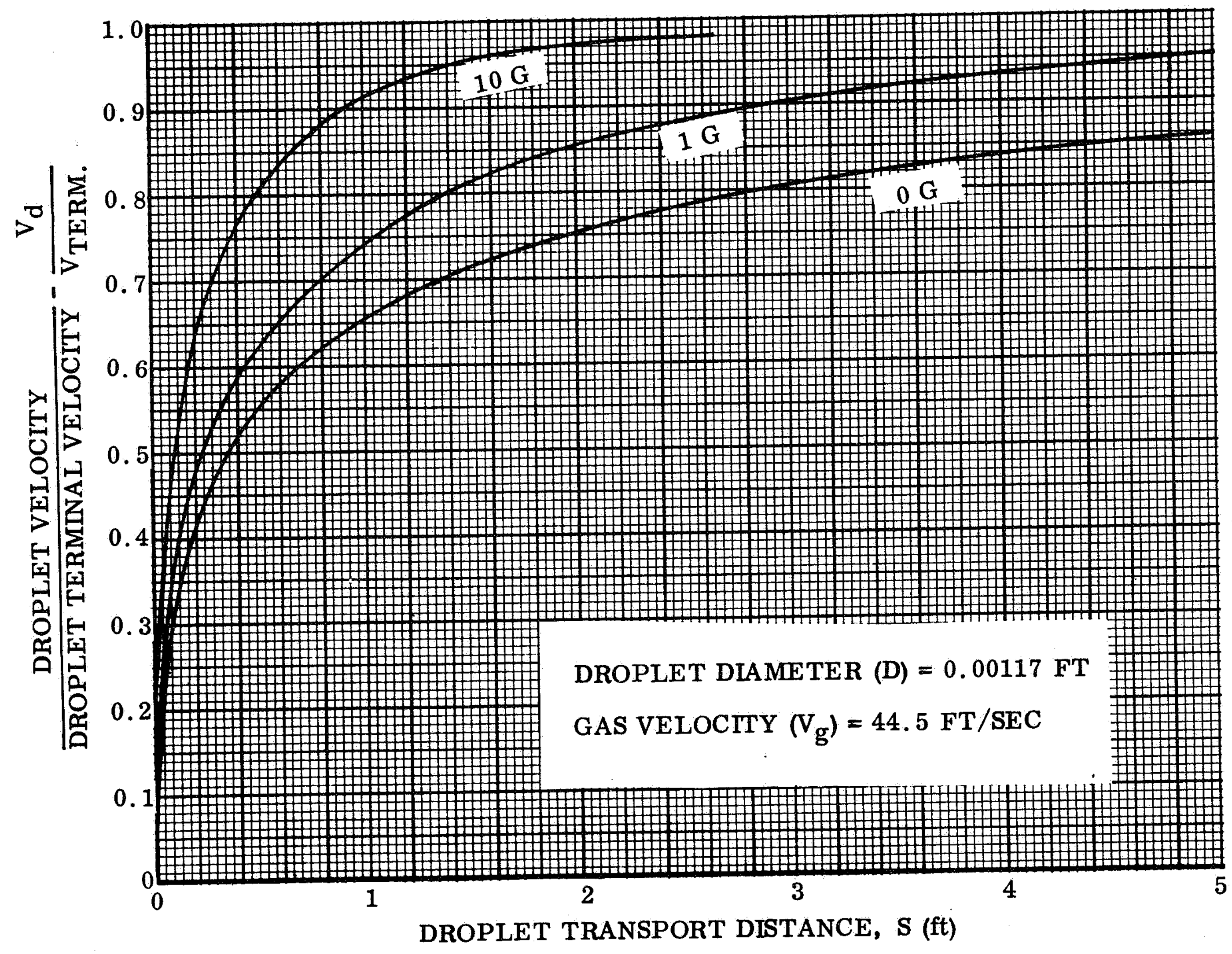


Figure 19.- Gravity Effect on Droplet Transport for C_D = K Case

It should be noted, that other approaches to solution of droplet transport have been developed. In reference 17, for example, the C_D vs Re relationship is divided into three regions: $10^{-4} < Re < 2$, $2 < Re < 500$, and $500 < Re < 10^5$. The corresponding relationships are: $C_D = 24/Re$, $C_D = 0.4 + 40/Re$, and $C_D = 0.44$; all of which produce integrable relationships when substituted into the dV/ds equation. Use of these relationships provides somewhat greater accuracy than the present method in the region $Re \simeq 100$ but less accuracy in the regions $Re \simeq 2$, and $Re \simeq 1000$. Selection of the most appropriate approach with regards to accuracy of the velocity and distance calculation depends upon the requirements of the particular case in question. Once an approach is selected however, assessment of g-sensitivity is accomplished merely by introducing the desired g-range into the selected relationships.

Liquid Behavior Control by Capillarity

The use of surface tension or capillary effects for the control of liquid behavior in low or zero-g is particularly attractive due to the absence of power requirements and the passive nature of the phenomena. Gravity sensitivity involves the comparison of liquid weight with the capillary forces present. For a cylindrical capillary passage the pressure across the liquid-gas interface is:

$$\Delta P = \frac{F}{A} = \frac{2 \pi R \sigma}{\pi R^2} \cos \theta = \frac{2 \sigma}{R} \cos \theta$$

where: F = Total force (parallel to tube axis)

R = Tube radius

σ = Liquid-gas surface tension

θ = Contact angle (measured through the liquid from tube wall to liquid-gas interface)

A = Tube cross-section area

This pressure difference (ΔP) represents the surface force available to support a column of liquid against gravity, or against another pressure which may be acting on the surface.

For the case of a passage of rectangular cross-section, the ΔP becomes:

$$\Delta P = \frac{F}{A} = \frac{2 \sigma (d_1 + d_2)}{d_1 d_2} \cos \theta$$

$$\Delta P = 2 \sigma \left(\frac{1}{d_1} + \frac{1}{d_2}\right) \cos \theta$$

where d_1, and d_2 are the widths of the passage sides. For passages of a more complex configuration, such as those in a porous metal plate, estimates of reasonably equivalent dimensions may be used for calculation; or the actual ΔP may be measured by experimentally determining the force which can be supported by the interface.

In the case of a column of liquid, supported against gravity in a cylindrical capillary tube, the height of the column is seen to be inversely proportional to the g-level. It is given by the following relationship:

$$h = \frac{2\sigma}{\rho g \; R}\cos\theta,$$

which describes the g-sensitivity of the system. The term ρ represents liquid mass density. Since h is also inversely related to R, it is clear that g-sensitivity can be controlled by proper selection of passage dimensions.

It is of interest to note that under actual operating conditions, the effective contact angle (θ) for a liquid in a passage can vary appreciably as pressures change or when flow occurs. For example, a small amount of liquid in a capillary tube (which could conceivably be an element of a heat exchanger core), under static conditions with no differential pressure across the tube ends, could appear as shown in figure 20a. Upon applying pressure at end (1), the interfaces would assume a configuration approaching that shown in 20b, with the low pressure interface flattening somewhat. The amount of flattening, and consequent increase in effective contact angle depends upon a variety of things including surface roughness and cleanliness as well as pressure differential and original contact angle. The result, however, is that the liquid element is capable of supporting a pressure differential along the tube, and a number of liquid elements in series can support a significant pressure drop. In zero-g, without the weight of the liquid to assist in clearing the passage, this problem of passage blockage may become a design consideration.

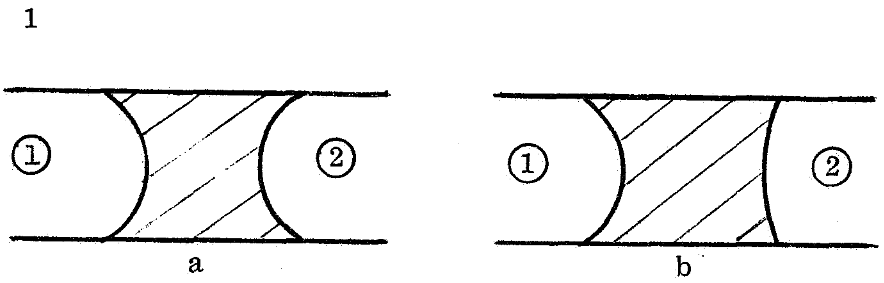


Figure 20 .- Effect of Pressure on Liquid in a Capillary Tube

Liquid Behavior Control by Centrifugation

In the absence of gravity, the separation of liquids from gases requires special consideration. One of the most frequently considered methods is centrifugation which, in effect, creates an artificial gravity. Sensitivity of a centrifugation process to real gravity forces is determined by comparing weight to centrifugal (or inertial) force. For the case in which the centrifugal force is equal and opposite to the gravitational force, which may be considered to represent a critical condition:

$$\omega^2 R = g,$$

in which: ω = Angular velocity of rotation

R = Radius of rotation

g = Gravitational acceleration

For values of $\omega^2 R$ greater than g liquid will be retained at the centrifuge rim. For values less than g, however, the liquid may fall inward from the rim over a portion of a revolution.

Analysis indicates that a second order effect of gravity on the time required for a liquid droplet to reach the rim from a point in the interior of the centrifuge may be expected. This effect, however, is unique for each set of geometry and flow conditions assumed, and may be considered negligible when the centrifugal acceleration at the rim is appreciably greater than g.

Solids Control by Gas Flow

The g-sensitivity of solid particles carried in a gas stream may be determined in much the same manner as was discussed for liquid droplets under "Liquid Behavior Control by Gas Flow." The significant difference to be considered between the analyses is the influence of particle geometry. This influence is apparent from the presence of the $C_D A$ term in the basic equation for critical velocity. For solid particles this equation becomes:

$$V_c^2 = \frac{2 \; v \; \rho_p \; g}{C_D \; A \; \rho_g}$$

where ρ_p refers to particle mass density. In the case of spherical or approximately spherical liquid droplets, the value of C_D may be readily determined from droplet size, (A), and flow conditions. In the case of solid particles, however, since the variety of possible geometries is extremely large, and the shape may be quite complex, there is no convenient analytical relation between C_D and particle configuration. Furthermore, it is quite probable that knowledge of particle configuration itself will be lacking.

As a consequence, it will probably be necessary for reasonably accurate particle behavior analysis, to obtain a value of $C_D A$, or critical velocity, experimentally with the particular particle configuration under question. (This can generally be accomplished by simply measuring free fall terminal velocity in still air at 1g). In addition, unless V_c is measured at the desired gravity level, an assumption must be made regarding its variation with gravity. As C_D depends upon Reynolds number, which in turn is a function of velocity, it is clear from the above equation for V_c, that this gravity variation hinges on the C_D -Re relationship. A good approximation of the desired V_c can be made for most particle transport problems by assuming the C_D -Re relationship for spheres as was shown in figure 15. While this assumption can introduce errors in transport calculations for particles whose geometry is appreciably different from spherical, its effect on the g-sensitivity of the process should not be significant.

Assuming the C_D -Re relationship for spheres, the analysis becomes essentially that given in the previous section for liquid droplet transport. For precise analysis, an effective diameter can be determined through the construction of critical velocity curves such as those in figure 8 and the behavior of the particle determined by numerical integration of basic transport equations in which the

$$C_D = .39\, e^{0.1015 \left(\log \frac{4000}{Re}\right)^{1.76}}$$

relation is inserted. As an alternative, reasonable approximations can be obtained by making the $C_D = K$ or $C_D = M/Re$ assumption, depending upon the Reynolds number of concern, and using the relationships for time, velocity and distance which were derived in the previous section.

A particular case of particle, or droplet motion, (which is introduced here because it may find more frequent use in dealing with solids) is that of settling behavior in quiescent gas. By letting V_g go to zero in the time, velocity, distance equations given for liquid droplets, and making the following substitutions:

$$V_p = -V_d$$

$$V_T = V_c \text{ and}$$

$$S_p = -S,$$

where V_p is particle velocity, V_T is terminal velocity and S_p is particle distance fallen, the settling characteristics of a particle are obtained. For convenience, directions are taken as positive downward.

For $C_D = M/Re$, where $V_T = \frac{2\, v\, \rho_p\, D\, g}{A\, M\, \mu}$

$$t = \frac{V_T}{g} \log \frac{V_T}{V_T - V_p}$$

$$S_p = \frac{V_T}{g} \left(V_T \log \frac{V_T}{V_T - V_p} - V_p \right)$$

$$S_p = V_T \left[t - \frac{V_T}{g} \left(1 - e^{-\frac{g}{V_T} t} \right) \right]$$

For $C_D = K$, where $V_T^2 = \frac{2\, v\, \rho_p\, g}{A\, \rho_g\, C_D}$

$$t = \frac{V_T}{2g} \log \frac{V_T + V_p}{V_T - V_p}$$

$$S_p = \frac{V_T^2}{2g} \log \frac{V_T^2}{V_T^2 - V_p^2}$$

$$S_p = \frac{V_T^2}{2g} \log \left(\frac{1 + 2\, e^{\frac{2g}{V_T} t} + e^{\frac{4g}{V_T} t}}{4} \right) - V_T t$$

Gravity sensitivity is determined here as in the previous case by introducing the desired g-range into the selected relationships. It should be mentioned that these equations, as well as those for droplet transport may also be applied to solid particle motion in liquids. In this case liquid density may not be negligible compared to the solid density, consequently $\rho_p - \rho_L$, (ρ_L = liquid mass density), should be substituted for ρ_p in the expressions for V_c and V_T. Gas density ρ_g is, of course, replaced by ρ_L.

Fluid Mixing

The process of fluid mixing may be considered, for engineering purposes, as consisting of two phases: an initial dispersion of gross portions of the solute into the solvent; and a final diffusion mixing on the molecular level. The initial dispersion results from convective processes within the fluids and provides a distribution of the solute throughout the solvent on a macroscopic scale. This sets the stage for the final diffusion mixing to take place due to molecular agitation (Brownian Motion). As diffusional velocities, in general, are relatively slow compared to convective velocities; the time required for mixing is quite sensitive to the extent, or uniformity, of solute distribution produced by the convective processes.

Gravity sensitivity of fluid mixing is considered here from the standpoint of these two basic mixing processes. The diffusion process is considered first as its g-sensitivity may be reasonably well determined analytically. In addition, for currently anticipated life support system functions, its g-sensitivity may be shown to be negligible.

Diffusion mixing.- A molecule, or particle of molecular size, in a fluid will experience an accelerating force F_g in the presence of a gravitational acceleration g; such that:

$$F_g = g\,(\rho - \rho')\,v_m$$

in which: ρ = particle (solute) mass density

ρ' = fluid (solvent) mass density

v_m = molecule or particle volume

(ρ and ρ' are strictly the reciprocals of the partial specific volumes; however, for relatively large molecules or groups of molecules, they may be considered as equal to the densities).

Due to frictional resistance to motion of a particle, a velocity V will result in a countering force F_v (viscous). For low Reynolds numbers this force, F_v, is proportional to V, such that $F_v = f_v F$, where f_v may be considered as a frictional resistance. When terminal velocity V_T due to F_g is reached:

$$F_g = F_v = f_v V_T, \text{ or } V_T = g(\rho - \rho') v_s / f_v$$

To determine diffusional force, the kinetic theory of gases may be applied to the solute molecules or particles giving:

$$pv = \frac{1}{3} m \overline{V^2} n,$$

in which p is the pressure on one surface of an assumed volume v containing n particles of mass m, and velocity v. Considering an incremental volume $(dx)^3$, having dn particles:

$$p\,(dx)^3 = \frac{1}{3} m \overline{V^2}\, dn$$

$$\text{or } p\,(dx)^2 = \frac{1}{3} m \overline{V^2}\, dn/dx$$

Since $p\,(dx)^2$ represents force on the incremental surface $(dx)^2$, $p\,(dx)^2/n$ may be considered as drag force per particle, F_d. Thus:

$$F_d = \frac{1}{3}\,\frac{m \overline{V^2}}{n}\,\frac{dn}{dx}$$

Assuming the kinetic energy of Brownian movement to be similar for particles and molecules:

$$pv = \frac{1}{3} m \overline{V^2} N = RT \text{ for one mole,}$$

where N is the number of molecules per mole, R is the universal gas constant and T is absolute temperature.

$$\text{Thus: } RT/N = \frac{1}{3} m \overline{V^2}$$

Substituting this into the equation for F_d,

$$F_d = \frac{RT}{Nn}\,\frac{dn}{dx}, \text{ or since:}$$

$$v_s N \rho = \text{Molecular weight } M,$$

$$F_d = \frac{R\,T\,\rho\,v_s}{M\,n}\,\frac{dn}{dx}$$

As in the case of gravitational force,

$F_d - F_v = f_v V_d$ where V_d is the diffusional velocity.

Therefore:

$$V_d = \frac{R\,T\,\rho\,v_a}{M\,n\,f_v}\,\frac{dn}{dx}$$

Since f_v is common to both diffusional and gravity induced motion, the ratio of diffusional velocity to gravity induced velocity is equal to the ratio of their respective forces, thus:

$$\frac{V_d}{V_T} = \frac{F_d}{F_g} = \frac{R\,T\,\rho}{M\,g(\rho - \rho')}\,\frac{dn}{dx}\,\frac{1}{n}$$

or: $$\frac{V_T}{V_d}\,\frac{dn}{dx}\,\frac{1}{n} = \frac{Mg}{RT}\left(1 - \frac{\rho'}{\rho}\right)$$

If the net velocity is V, and the diffusional and gravity induced velocities are opposing:

$$V = V_d - V_T \text{ which can be}$$

written: $$V = \left(1 - \frac{V_T}{V_d}\right) V_d$$

Thus, the actual velocity is equal to the pure diffusional velocity (which is independent of gravity), modified by the factor $(1 - V_T/V_d)$ in which V_T/V_d is a direct function of gravity.

The expression $\left(\frac{dn}{dx}\,\frac{1}{n} \right)$ is seen to be the concentration gradient in the direction of diffusion, as a proportion of the actual concentration at that point. It is clear that the g-sensitivity, which may be represented by V_T/V_d, is inversely proportional to the concentration gradient. Consequently, it may be expected that very early in a diffusion mixing process, g-sensitivity will be negligible; but as diffusion progresses and the concentration gradient approaches zero, the process can become sensitive to gravity. In the design of a process involving liquid mixing, the g-sensitivity for diffusion can be determined by specifying a concentration gradient corresponding to an adequately mixed solution, and solving for V_T/V_d.

Conversely, an allowable g-sensitivity may be specified in terms of V_T/V_d and the concentration gradient computed which corresponds to the mixing level just at the time this allowable g-sensitivity is reached.

As an example, an extreme case for g-sensitivity in a life support system process will be considered. As g-sensitivity increases with both molecular weight and density of the solute, the hypothetical mixing of a liquid of molecular weight 500 and density 2 with water at 500°R will be assumed. A higher molecular weight-density combination is highly unlikely in LSS mixing processes.

Thus: $\frac{V_T}{V_d} \frac{dn}{dx} \frac{1}{n} = \frac{500 \times 32.2}{1545 \times 32.2 \times 500} \left(1 \; - \frac{1}{2} \right) = \frac{1}{3090}$

If it can be assumed that adequate mixing has occurred when the concentration gradient has decreased to 2 percent of concentration, the velocity ratio at that time becomes:

$$\frac{V_T}{V_d} = \frac{1}{61.8} \simeq .0162$$

Thus, the actual mixing velocity (V) equals approximately 98 percent of the pure diffusional velocity (i.e. the velocity which would occur under zero-g). It appears, therefore, that the diffusional mixing process may be considered for practical purposes to be independent of gravity.

Convective Mixing.- Mixing rates based on diffusion alone are unacceptably slow for most life support system processes. Generally, convective mixing must be provided to reduce the diffusion path lengths such that the final diffusion process can be completed in a reasonable time period. Thorough convective mixing can be sufficient to reduce the required diffusion path lengths to microscopic size, thus effectively eliminating the need for further diffusion; or convection can provide only minimal dispersion of the solute leaving relatively large unmixed regions, or gaps, to be mixed by diffusion. The total time required for acceptable mixing is determined primarily by the sizes of these unmixed regions.

Consideration of the factors which determine the extent, or thoroughness, of the convective mixing process leads to the identification of a number of interrelated variables, each of which may also become involved in the determination of g-sensitivity of the process. These variable and their interrelationships are indicated in figure 21.

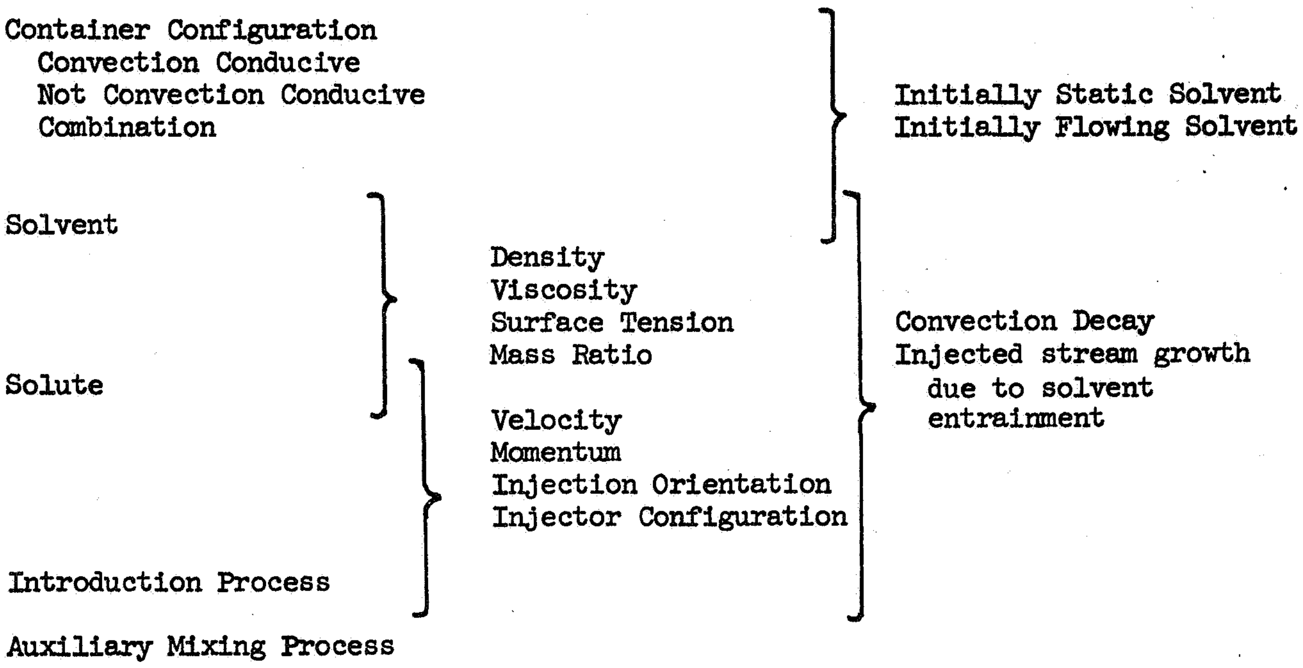


Figure 21. Factors Involved in G-Sensitivity of Convective Mixing

Since gravity effects are manifested as behavior due to weight, and this behavior, in the case of mixing, is upward or downward motion of the solute within the solvent, container configuration can be an important factor in determining g-sensitivity by limiting the extent of this motion. In addition, it is particularly important as it may be one of the variables over which the designer has the greatest control. Properties of the solvent and solute, including relative masses, velocities and momentum determine injected stream entrainment of the solvent and convection decay periods, which in turn affect the speed and extent of gravity induced motion. The solute introduction process, particularly with regards to injection orientation and velocity, similarly affects gravity induced behavior. Auxiliary mixing devices, if utilized, may in themselves be g-sensitive as well as directly regulating the g-sensitivity of the mixing process. In addition, since the g-sensitivity of convective mixing is closely related to the speed of gravity induced solute travel and this is in turn a function of the bouyant force resulting from differences in solute/solvent densities, an additional factor, the Reynolds number, should be mentioned. While it is implicitly included by listing density, viscosity and velocity, it is of particular significance in that a sufficiently large Reynolds number (of the order of a few thousand) assures initial turbulent mixing of the solute with the solvent; thus it can have a marked effect on reducing the density difference between the two.

At present, there is no function or set of functions available which adequately expresses the relationships necessary among the variables mentioned to enable prediction of convective behavior for an arbitrary mixing process. Since the prediction of g-sensitivity of convective mixing, for the general case, involves analysis of the manner in which gravitational forces enter into these desired functions it is apparent that a generalized analytical procedure for predicting g-sensitivity of this form of mixing cannot immediately be developed. In view of this, two approaches to the problem are suggested at this time. The first involves a combined experimental/analytical treatment of the convective mixing phenomena to establish the desired parametric relationships and from them a generalized technique for g-sensitivity prediction. The second may be considered as an interim experimental approach for assessing approximate g-sensitivity of currently required hardware which must be designed and developed prior to the completion of a generalized analytical prediction technique. The first approach (referred to here as the parametric approach) should provide g-sensitivity prediction criteria of a similar nature to that developed in other sections of this report, while the second approach (experimental approach) should serve as a temporary expedient for handling more immediate problems of g-sensitivity assessment.

The parametric approach, as envisioned, includes a series of mixing experiments at various simulated g-levels, designed to examine in a systematic manner the variables of figure 21. Gravity variations may be simulated at one-g by preselection of appropriate density solutes and solvents. The experimentation would be directed and supported by dimensional analysis and by direct analytical treatment of the variables where possible. Gravity effects would be brought into the analysis by use of the settling equations developed in the section on Solids Control by Gas Flow. The expected results would be a set of partially empirical parametric relationships from which the effect of gravity on the overall convective mixing process could be determined.

Pending the availability of such relationships, it is felt that g-sensitivity of a specific convection mixing process can be detected for a particular component or subsystem configuration by a series of tests at one-g. This experimental approach involves basically a series of mixing tests with the actual hardware (or a full scale model) oriented at various angles with respect to the gravity force vector.

As the gravity force is directional, it is to be expected that its effect, if any, on a mixing process would have directional characteristics. Thus, a detectable gravity effect on an overall mixing process would be evidenced by local mixing rate sensitivity to component orientation. It might further be expected that these local mixing rate variations with orientation would be most pronounced between the top and bottom of the mixing vessel. For example, if a mixing process were initiated in a container and the local solute concentration change rate monitored at a point near the container bottom; and if the container were then inverted, the mixing process re-initiated in an identical manner, and the local concentration change rate again monitored at the same location, which would be at the top; then identical concentration change rates would indicate g-insensitivity along the vertical axis in the vicinity of the measurement. Conversely, a significant difference between the concentration change rates would indicate gravity dependence. Repetition of these experiments, using points at opposite ends of orthogonal diameters of the container, should permit detection of g-sensitivity of the gross mixing process within the container.

In the case of spherical containers the selection of a particular set of orthogonal axes is unimportant, however, for containers differing appreciably from the spherical shape, or having projections, such that portions of the solvent are not in the principal convective current paths of the container, special consideration should be given to selection of the axes. This is due to the potentially greater susceptibility of such "isolated" regions, or irregular shapes, to g-sensitivity of mixing. In general, one of the selected axes should span the greatest solvent dimension, while other axes should pass through extended or "isolated" solvent regions should they exist. As this may involve measurement points in addition to the ones on the three orthogonal axes, judgement must be exercised in their selection to minimize the overall task without sacrificing validity of the results.

In the design of a system involving a required fluid mixing process, it is necessary to consider a desired or acceptable mixing rate. As mixing processes are theoretically never complete, this implies specifying a time period within which a certain mixing level, or percentage of complete mixing is reached. For a particular case, compliance with this acceptable mixing criteria may be determined by prediction or actual mixing rate measurements. Gravity sensitivity of a mixing process thus refers to variations in the mixing rate due to variations in the applied gravity field. If a change in the gravity field can reduce the mixing rate below a specified acceptable level, then this g-sensitivity may be unacceptable; while changes above the critical level, though they result in significant g-sensitivity, may be unimportant to the designer. Consequently, it is desired, not only to detect mixing g-sensitivity, but also to determine the likelihood of a decrease in the mixing rate below a desired level due to its g-sensitivity.

As the concentration change rate measurements proposed for this "experimental approach" are actually local mixing rate histories, any significant difference observed for a given location, between its top and bottom orientations, provides a semi-quantitative measure of the g-sensitivity of the mixing process. Furthermore, by comparing these local mixing rate histories to the desired or acceptable mixing rate, an assessment may be made as to the acceptability of the g-sensitivity. In general, if all the local solute concentration measurements taken at a given g-level reach the acceptable range with the required mixing time period and remain within that range, then it can be assumed that the overall mixing process will also be acceptable at reduced g-levels. It is possible to conceive of a specially configured container having an auxiliary convection mechanism which would violate this rule; however, it would probably require a design directed toward that purpose and the chance of its being encountered in practice is highly unlikely.

Mechanical Device Operation

With regard to g-sensitivity, mechanical device operation may be considered from two aspects. One is concerned with the effects of gravitational forces on lubricants, while the other involves the effects of these forces on actual hardware items.

The general fluid mechanics problems of lubricating machinery involve practically all phases of the control of liquids with the possible addition of the control of semi-solids such as greases and particulate solid materials such as graphite and molybdenum disulphide. For machinery such as that used in the ILSS, the general liquid handling problems are, however, avoided because no appreciable size reservoir and feed system is provided. The fluid mechanics problem is basically one of maintaining a film of lubricant throughout a required region, the film having a thickness of capillary dimension or less. Assessment of g-sensitivity thus becomes a comparison of capillary or surface tension forces with the fluid weight. Film thicknesses in these lubrication situations are of such a size as to make the capillary forces very much greater than the weight forces, and the relationships for computing these forces were presented in the section titled, Liquid Behavior Control by Capillarity.

A comprehensive study of the g-sensitivity of lubrication systems would include all of the earlier liquid control methods discussed in this volume of the final report plus some extension of that work into combined effects to deal with possibilities such as centrifugation to clear the foam from lubricating oils. In addition, the heat transfer problems of lubrication systems can be handled by the methods developed in the section on Heat Transfer Between Fluids and Solids.

Forces acting on the hardware elements or components may include electrical, mechanical, manual, inertial, weight, and fluid pressure. Assessment of g-sensitivity involves a comparison of the item weight with the other forces present. In general, this is a straight-forward analysis with required force vectors being available or readily obtained by computation or measurement. Where necessary force information is inaccessible, as may be the case for sealed control devices or items involving unusually complex motions, an approximate assessment of g-sensitivity may be obtained experimentally by measuring performance changes which may occur as the result of orientation changes during operation in one-g. The approach is related to that suggested in an earlier section for the experimental assessment of gravity effects on fluid mixing. In the mechanical device case, however, the number and selection of preferred test orientations is a judgement problem based on knowledge of the item's operation, primarily its motions and force directions. In general, the magnitude of the performance change due to reorientation will be directly related to the g-sensitivity of the item.

Flame Propagation

The propagation of flames is a very complex physical and chemical process. Fortunately, however, almost all of the elemental processes involved are nearly unaffected by gravity. The one outstanding exception is the natural or bouyant convection which gives flames their characteristic shape. The hot products of combustion and the other gases nearby are very much less dense than the surrounding gas, and are therefore strongly propelled away from the gravitational pull of an attracting body such as the earth, or in the direction of any general linear acceleration of the system under consideration. Gas velocities ranging up into the turbulent flow region may be created by this bouyant ventilation process. Ventilation may also be and in many practical cases is forced by an agency not directly related to or controlled by the flame, such as a fan or a motion of the flame holder. The effect on the flame is roughly similar for either bouyant or forced ventilation. It is not identical, but the similarity is sufficient so that we may here appropriately consider how the ventilation affects the flame.

The elementary processes of combustion may be classified as pertaining to either the release and absorption of heat, or the transport of heat and mass. The heat release and absorption phenomena such as the oxidation/reduction chemistry; the pertinent chain reactions; molecular dissociation; and specific and latent heats of the substances involved may be largely disregarded as g-insensitive in themselves although they can of course be affected by other processes which are g-sensitive. Such sensitivity does appear in the transport processes.

From consideration of the heat balance of a flame it is clear that the heat released by the chemical reaction goes initially into changing the temperature and the chemical and physical states of the materials involved in that reaction A part of this heat, known as the net heat release, is quickly transported away from the flame by radiation, conduction and convection, and for highly flammable materials this is the major part of the heat. It appears that for combustion to occur and continue, the mass transport must carry fuel and oxidant to the flame fast enough so that the heat released can maintain the temperature above the ignition point despite the cooling effects of the heat transport. The g-sensitivity of heat transport phenomena is considered in the section, Heat Transfer Between Fluids and Solids; and of mass transport in the following three sections, particularly the section on Fluid Mixing. Numerical results derived from relations such as are presented in those sections will lead to the conclusion that most of the heat and mass transported to and from flames is transported by convection. This applies at least to typical flames an inch or more high in normal gravity.

Considering the interplay of the effects of heat and mass transport, it can be seen that interference with the mass transport can reduce the heat release rate and therefore the heat transport. Direct attempts to reduce the heat transported away from the flame, however, will not be able to do so without interference with the mass transport. At least this will be true on a steady state basis, for with the temperature high enough for combustion, the fuel and oxidant will combine and release heat as they arrive at the flame zone, raising the temperature until the heat is carried away as fast as it is released.

Changes in the amount of ventilation can change the rate of heat release in rather involved ways, as for instance in the blowing out of a match. In this case the ventilation carries the hot gases away from the fuel, interfering with the mass transport to the flame zone because of the limited flame speed. In the absence of ventilation, however, it seems inevitable that combustion must be relatively slow, for convection can move masses much farther and faster than diffusion. This does not mean that flames cannot burn and propagate in the absence of ventilation, for this absence also reduces the heat loss rate, and the flame zone may stay suitably hot even with the low rate of heat release.

There is analytical and some experimental evidence that flames can burn in the absence of both forced and bouyant ventilation, but this may be possible only in a transient condition. There appears to be some logic to the concept that the diffusion of oxygen to a flame under completely quiescent conditions must be obstructed by the outwardly moving products of combustion, and that the obstruction must eventually become so effective that conduction and radiation will cool the flame zone to such an extent that the chemical reaction rate drops below some critical minimum.

Summarizing the various factors mentioned above the combustion picture may be roughly represented by the following table:

Ventilation	Effect
Zero	Slow burning/probably transient
Low	Faster burning/increasing with ventilation
High	Rapid burning/flame instability approaching
Blow out	Flame carried away.

In the absence of forced ventilation, flames an inch or more high, burning in normal gravity, are in the low to high ventilation region, and the condition is self-stabilizing because as the ventilation approaches the blow out condition the decrease in heat release rate reduces the ventilation. The ventilation velocity associated with such flames has been approximately assessed by experiments on small highly flammable specimens. Pieces of paper towelling and filter paper about two inches high were burned in a small wind tunnel with downward ventilation. The specimens were ignited in the middle and it was found that at ventilation velocities of the order of one or two feet per second, the flame propagated downward as fast as upward. These results may be roughly verified by moving a burning match or candle upward in still air at a velocity which gives the flame approximate symmetry about a horizontal plane. The outer mantle of hot gases surrounding such a flame burning in the absence of forced ventilation is moving upward at about the one foot per second velocity, but the central core of very hot gas moves faster. The results are not highly accurate, but they strongly indicate that in the absence of gravity a forced ventilation rate of one or two feet per second will allow or cause flames to propagate in the direction of ventilation about as they would propagate upward in normal gravity without forced ventilation.

CONCLUSIONS AND RECOMMENDATIONS

(1) The majority of processes in the ILSS, and probably within life support systems in general, are of such a nature that their g-sensitivities can be satisfactorily assessed by analyses. This precludes the need for extensive testing of specific ILSS processes.

(2) Of the 92 ILSS processes investigated, 69 of which were found to have some degree of g-sensitivity, all but four were eliminated as possible test candidates by analyses and other screening processes. In certain cases, however, the analyses performed were based upon assumptions and basic data which themselves were considered to warrant experimental verification. The four remaining ILSS processes represented liquid-mixing and flame propagation phenomena, while the analytical problem areas included liquid droplet release, heat exchanger passage plugging, and liquid film stability.

(3) From consideration of the ultimate value of a possible test program it is concluded that the greatest benefit can be realized from experimentation to validate and support the analytical problem areas. The ILSS processes of liquid-mixing and flame propagation are felt to be of less value, as future life support system designs are expected to appreciably reduce or eliminate the importance of their g-sensitivities.

(4) As a consequence of (1) above, it is important that analytical techniques for determining g-sensitivity be included as an integral part of space vehicle design analysis. The Gravity Sensitivity Prediction Criteria while based on certain general processes found to be represented in the ILSS, should provide useful analytical tools and relationships for this purpose. These Prediction Criteria are considered as a first step or phase in the development of a "Handbook" which could be extended eventually to include essentially all processes common to anticipated future space systems.

(5) It is recommended that experimentation be performed to verify the assumptions and basic data used in the screening analyses. It is also recommended that the Prediction Criteria be further developed and expanded into a "Handbook" and that it incorporate the results of the verification experimentation.

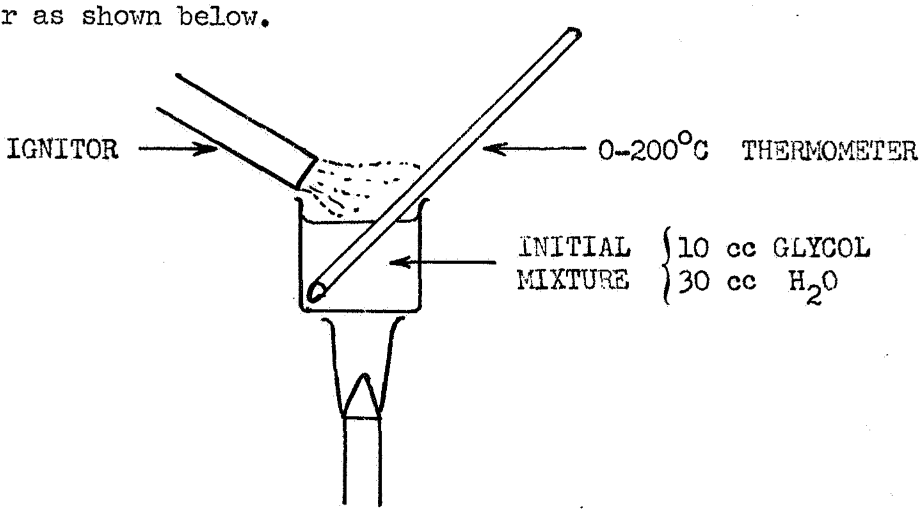
APPENDIX - FLAME PROPAGATION PRELIMINARY EXPERIMENTATION

During the evaluation of methods for possible flame propagation testing, the requirement for additional data, of an experimental nature, became evident. The sensitivity of low-g test costs to the duration of the low-g test period dictated a need to know approximate burning rates of the materials to be considered. The possibility of simulating a low-g environment for the flame propagation process appeared worthy of investigation. In addition it was felt that certain critical techniques and instrumentation methods should be verified prior to further consideration. As a consequence, two types of preliminary experiments were performed. The first was essentially a screening test of ILSS and other flammables, in which ignition and flame stabilization times were determined in one-g. The second involved combustion testing of selected materials exposed to a controllable downward ventilation. An arc-spark ignitor was fabricated and tested, as was an elementary low velocity wind tunnel. Specimen mounting techniques and data recording methods were examined. The testing is described below.

One-G Material Screening Tests

Silicone oil, DC331.- This liquid is used in the ILSS in some quantity for heat transfer at rather high temperatures. Its combustibility was briefly investigated by pouring about 20 cc into a light porcelain dish which was heated from below with a bunsen burner. A soft gas flame was intermittently played over the top of the liquid until it ignited. Ignition occurred after about thirty seconds of heating. The heating burner was then removed. The flame nearly died. The heater was replaced. The flame grew. The heater was removed. The flame died. The flame had been smoky with small pieces of soot. The ash volume remaining in the dish considerably exceeded the original DC331 volume. Ash blisters were formed on the sides of the dish, indicating that the ash skin can be nearly gas tight.

Propylene glycol.- This is used in the ILSS, but mixed with three parts of water. The flammability of the mixture was investigated. A paper towel wet with the mix survived about sixty seconds in the bunsen burner before the flame would persist after the igniter was removed. About 40 cc was then checked out in a small beaker as shown below.



The sample was heated gently about fifteen minutes, boiling away about one-half. The temperature indicated rose from 102°C to 107°C. The steam or escaping gas:

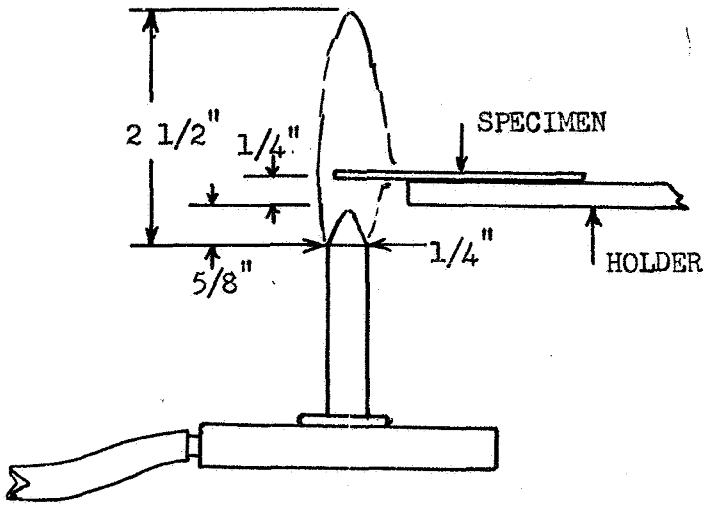
> before ten minutes, extinguished the igniter;
>
> after twelve minutes, burned when mixed with igniter gas;
>
> after fifteen minutes, burned and continued after the igniter flame was removed.

Just after fifteen minutes the fire was extinguished and fifteen cc of the mix was cooled and weighed, giving a density of 1.024 g/cc at about 25°C, which represents a mixture of about two parts glycol to one water.

Of the ILSS liquids, only DC331 can be considered as a fire hazard. No appreciable quantity of lubricating oil is on board, and the propylene glycol is so diluted with water that it is more a fire extinguisher than a fuel. The DC331, however, burns vigorously if hot enough and is used at temperatures near enough to its (420°F) flash point so that it is reasonably conceivable that local overheating of the system could simultaneously cause a leak and preheat and ignite the oil. The g-sensitivity of such combustion, or, more exactly, the relationship between gravity and ventilation effects could conceivably be evaluated by careful analysis and test. The analysis, to some degree, and the testing, to a very considerable degree, would, however, be hampered by the nature of the fuel in question, and it is felt that a surrogate fuel (e.g. ethyl alcohol or normal pentane) would be more suitable. A clean burning liquid could be selected in order to prevent obscuring the pictures of the fire with smoke, and this liquid could have a room temperature flash point eliminating the serious difficulties of maintaining a test chamber, and probably an entire test capsule, at a considerably elevated uniform temperature, say 450°F. The surrogate liquid also could be one on which appreciable analytical and experimental work has been done, which would provide invaluable analytical and experimental background data.

Solid fuels.- Specimens for test (certain plastics plus structured and composite materials) were mostly selected from those listed in the memorandum "Materials within the ILSS" of March 10, 1967 from Kenneth A. Caldwell to Program Manager, ILSS. Most of them were obtained from the ILSS stock at Langley Field. Not all of the items of the memorandum were tested because the memorandum description did not clearly identify the material and/or because it was not available from ILSS stock. Nine "non-memorandum" specimens were also tested. Seven of these were received from Langley as "ILSS material," and paper towels and filter paper were selected because of their ubiquity and their combustion characteristics.

Each test specimen was exposed to the flame as sketched below.



The ignition period started when the specimen was inserted into the flame and ended when the flame was removed. The timing of events was recorded by a foot controlled electric timer and a stopwatch. The results are shown in Table 10. The general pertinent result is that the materials are rather hard or at least slow to ignite, and therefore that only the most flammable of the ILSS materials can yield useful information in a reasonably economical zero-g drop test program.

An arc ignitor was constructed for further material screening and as an ignition means of a type which would be useful in low gravity drop testing. An electrical schematic and a sketch of the ignitor electrode assembly are shown in Figure 10. The arc fires more or less concentrically around the graphite center electrode. The results of firing this ignitor in contact with certain materials are shown in Table 11.

Considering the results of the burner and arc ignition tests, the following solid materials were selected as candidates for further experimentation.

Description	Material (See Tables 10 and 11)	Approx. Ignition Delay (secs.)
Paper Tag	27B1	1.0
String	27B2	0.5
Paper Masking Tape	20C	0.8
Paper Towel	58	1.0
Filter Paper	59	1.0
Polyethylene Sheet (10 Mil)	7	1.0

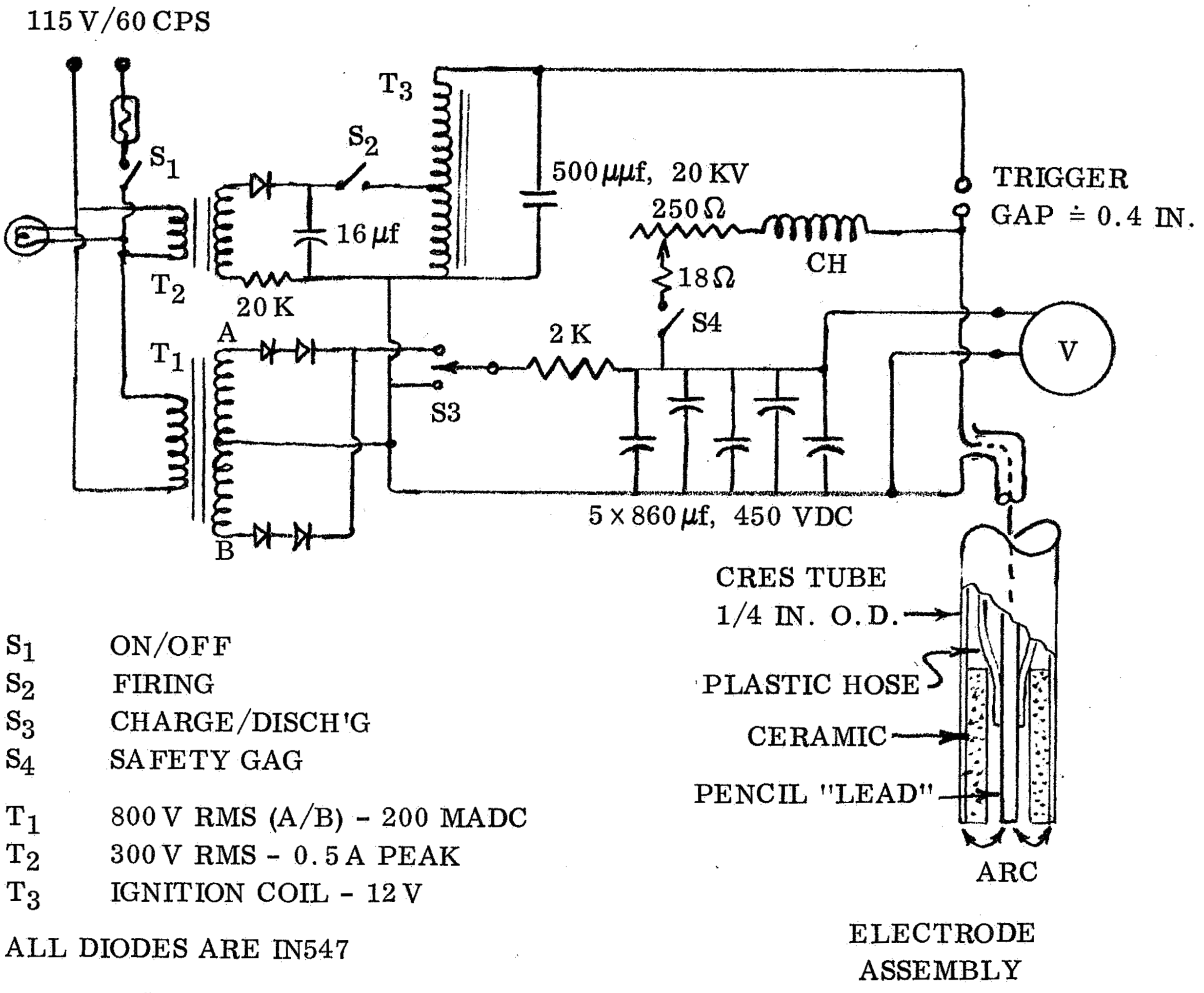
Table 10.- Bunsen Burner Ignition Trials

Test Number	Material Number	Description of Test Specimen	Igniter Duration (Secs.)	Appearance of Burning	Post Ignition Burning (Secs.)	Remarks
1	7	Polyethylene Sheet (10 Mil)	0.5	No		
			0.9	No		
			0.9	Yes	Cont.	Molten drops fall burning, go out where they hit paper
2	14	CO_2 Concentrator Insulation - Fiberglass Mat with Red Silicone Mat with Red Silicone Covering	5.6	Yes	No	Weak flame in burner
			15	Yes	2	White ash
			20	Yes	9	(Specimen well over burner) Flame & glow died simultaneously
3	29B	Black Terminal Strip — End of strip	5	Yes	1	Small flame
		Same area, still hot	10	Yes	2	Flaming and crackling in burner
		Same area, still hot	15	Yes	5	Flaming and crackling in burner - considerable afterglow
4	11	Tan Fiberglass Sleeve, Silicone (?) Covered	5	Yes	4	
			6	Yes	6	Some afterglow
5	51	Wire - High Frequency Coaxial Cable (Belden 8263 RG-59 B/U 70903)	3	Yes	No	Outer insulation burnt but flexible
		Outer insulation only	2	No		
		" " "	2	Yes	No	
		" " "	5	Yes	Cont.	
		Inner insulation only	3.6	Yes	Cont.	
		" " "	2.5	No		Some melting
6	27B	Paper Tags - Heavy Manila (2½" x 5¼")	0.3	Yes	Cont.	One inch burned in 16.7 Sec.
		String	0.6	No		
		Tag	1.0	Yes	Cont.	Across 2½" Horizontal Edge in 51 Sec.
			1.0	Yes	Cont.	Upward along 2½" Vertical Edge in 5½ Sec.
7	52	Shrinkable Sleeving - Black 7/16" OD	2.8	Yes	1	
			5	Yes	2	Chars, smokes, odor unlike polyethylene
8	53	Shrinkable Sleeving - Clear ½"	1.1	No		Melt, no burn
			1.5	Yes	Cont.	Drips, polyethylene odor
9	54	Shrinkable Sleeving - Large Tube, Cloudy	1.5	No		
			1.6	Yes	Cont.	No drip, Melt + char, polyethylene odor
10	55	Asbestos Insulated Wire (Progressively heated)	60	Yes	5	Weak flame. Insulation weakened but intact.
11	20A	Black Adhesive Tape	1.0	Yes	0.5	
			1.1	Yes	Cont.	

The "Material Numbers" are those shown on a U.S. Government MEMORANDUM of March 10, 1967 from K. A. Caldwell to Program Manager, ILSS concerning "Materials within the ILSS." Numbers 1 through 50 appeared in that memorandum. Numbers 51 and on are hereby assigned for identification.

Table 10.- Bunsen Burner Ignition Trials - (Cont.)

Test Number	Material Number	Description of Test Specimen	Igniter Duration	Appearance of Burning	Post Ignition Burning	Remarks
			(Secs.)		(Secs.)	
12	20B	Yellow Adhesive Tape	1.5	Yes	0.5	
			2.5	Yes	Cont.	Melt, char, smoke
13	56	Shielded Cable - Gray - 4 Conductor	10.	Yes	3	Melt and char
14	44	White Plastic Wrapped Cable - 4 Conductor	30	No		Cover off bottom, remainder brittle
15	57	Black Shielded Cable - 3 Wire - Belden 8423	5	Yes	0.5	
16	45	Shielded Pair - Yellow Plastic Cover (Shrunk)	4	Yes	No	
		Cover Only	12	Yes	0.5	Burned and dripped in igniter flame
17	12	Wire Sheath - Heavy Fiberglass with Epoxy (?) coating	20	No		Coating heated
			40	Yes	Cont.	Heated through, it burns strongly.
18	20C	Paper Masking Tape — Corner or Torn Edge	0.2	Yes	Cont.	
		Cut Edge	0.3	No		
		" "	0.4	Yes	Cont.	
		Surface	0.8	No		
		"	0.9	Yes	Cont.	
19	58	Paper Towels	0.3	Yes	Cont.	
20	27A	Paper Tag -- Round White	1.5	Yes	No	Charred
			2.0	Yes	Cont.	Burned 1/2" horizontally in 8 seconds.
21	5	Adhesive Aluminum Foil	1.0	Yes	2	It appeared that a large specimen could continue to burn upward.
			3.0	Yes	5	



S_1	ON/OFF
S_2	FIRING
S_3	CHARGE/DISCH'G
S_4	SAFETY GAG
T_1	800 V RMS (A/B) - 200 MADC
T_2	300 V RMS - 0.5 A PEAK
T_3	IGNITION COIL - 12 V

ALL DIODES ARE IN547

CH 400 T #24CU ON 10 MM GLASS TUBE (≐ 80 μH)

Figure 22.- Arc Ignitor Schematic

Table 11.- Arc Ignition Trials

Test Number	Material Number	Description of Test Specimen	Arc to Ignite		Remarks
			Volts	Ohms	
101	58	Paper Towels	200	18+	
102	7	Polyethylene sheet (10 Mil)	400	100/200	A smaller arc seems to generate enough heat but material pulls away.
103	27B	Heavy Paper Tag String	400 300	100 100	
104	54	Large Polyethylene Shrink Tubing	300	18+	Like Test 18 but seems to require more heat and shrinks away less.
105	20A	Black Adhesive Tape	225	18+	Ignites with almost any arc.
106	11	Tan Fiberglass Sleeve	400	18	Burned for one or two seconds.
107	20B	Yellow Adhesive Tape	225	18+	Ignites with almost any arc.
108	20C	Paper Masking Tape	300	0-100	Burned 1" across horizontal edge in 5 seconds.
109	59	Filter Paper ED631 (Ashless)	150	0	Burned horizontally about 3½ Secs. per inch. Burning seemed to accelerate for about one second. After ten seconds or so, the burning zone was an inch or more wide.
110	227A	Paper Tag -- Round White	X	X	Sustained combustion was not initiated by any arc available. 460V, 18 burned a 1/4" hole through the tag, but no fire resulted.

Wind Tunnel Combustion Experiments

Downward ventilation wind tunnel experiments were performed to investigate the possibility of simulating low-g combustion by cancelling the gravity induced bouyant convection with a forced down draft; to examine certain critical test techniques; and to obtain additional indicationg of low-g burning rates.

Procedure.- A small experimental vertical wind tunnel, shown in figure 23. was set up to provide controlled low turbulence ventilation for the test specimens. The throat of the tunnel is five inches square and the specimens ranged in size from thread diameters to two inch circles of paper towel and filter paper. The tunnel shielded the specimen from random ventilation created by room turbulence and provided adjustable low levels of downward ventilation. Ventilation rates were determined by an orifice plate below the test section and a water manometer. Specimens were ignited by an electric spark or arc (see figure 24) and the burning was monitored by a motion picture camera running at normal speed. Burning rates were determined from frame-by-frame measurements of the motion pictures. All tests were run in air at approximately 14.5 psia, 75°F. Ventilation levels ranged from zero to about 2.7 feet per second downward.

The following materials, which include four of the above listed ILSS materials, were tested. The ILSS paper tag string and polyethylene sheet were replaced with thread, insulated wire, and the liquids ethyl alcohol and ether, as these appeared to be more promising candidates for eventual drop testing.

Filter Paper (ED 613 Ashless) (No. 59)

Paper Towel (Crown Zellerbach No. 015)

Paper Masking Tape (No. 20C)

Paper Tag (No. 27B)

Thread . . . No. 50 Mercerized Cotton (pink)

Ethyl Alcohol

Ethyl Ether

Insulated Wire

Thread screening tests were made before the wind tunnel experiments in order to select a suitably fast burning material. Different spools of thread which, except for color, were apparently similar had markedly different burning rates. It is not known whether the dye has any appreciable bearing on the flame propagation. The fastest burning thread was selected for the tunnel tests.

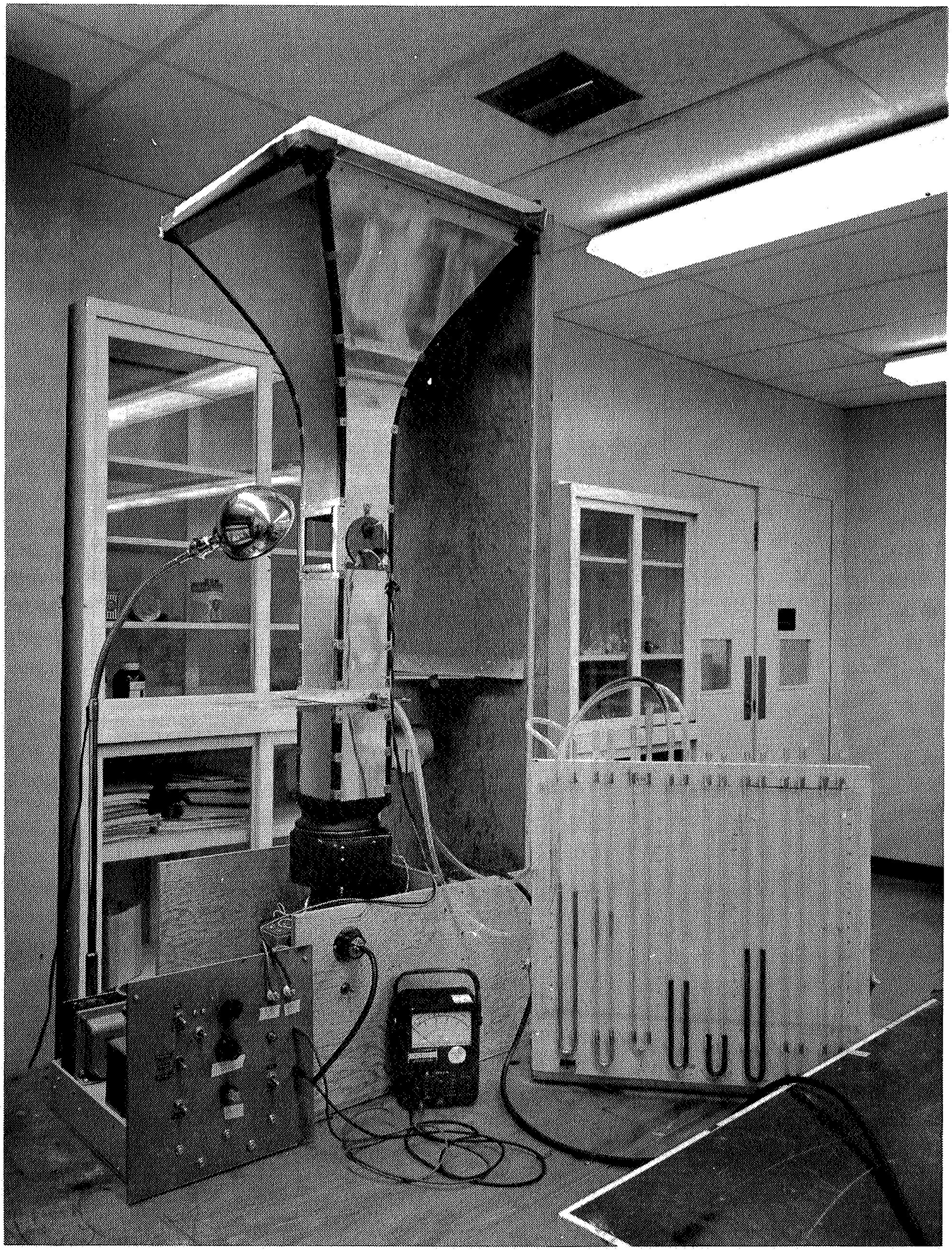


Figure 23. Vertical Wind Tunnel

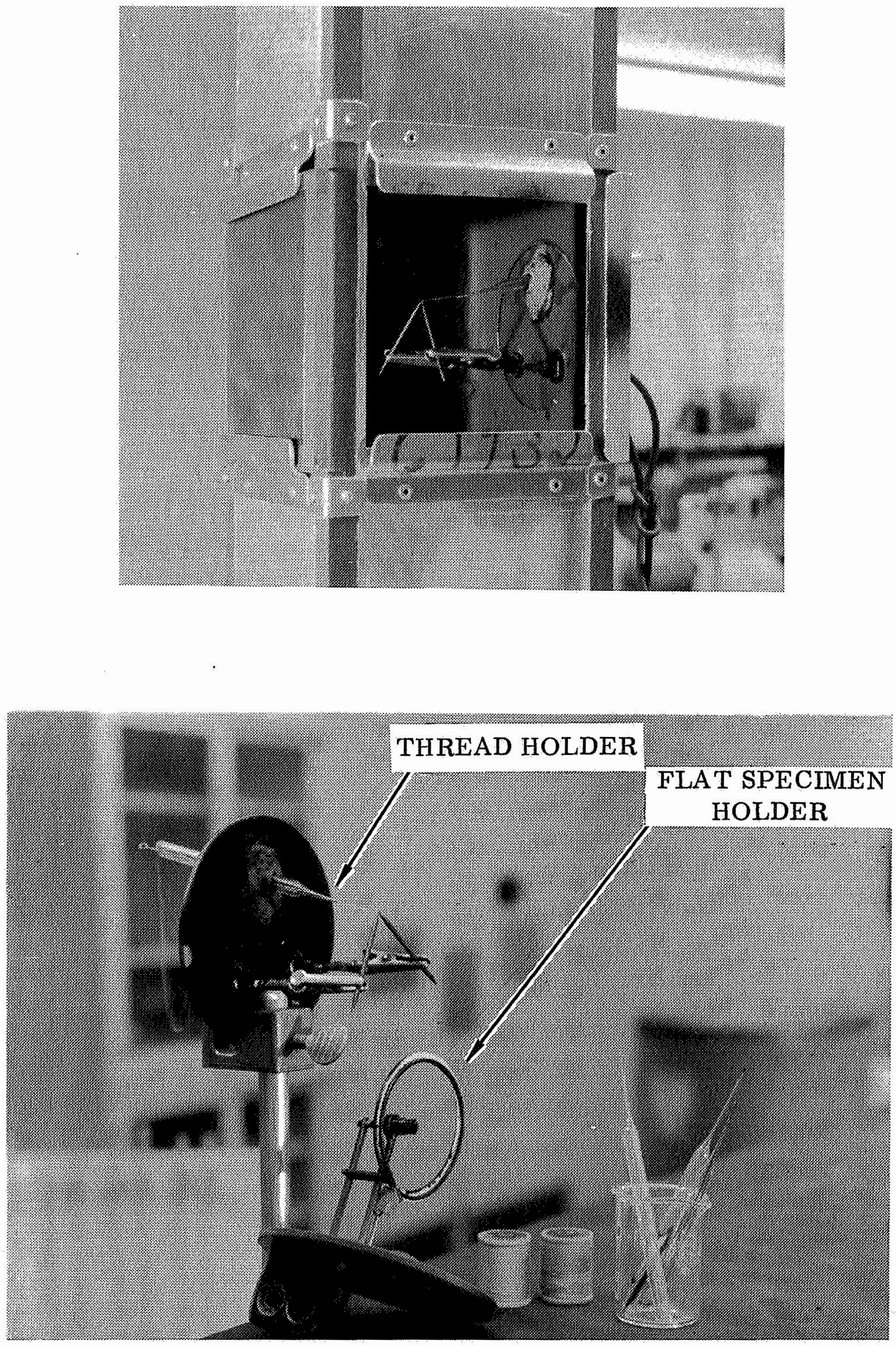


Figure 24. Ignition Arrangement

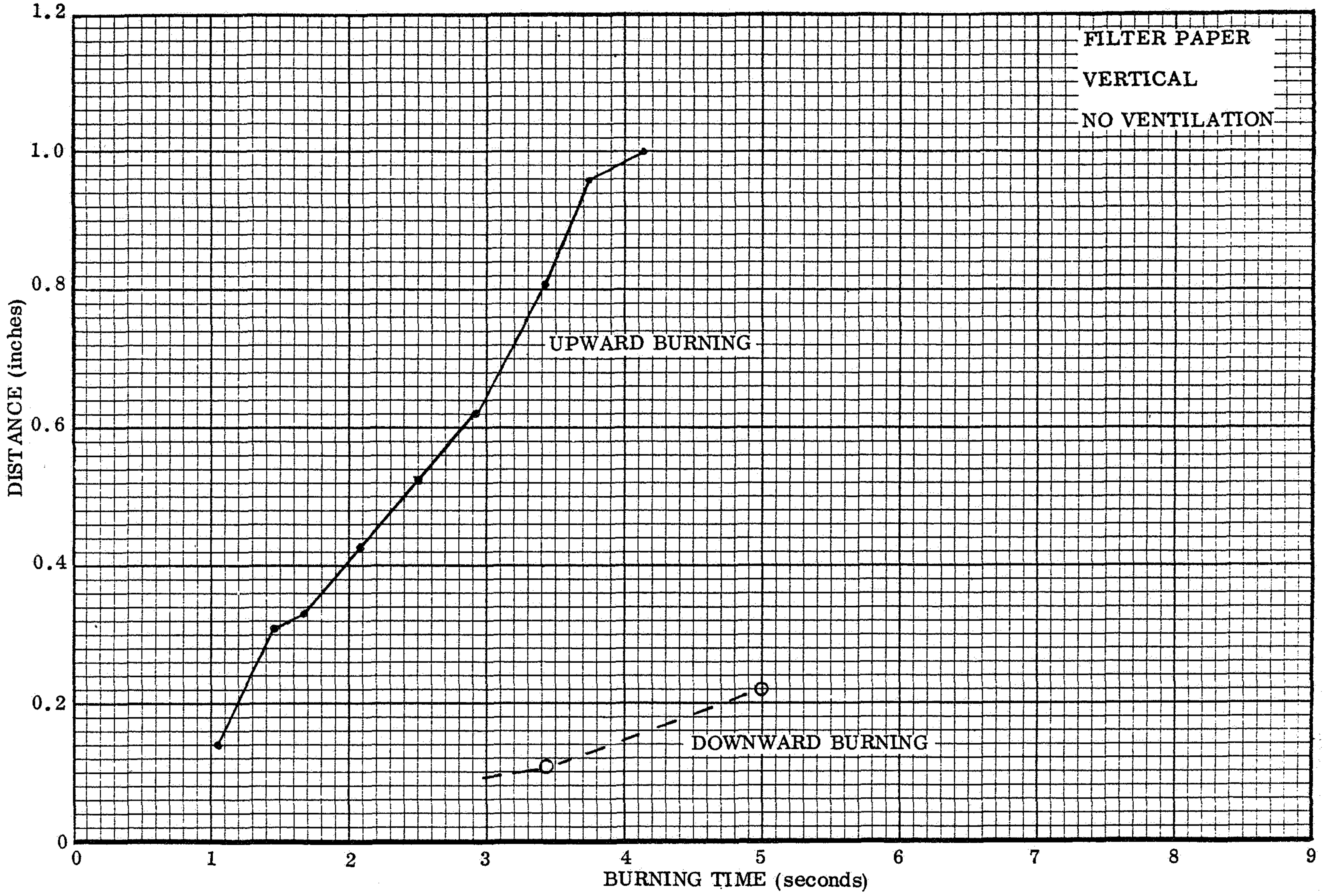


Figure 25.- Flame Propagation Test Data

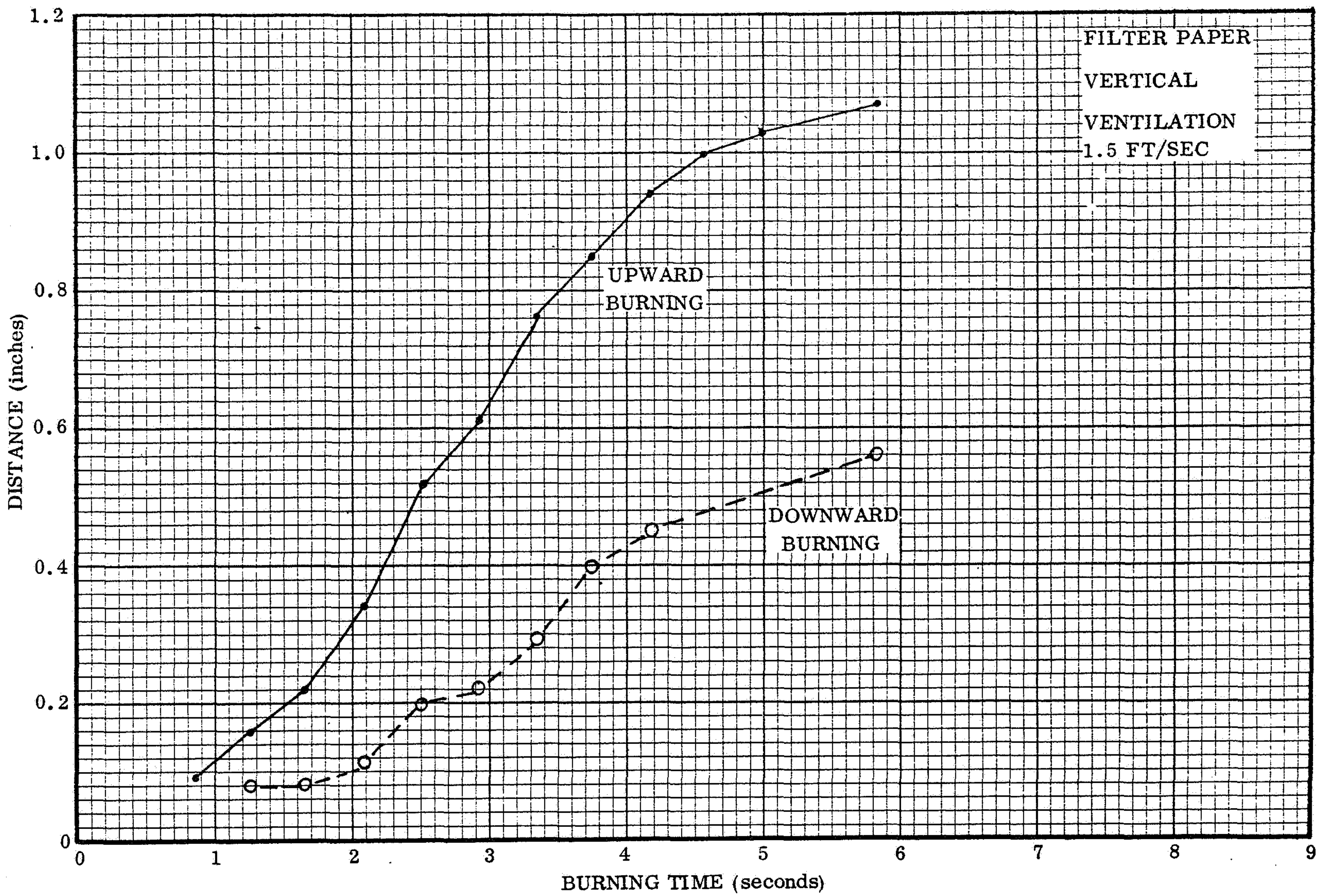


Figure 26.- Flame Propagation Test Data

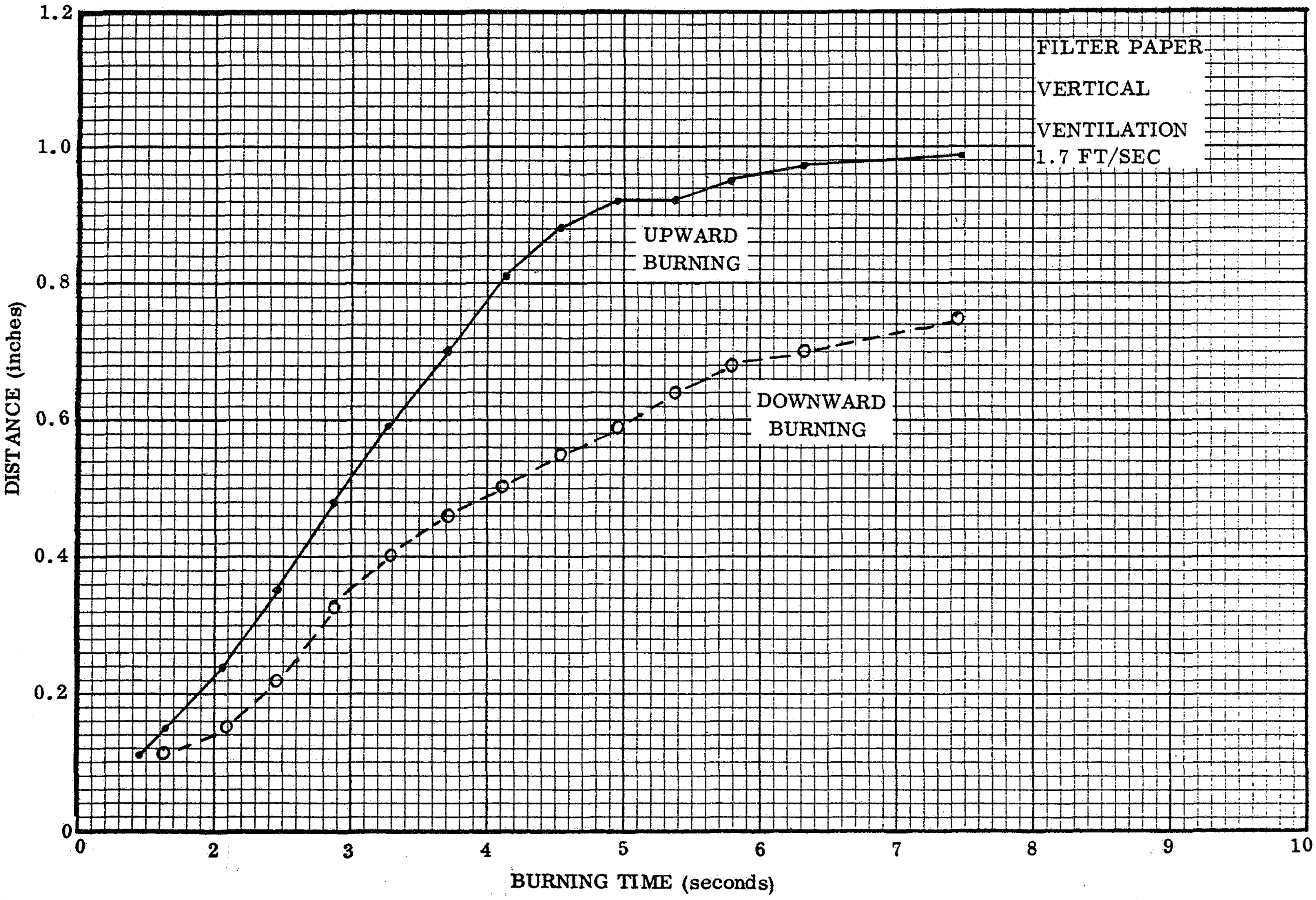


Figure 27.- Flame Propagation Test Data

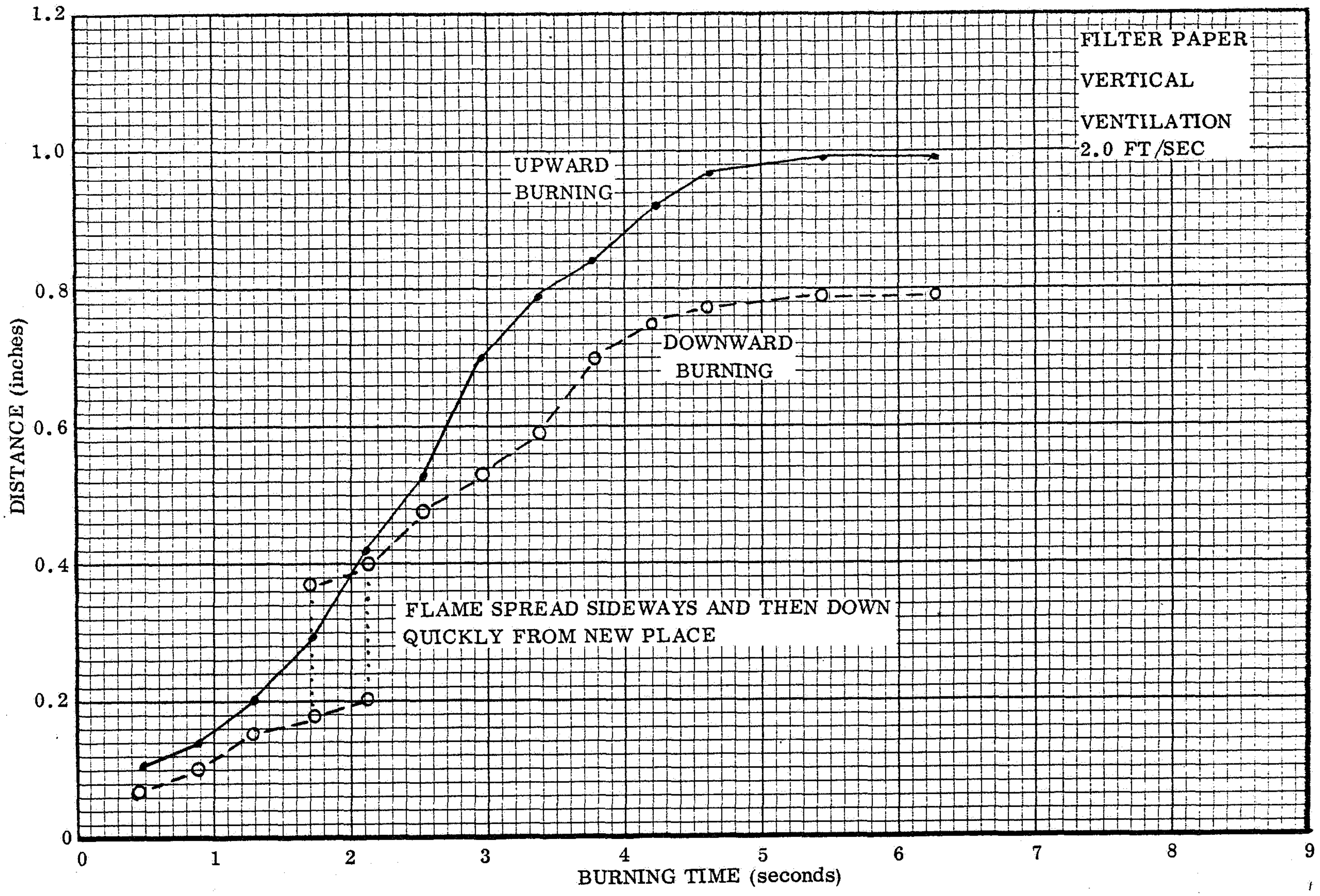


Figure 28.- Flame Propagation Test Data

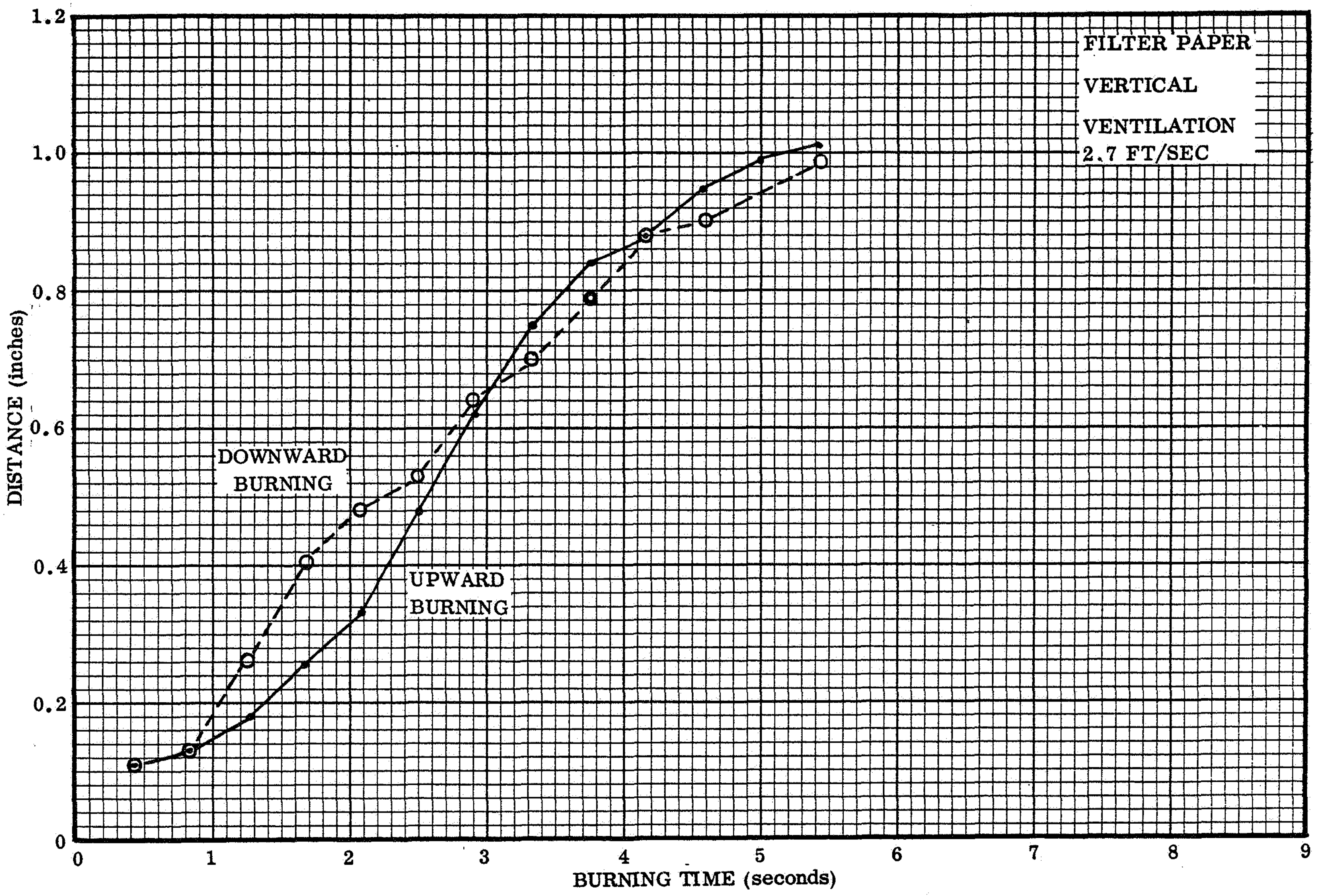


Figure 29.- Flame Propagation Test Data

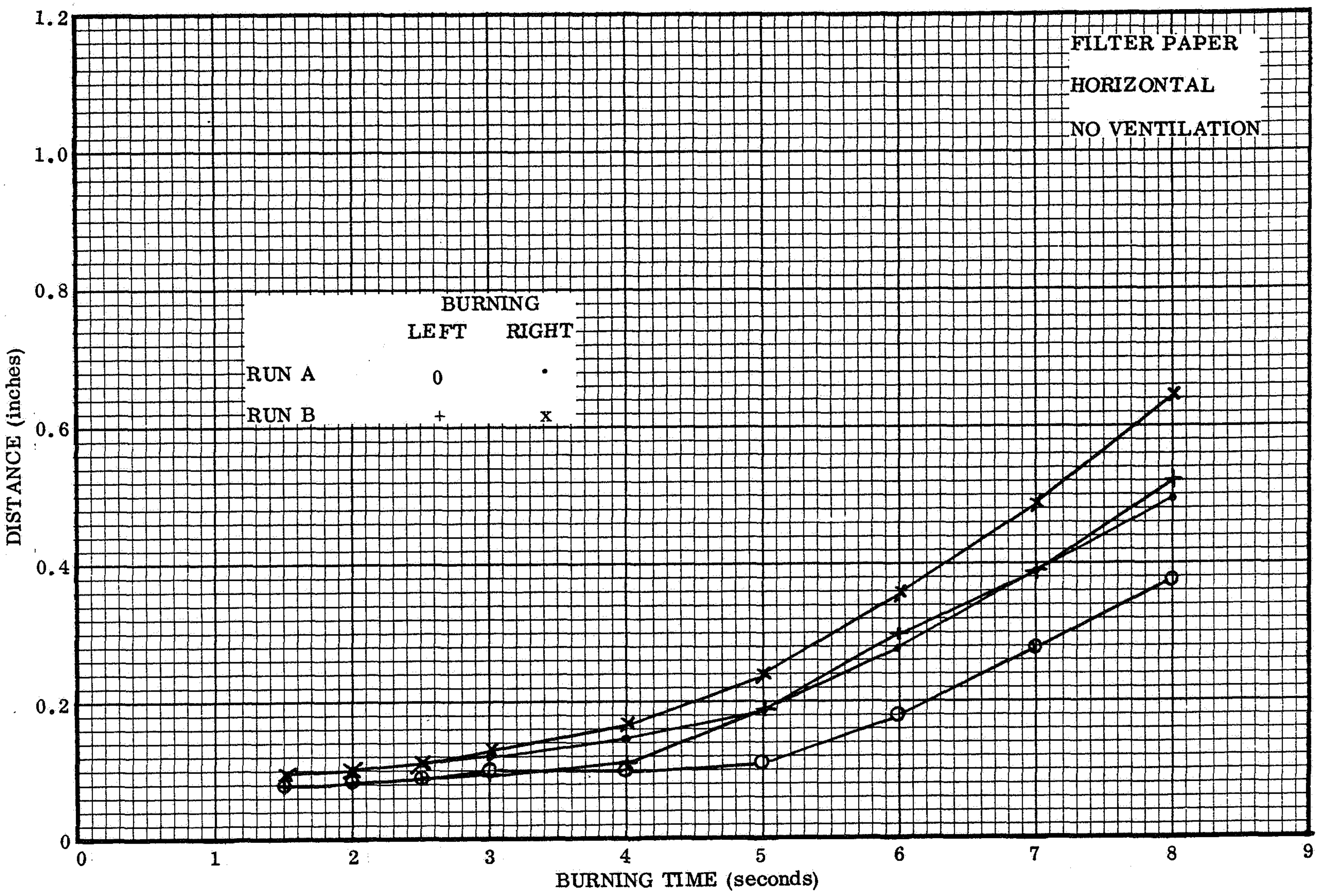


Figure 30.- Flame Propagation Test Data

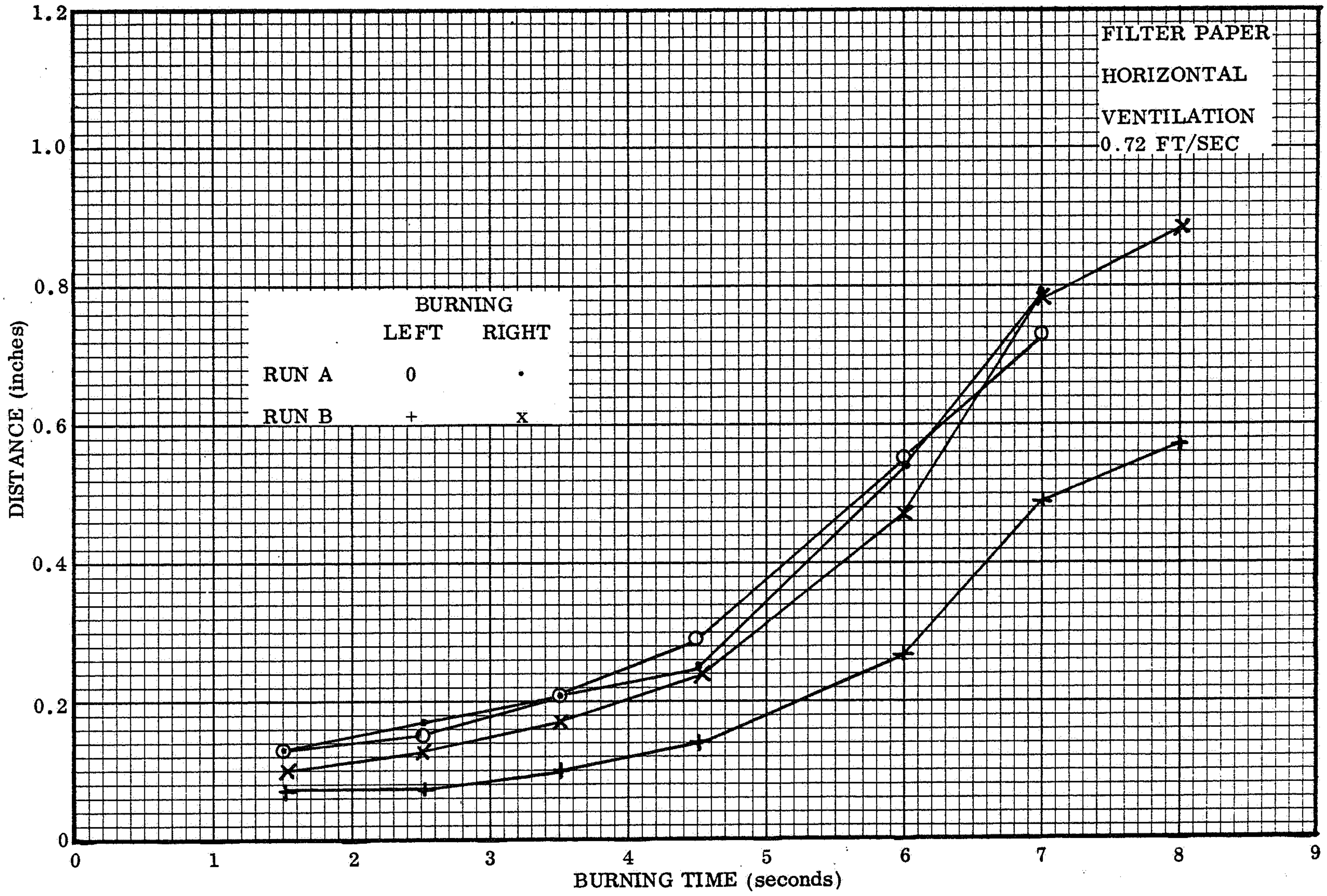


Figure 31.- Flame Propagation Test Data

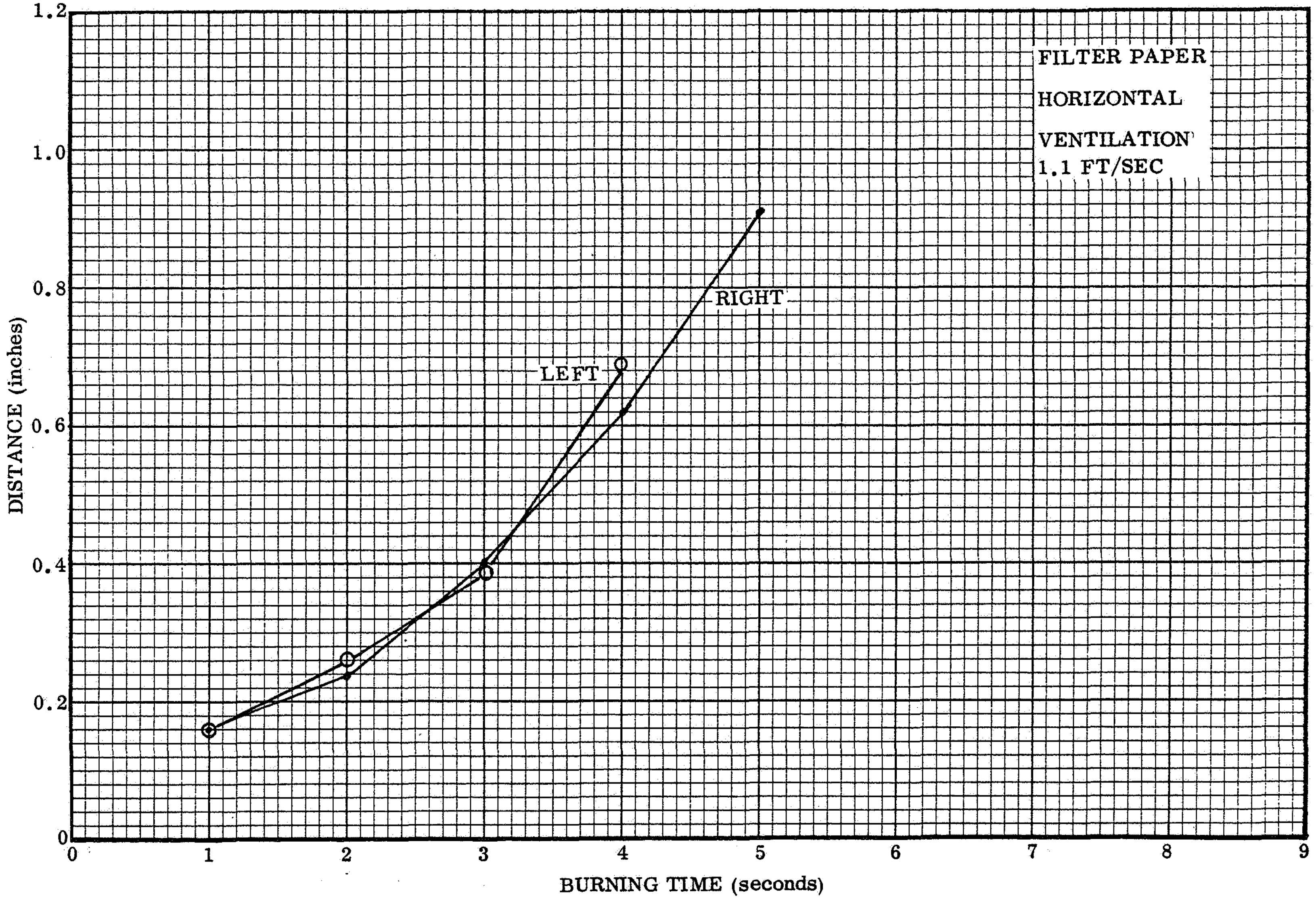


Figure 32.- Flame Propagation Test Data

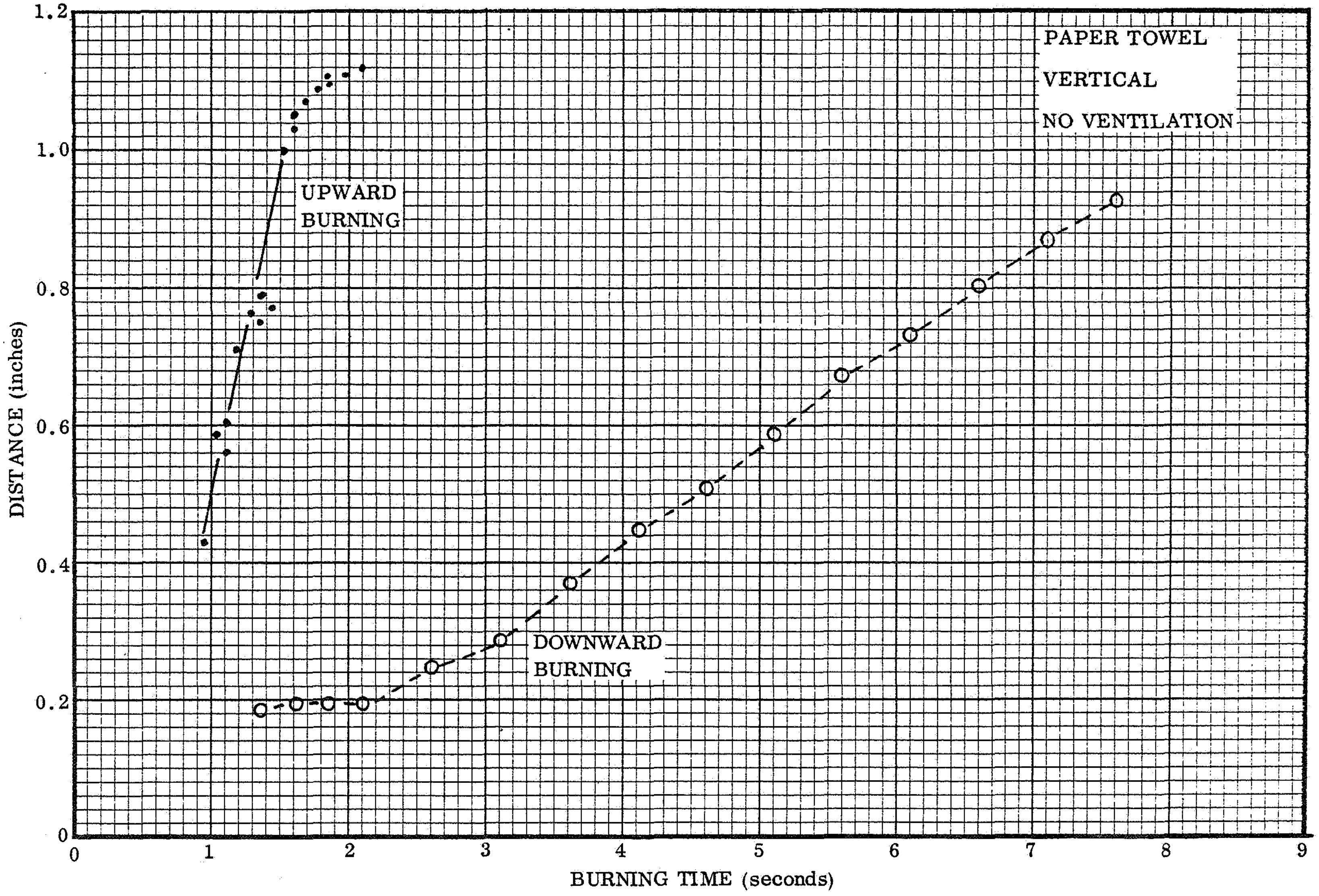


Figure 33.- Flame Propagation Test Data

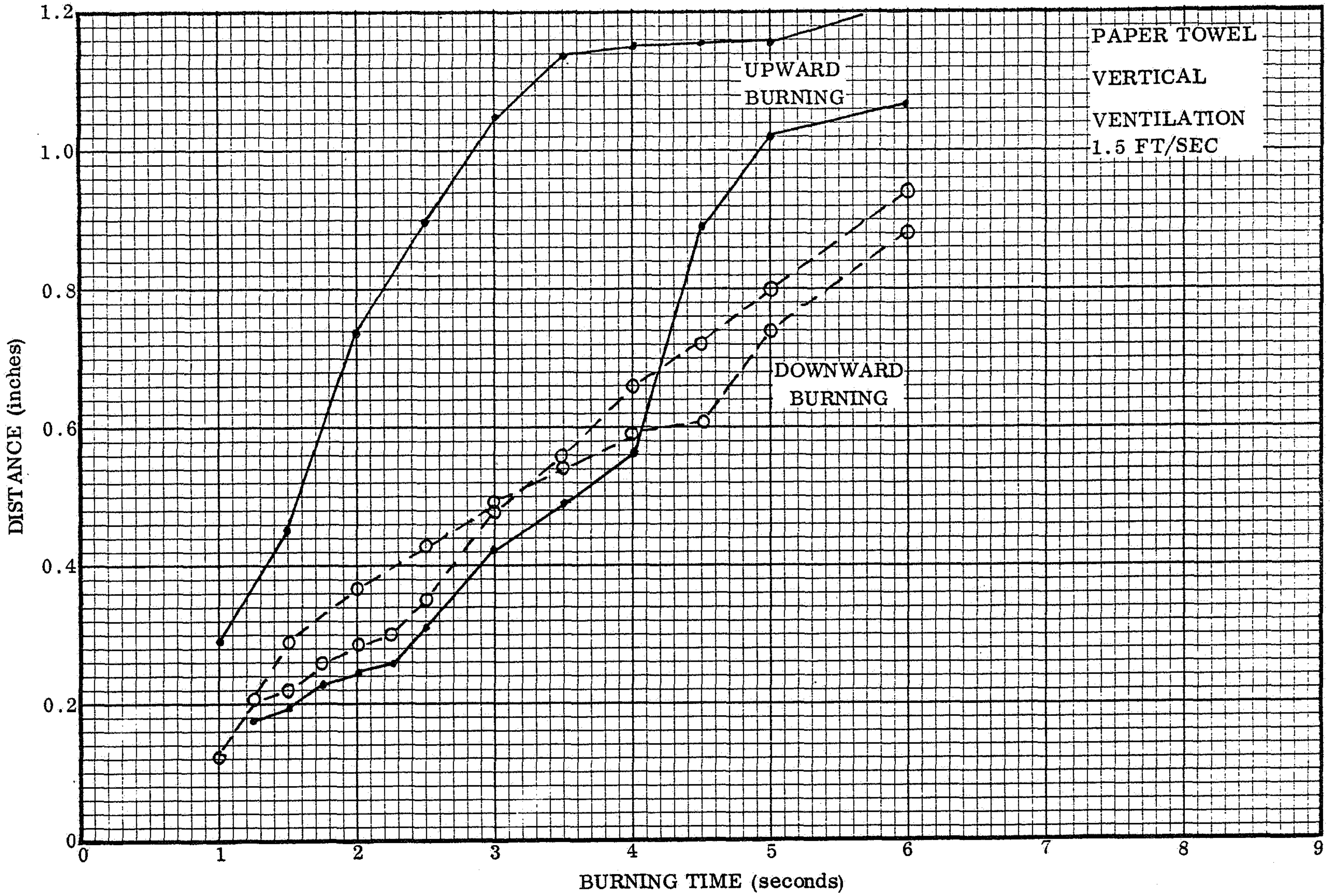


Figure 34.- Flame Propagation Test Data

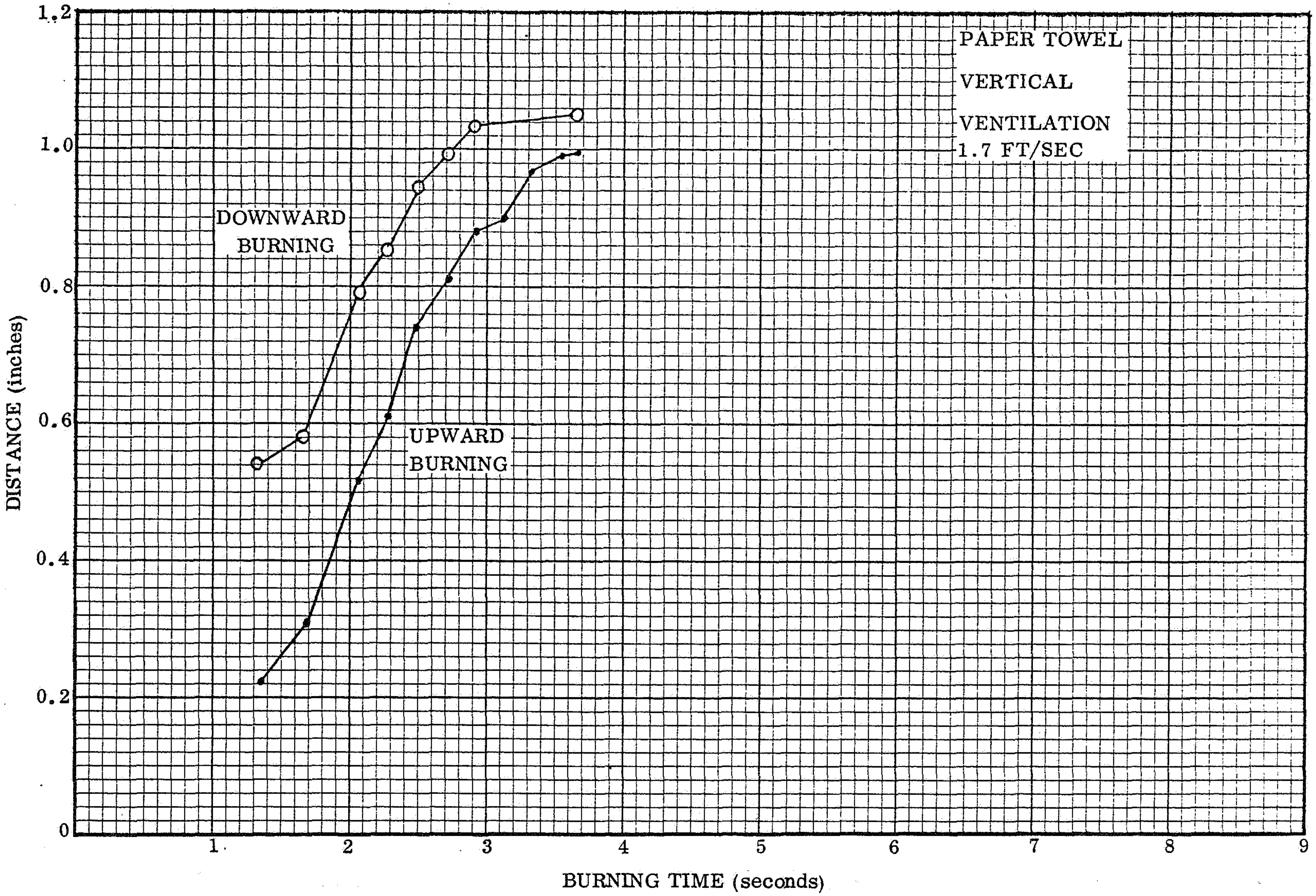


Figure 35.- Flame Propagation Test Data

Results.- Figures 25 through 35 present data from the motion pictures of burning paper specimens. They represent Flame Propagation measured by the movement of the first darkening of the paper apparently due to the heat of the advancing flame. The ventilation rates reported here and for the other tests are all nearly vertical downward and are the mean velocity in the unobstructed tunnel throat.

The masking tape burned approximately as fast as the paper, but it was not found useful for our purposes and no flame propagation rate is reported here. The visible surface darkened gradually during the burning with no apparent dark edge advancing across the tape.

The paper tag flame propagation is not reported graphically here because, although the tag burned progressively, it burned so slowly (about 20 secs/inch) as to be of little utility for drop testing.

Figure 36 presents the data from the burning of Number 50 mercerized cotton thread. In this case the advancing edge of the flame was used to trace the rate of propagation. The thread was approximately horizontal and the flame was shaped like a small egg that travelled along it.

The various solid fuels mentioned above were all ignited by electrical arcs generated by the arc ignitor system developed for the earlier work. The voltage on the capacitor bank and the series resistor value were in each case adjusted to a value near the minimum required for ignition. The thermal/mechanical effects of the arc were, however, appreciable, and they persisted for times ranging from about 1/4 second to over one second. This period is roughly represented on each chart by the time elapsed before any points appear.

The same arc source was used to ignite ethyl alcohol droplets suspended near the end of a small glass pipette, but the thermal disturbance generated was so appreciable and indeterminate that the results were felt to be of little value. Burning rates were therefore not computed. To correct this condition the arc ignitor was adjusted to create only sparks, but with this it was found that the alcohol droplets would rarely ignite from ambient air conditions. Medical grade ethyl ether droplets, however, ignited consistently with the spark and burned rapidly. The ether combustion rates are reported in figure 37. Here the length times the diameter of the droplet (see also figure 38) is plotted against time. This product (sq. mm.) starts from a maximum and decreases as the droplet burns away, but does not approach zero because the last remnant film of ether enclosed (was wrapped around) the finite approximately cylindrical neck of the suspending pipette.

Discussion.- The generally erratic characteristics of flame propagation are apparent from a review of the test results. Some organized effects are, however, discernible. The burning of the filter paper is more consistent and regular than the burning of the paper towels. A complete review of possible causes, such as variations in moisture content, arc carry-over effects, configuration differences, etc., is not considered necessary. It does seem pertinent, however, that the filter paper is carefully controlled during its manufacture and is intended to be burned.

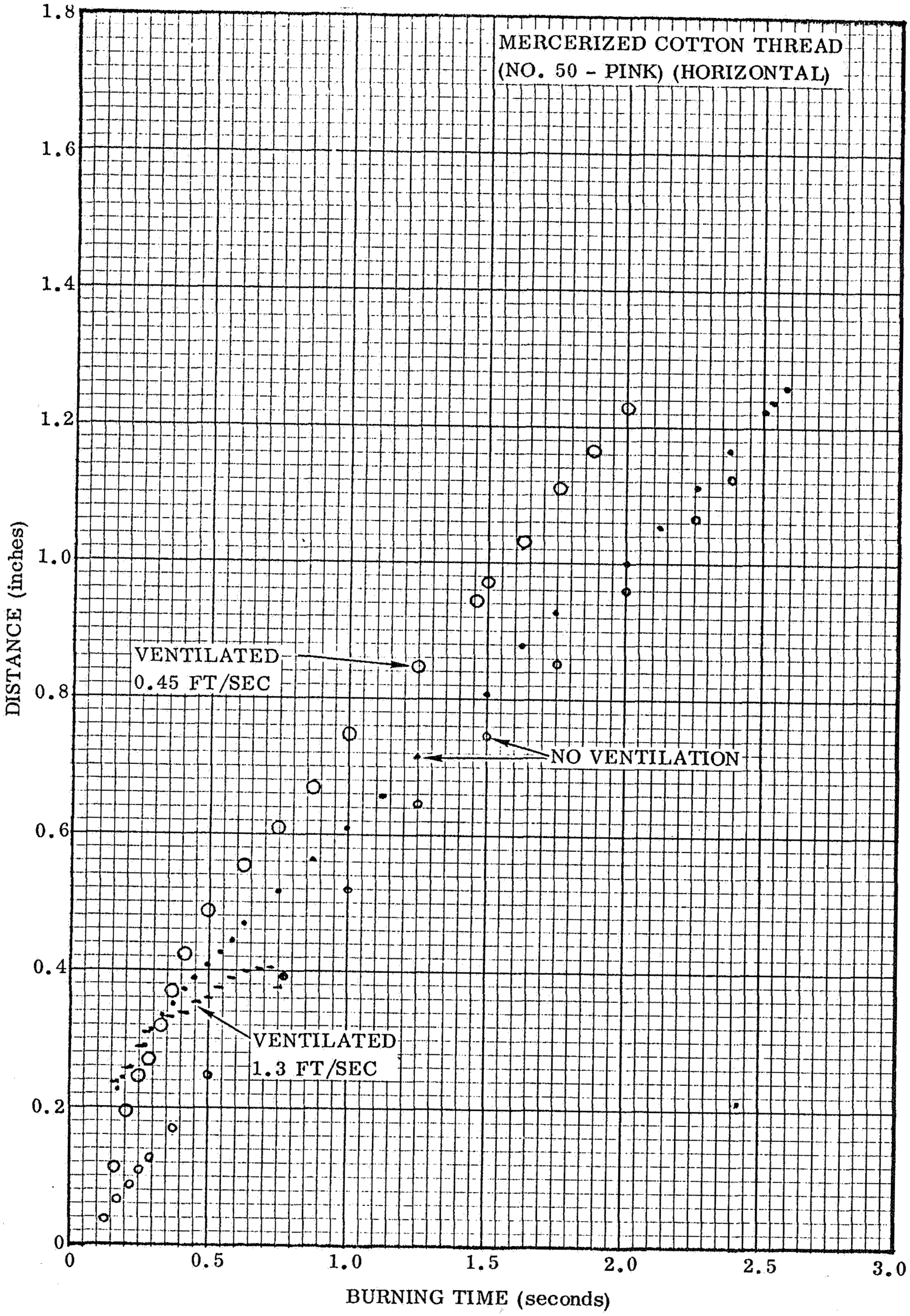


Figure 36.- Flame Propagation Test Data

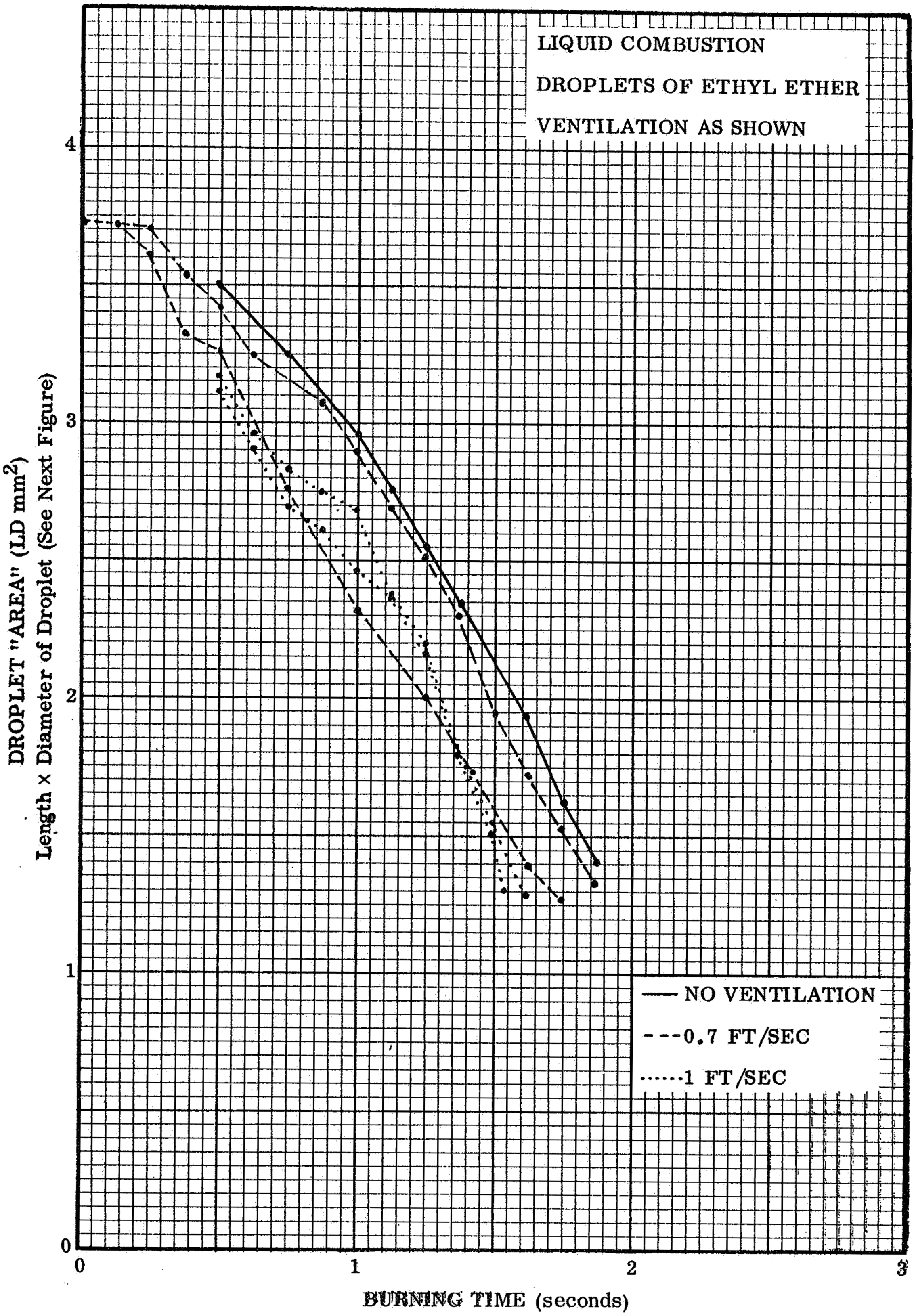


Figure 37.- Flame Propagation Test Data

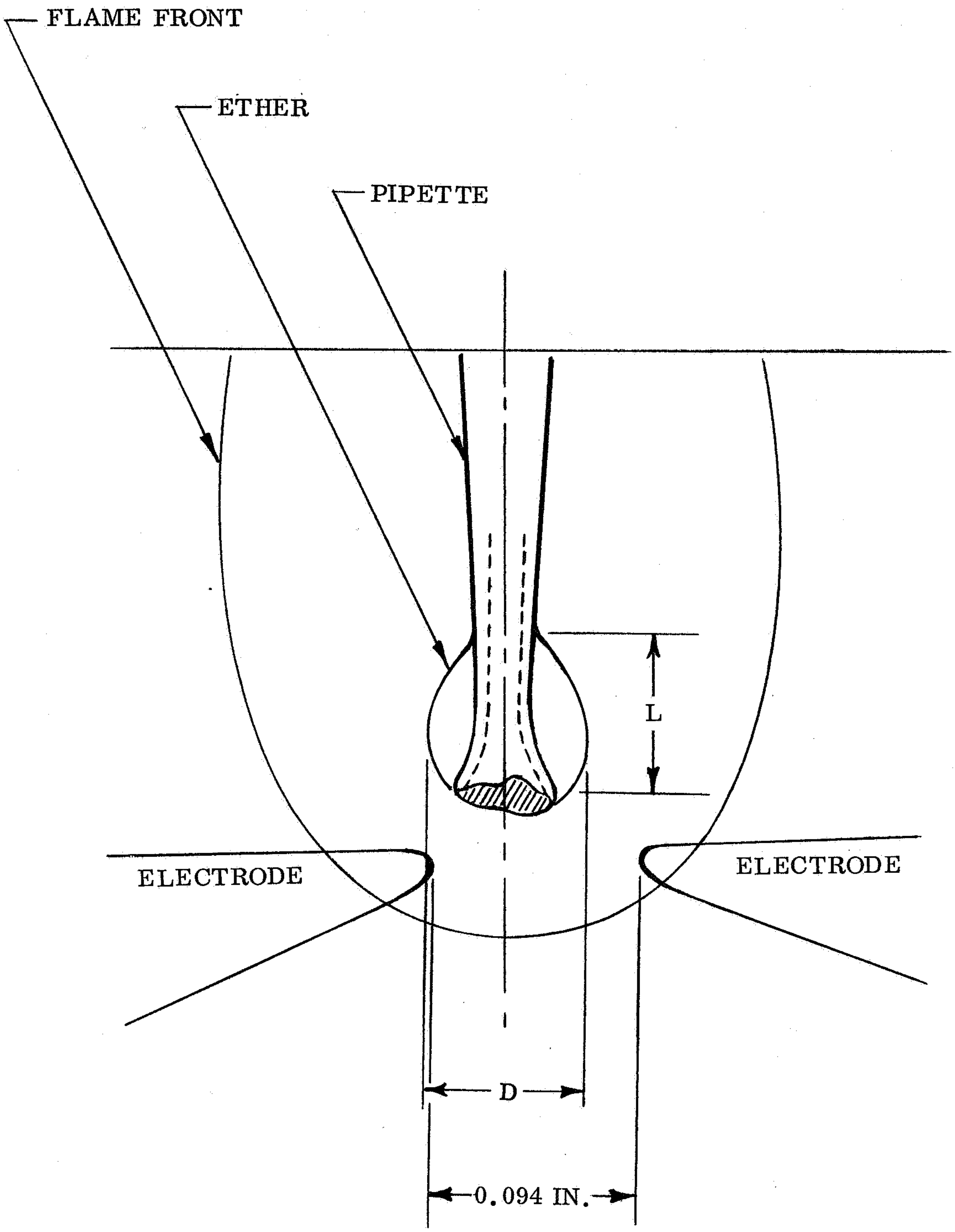


Figure 38.- Sketch of Burning Ether Droplet
(No Ventilation)

The upward burning rate of the vertical filter paper samples approximates 0.27 inches per second and is little affected by the rates of downward ventilation used in this experimentation. Without ventilation, and at least in the early stages, the flame seems to propagate downward on vertical specimens or sideways on horizontal specimens at about .02 inches per second. This rate is considerably increased by downward ventilation and may approximate what would be found in the zero-gravity/zero-ventilation condition.

Considering the roughly 1/4 inch per second upward burning rate of the filter paper as a standard for comparison, this burning rate is approximately equalled in the horizontal direction by a one foot per second downward ventilation, and in the downward direction by a 2-1/2 ft/per second downward ventilation. Also, for the rather erratic paper towel results, about 1/2 ft/per second ventilation appears to inhibit or slow down the upward burning quite appreciably. There seems for these specimens to be some rough equivalence between normal g-convection and a ventilation rate approximating 2 ft/per second. The equivalence is very approximate, but it indicates that for the drop tests the principal attention should be given to ventilation velocities below this figure, with less emphasis on stronger forced convection. In addition, the ventilated flame propagation downward appears to stabilize in 2 or 3 seconds, which implies the eventual need for at least a 4 second drop test facility.

The mercerized cotton thread promises to provide very useful experimental data on flame propagation in or near the zero-gravity/zero-ventilation condition. It ignites easily and burns rapidly and consistently, and the flame rate appears to stabilize so quickly that a 1-1/2 second drop test should provide useful information. The small egg-shaped flame, at times, became essentially symmetrical about the horizontal thread axis with the .45 ft/second downward ventilation. The 1.3 ft/second distorted the flame downward. The appearance of the flame and its relatively steady motion appear to indicate that diffusion can indeed support combustion and it is believed that drop tests of burning threads would provide very useful experimental evaluation or extension of the combustion analyses.

The combustion of liquid droplets has received considerable study in the past two decades, as was pointed out in the section on Flame Propagation in the ILSS. The data reported here in figure 37 is comparable with the "K" factor or evaporation constant mentioned in that section, but not directly. Repeating from that section:

$K = \frac{d}{dt}(D^2)$, and the results of certain experiments were reported there as K in mm^2/second. Figure 37 shows LD in mm^2. The slope of the LD versus time curves is about 1.4 mm^2 per second, which is nearly comparable to the data reported in the Test Methods Evaluation section, but a correction must be made for the characteristics of the liquid and possibly for heat loss to the support. The burning rate appears to stabilize quite quickly, and, although that appearance may be an accident of the geometry of the droplet support, it is believed that 2 seconds of free fall would suffice for the zero-g testing.

Test Methods Development.- Certain of the apparatus and test methods developed for the preliminary experimentation as useful guides for possible g-sensitivity testing, though the downward ventilation technique does not satisfactorily simulate low-g. Significant developmental features are described below.

The use of motion pictures for recording data is by no means new, but two features of its application here are worth mentioning. Data reduction from such pictures can be quite time consuming, but the reason is often that more information is available from them than was expected. On the other hand, the dimensional scale can be quite puzzling and some well known reference should be included in the picture whenever practicable.

Holders for the paper test specimens (figure 24) were satisfactory for this testing but are not recommended for the drop testing. A peripheral set of spring clips, each having one jaw rigidly mounted would provide more accurate and convenient support. Disturbance of the test environment by the sudden cancellation of gravity forces at capsule release must be minimized in such designs.

The liquid droplet support was only marginally satisfactory. The positioning of the droplet was indefinite, the actual droplet volume and area were problematical, and the heat transfer along the support may have been appreciable. Two glass or quartz fibers arranged like optical cross-hairs with the spark electrodes mounted in or near the third orthogonal axis should greatly reduce these difficulties.

The glass pipette support for the thread worked out very nicely. Gravity, however, deflects a cantilevered inch of the thread quite appreciably. The effect is, of course, greatly reduced with a shorter projection, or could be eliminated by vertical orientation.

The "Arc Ignitor" was a most useful general purpose tool, however only a part of this system would need to be included in a drop capsule for reduced gravity testing. A suitable capacitor bank, for example, could be mounted in the capsule and charged by a ground support system which would be disconnected before capsule release. The arc could then be initiated during the drop by a capsule-borne spark generator.

The ether droplets were ignited by a spark from the automotive ignition coil (top of T_3 in the schematic, figure 22). The 500 picofared condenser was disconnected to reduce the mechanical disturbance caused by the spark. Also, the more quiet discharge (without 500 pf condenser) provided more reliable ignition.

An extension of the arc ignitor was used for some exploratory testing on the inflammation of insulated wires. For this, the primary of a small welding transformer was connected directly across the capacitor bank through an automobile started switch. Wire specimens about an inch long were connected directly across the transformer secondary. The transformer characteristics are:

Primary	250 Turns No. 15
Secondary	5 Turns No. 2
Weight	5.8 Pounds

Operation of the system indicated that a larger transformer might provide appreciably more energy transfer, but the device used heated short wires quite effectively despite an overall efficiency that ranged down toward ten percent at high capacitor bank voltage (approximately 450.V). Number eighteen copper wire or smaller could be heated very quickly to any temperature up to and including "burnout". No measurements of heating rate were made, but visually it appeared instantaneous and calculations point to the millisecond region. This surge heating of a bare wire to incandescence produced a smooth temperature profile which appeared nearly uniform at first and cooled very quickly at the ends and somewhat more slowly in the middle. Overheated bare wire burned out in the middle. Overheated insulated wire usually burned out at the ends, but sometimes in the middle, especially if care was taken to make good connections and to minimize the bare end length. Over heated Teflon insulated wire usually did not rupture its insulation.

Combustion checks were run by holding a kitchen match flame to the insulation and operating the surge heater at a voltage level about ten percent below burnout.

Teflon insulated No. 22 did not burn.

Rubber base insulated No. 18 did burn and the fire consumed most of the insulation.

Wires from "shielded cable" (Material Number 11) burned and the fire consumed most of the insulation.

The useful bearing of this work on possible g-sensitivity testing is felt to be that, for insulated wire testing, means are available for controlled heating of the conductors so quickly as to occupy no significant fraction of the drop time.

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LIBRARY CARD ABSTRACT

CONVAIR DIVISION OF GENERAL DYANMICS, FINAL TECHNICAL REPORT, STUDY OF ZERO GRAVITY CAPABILITIES OF LIFE SUPPORT SYSTEM COMPONENTS AND PROCESSES, by J. C. Ballinger, G. B. Wood, and J. R. Burnett, February 1968.

This study was conducted in order to define the zero gravity capabilities of the life support components and processes contained in the Langley Research Center Integrated Life Support System (ILSS).

Primary emphasis was placed on three major tasks:

(1) The identification and analysis of gravity-sensitivities inherent in the performance of the ILSS components and processes;

(2) The investigation of methods for experimentally evaluating those critical items for which zero gravity performance could not be adequately determined by analytical techniques.

(3) The formulation of generalized criteria for assessing the gravity-sensitivity of alternate or advanced life support system processes as well as those originally incorporated in the ILSS.