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PROGRESS REPORT ON
HIGH ALTITUDE PLASTIC BALLOONS
CONTRACT NONR-710 (01)
December 3, 1953 to November 10, 1955
VOLUME XIII
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PROGRESS REPORT ON RESEARCH AND DEVELOPMENT IN THE FIELD OF HIGH ALTITUDE PLASTIC BALLOONS

CONDUCTED UNDER
CONTRACT NONR-710(01), NR 211 002
FOR PERIOD DECEMBER 3, 1953 to NOVEMBER 10, 1955
WITH THE
OFFICE OF NAVAL RESEARCH

AND SPONSORED JOINTLY
BY THE ARMY, NAVY, AND AIR FORCE

PREPARED BY THE
DEPARTMENT OF PHYSICS
UNIVERSITY OF MINNESOTA
MINNEAPOLIS 14, MINNESOTA

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Section I. SHROUD THEORY: THE BUOYANCY POTENTIAL OF SHROUDED BALLOONS

Introduction

There are several ways in which a balloon system can be given altitude stability. Perhaps the most straight-forward is to provide a ballast dropping device set to drop ballast whenever the balloon descends to a certain preset "floor". This system has the disadvantage, however, that the ceiling of the system is raised every time ballast is dropped because of the permanent loss of gross of the system. Moreover, there is the possibility that the controls will "overballast" and send the balloon back up to ceiling where it valves gas, unnecessarily increasing the ultimate ballast need. For very long duration flights the constant expenditure of ballast may require that the original ballast load dwarf the payload by comparison.

To some extent, a bare balloon may get stability from its buoyancy potential characteristic. (The concept of buoyancy potential is discussed below.) For bare balloons the stability, if any, from this source is usually small. On the other hand, the buoyancy potential characteristics of shrouded balloons sometimes makes it possible to gain stability even against losses of lift as great as those that occur at sunset.

A "shroud" is simply a canopy over a balloon. It usually has a weighted hem which is allowed to hang open. The balloon inside valves its lifting gas in the usual way (through a duct passing outside of the canopy). The volume between the shroud and the balloon fills with air and this air contributes lift according to its pressure, superheat and volume.

The central problem of shroud theory is to calculate the lift of a shrouded balloon system at various pressure altitudes and superheats, and to construct a buoyancy potential diagram on which the flight characteristics of a shrouded balloon system can be summarized. This will be done after a general discussion of the concept of buoyancy potential.

Buoyancy Potential

Buoyancy potential is simply a way of expressing the lift of a balloon system. It is defined in such a way that the change in buoyancy potential is equal to the change in lift of the system. This leaves the buoyancy potential with an undetermined zero, just as in the case of other potentials. A convenient zero is chosen arbitrarily.

The lift of a balloon system is equal to the weight of air displaced minus all the dead weight including the weights of all enclosed gases. In the case of a bare balloon, the weights can be expressed in terms of the weight of lifting gas in the balloon, M, which is constant. Thus the weight of displaced air is $M\sigma \frac{T+\theta}{T}$, where σ is the ratio of the molecular weight of atmospheric air to the molecular weight of the lifting gas, T is the absolute ambient air temperature, and θ is the balloon gas superheat. The lift of a bare balloon will be $M\sigma \frac{T+\theta}{T} - M - W$, where W is the dead weight of the balloon and payload. Dropping the constant terms, one can write the buoyancy potential, P, as

$$P = M\sigma \frac{\theta}{T} \qquad (1)$$

so that, indeed, the change of lift equals the change in buoyancy potential. (The zero of buoyancy potential has been taken to correspond to zero superheat.)

Since both M and σ are constant in the above example, it is clear that a bare balloon can change its buoyancy potential only through changes in superheat. If the superheat at a high altitude is less than it is at some lower altitude, the balloon will be stable against descent. However, the superheat during the daytime usually has a value which is greater than any night-time superheat anywhere down through the atmosphere, which means that there usually is no chance for a bare balloon to stay up through sunset. A typical superheat situation is shown in Figure 1, and the buoyancy potential of bare balloons is discussed further below in the section on buoyancy potential diagrams.

Equation (1) would not apply if the balloon were to take in air when it descends, since $M\sigma$ would then be effectively increased and the buoyancy potential would be increased even at the same superheat. In the case of a shrouded balloon, this effect is capitalized upon to the greatest degree by using a canopy which can take in large amounts of air. The derivation of the buoyancy potential for shrouded balloons can be expected to be somewhat more complicated since the system contains both air and helium, and the lift of the air depends on the pressure as well as on the superheat.

Buoyancy Potential for Shrouded Balloons

Again restricting the discussion to cases where no helium is valved, the mass of gas in the balloon itself remains constant. The weight, A, of air under the shroud will not in general,however, be constant. Assuming the superheat for the helium in the balloon and air under the shroud to be equal, one can write for the total weight, G_t, of displaced air

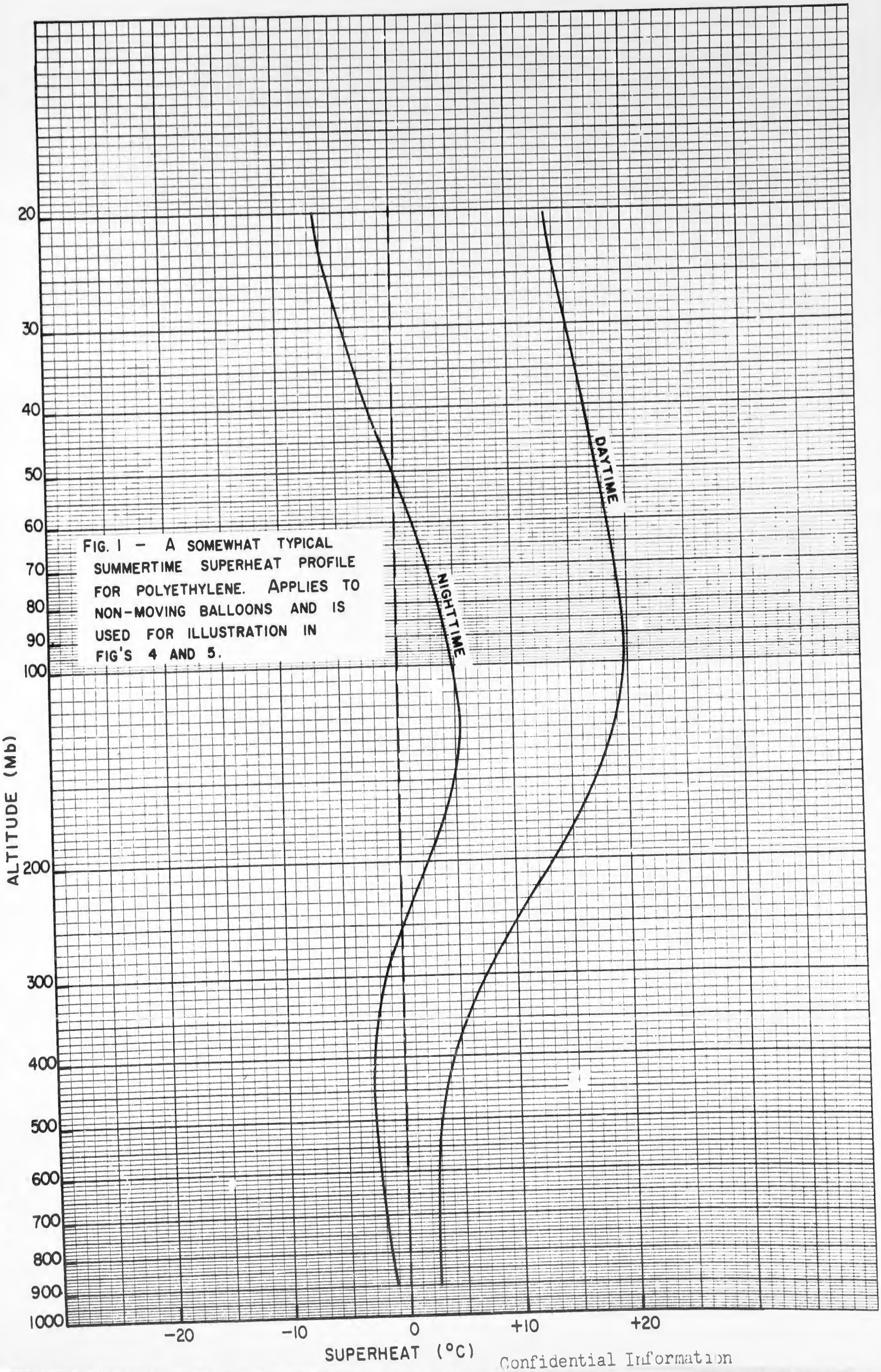
FIG. 1 — A SOMEWHAT TYPICAL SUMMERTIME SUPERHEAT PROFILE FOR POLYETHYLENE. APPLIES TO NON-MOVING BALLOONS AND IS USED FOR ILLUSTRATION IN FIG'S 4 AND 5.
DAYTIME
NIGHTTIME
ALTITUDE (Mb)
20
30
40
50
60
70
80
90
100
200
300
400
500
600
700
800
900
1000
-20
-10
0
+10
+20
SUPERHEAT (°C)

$$G_t = M\sigma \frac{T+\theta}{T} + A\frac{T+\theta}{T}$$

Solving this expression for the weight of air under the shroud, one can write the total lift of the system as

$$G_t - M - A - W = G_t \frac{\theta}{T+\theta} + M(\sigma - 1) - W$$

Again dropping the constant terms one has for the buoyancy potential of shrouded balloons:

$$P = G_t \frac{\theta}{T} \qquad (2)$$

This is a remarkably simple result, considering that the lift of the helium balloon is altered by virtue of floating in the superheated air under the shroud, and that the different size of the helium balloon at different altitudes alters the relative volume available for air under the shroud.

Shroud Volumes

The derivation of the buoyancy potential for shrouded balloons is by no means complete with the above expression (Equation (2)), since the total amount of air displaced remains to be determined. The weight of air displaced, G_t, is of course the product of the outside air density times the total volume of the shroud. The volume of the shroud will in general depend on the size of the helium-filled balloon and on the lifting power of the air under the shroud. The lifting power of the air is in turn proportional to the product of the air pressure and superheat.

Figure 2 shows the balloon and shroud when the system is at ceiling. (In the example shown, the balloon and shroud each have 120-ft gore lengths,

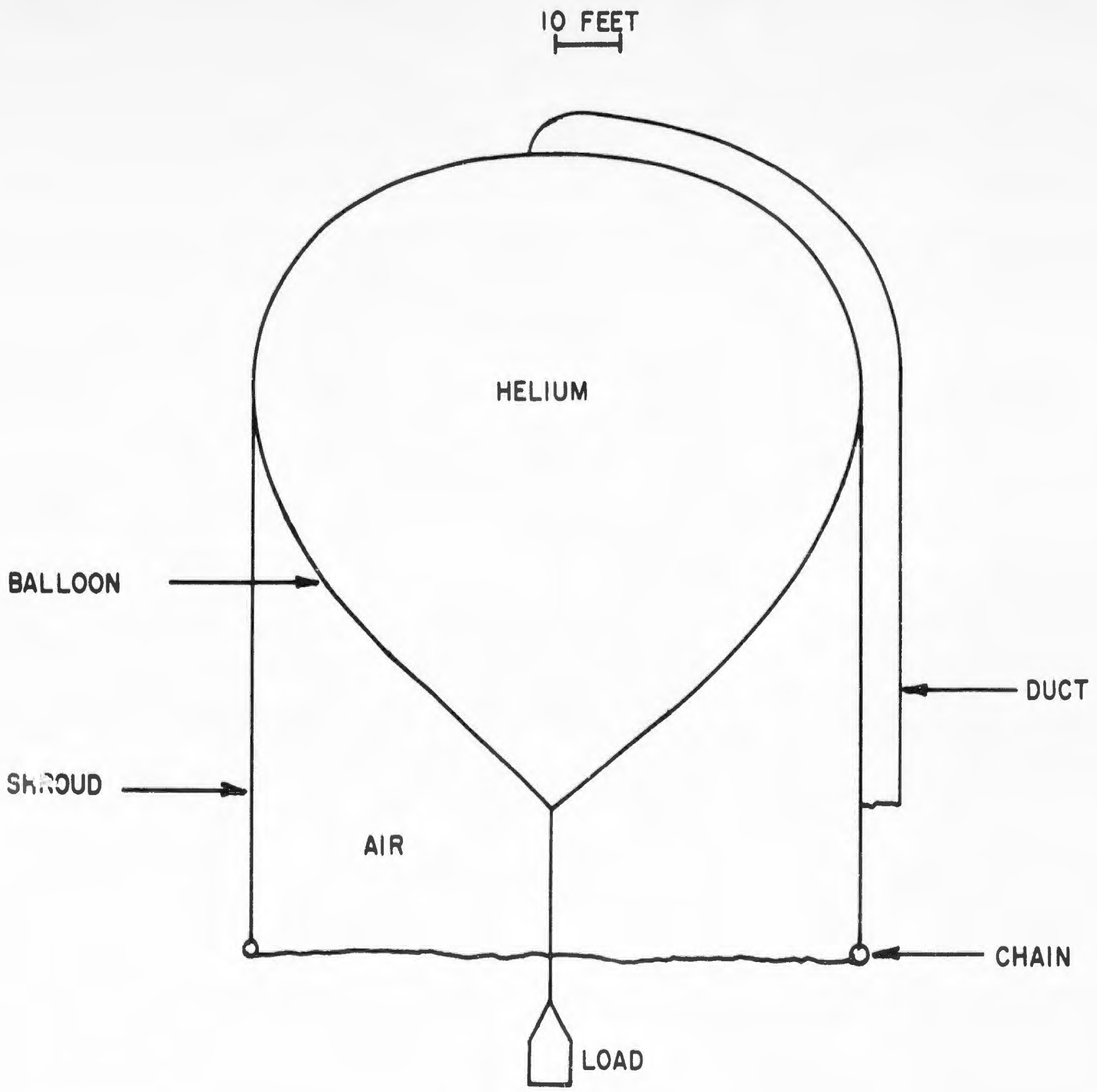

FIG. 2 - SHROUD AND BALLOON SHAPE AT CEILING ALTITUDE. GORE LENGTH IS 120 FEET

and the shroud is a cylinder made with the same diameter as the full balloon.) The volume of air under the shroud is 0.9 times the volume of the helium balloon. In this case the total volume of the system is independent of the air lift, i.e., independent of the value of $p\theta$ (p = millibars pressure altitude; θ = ^{o}C superheat).

Figure 3 shows the shape of the outside shroud when the balloon is very small and for the case where $p\theta$ has the value 400 mb-^{o}C. The balloon and shroud are each made of one-mil polyethylene, and the chain in the shroud hem weighs 20 pounds. It can be seen that the total volume of the shroud is very nearly the same as for the case with the full balloon. For $p\theta \ll 400$ mb-^{o}C, the volume of the shroud shrinks and begins to depend on the size of the helium balloon, i. e., on the pressure altitude. For $p\theta > 400$ mb-^{o}C, however, the volume of the shroud remains relatively constant. Actually, a large range of $p\theta$ values need not be considered since it will be shown that the system tends to move in such a way as to keep the same value of $p\theta$, a value which is established at ceiling, and which in a typical case might be 25 mb x 16^{o}C = 400 mb - ^{o}C.

The shroud shapes were calculated by forward integration of the appropriate differential equations. These differential equations are obtained by considering the forces of gravity, pressure, and tension acting on the fabric of the shroud. In making the integration, one must choose the proper initial conditions to insure that the solution represents a shroud of the proper gore length, that is, one must solve an eigenvalue problem for each value of $p\theta$.

The fact that the volume of the shroud is independent of $p\theta$ for the range of $p\theta$ of interest comes about because a $p\theta$ of several hundred

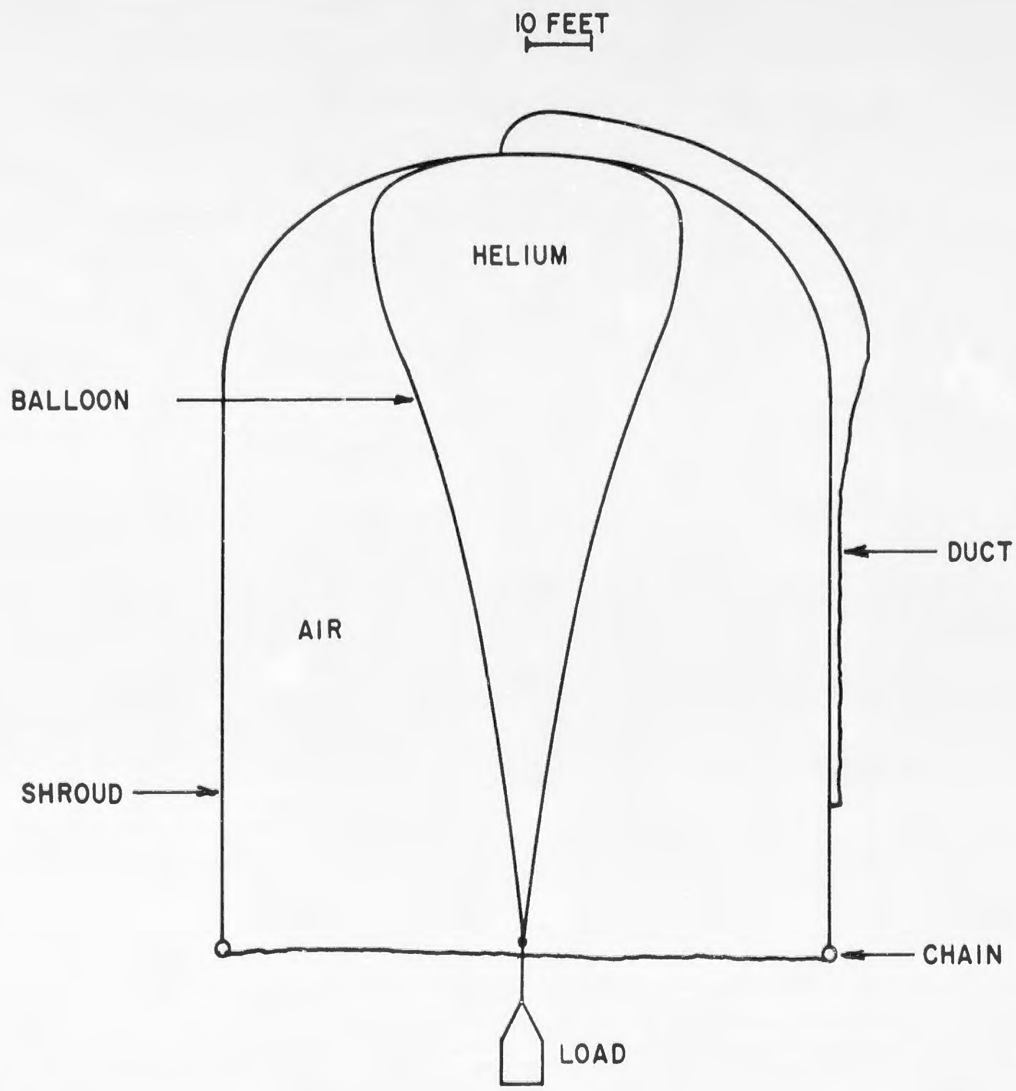

FIG. 3 – SHROUD AND BALLOON FOR BELOW CEILING ALTITUDE. SHROUD SHAPE CALCULATED FOR $\rho\theta$ HAVING VALUE 400 Mb.–°C. SHROUD AND BALLOON ONE –MIL POLYETHYLENE, 120 FOOT GORE LENGTH AND CHAIN WEIGHT 20 POUNDS

mb-°C is sufficient to push out on the shroud so that a large part of it becomes merely a straight cylinder. In other words, the $p\theta$ values of interest are sufficient to "fill out" the shroud to its full volume.

Buoyancy Potential Diagrams

In general, the buoyancy potential will be a function of both p and θ. If θ changes, a system will move in such a way that the net lift (and hence buoyancy potential) will not change. This will require that the system move to some new pressure altitude to regain the buoyancy potential at the new superheat. Of course, a ballast drop or loss of lifting gas would require that the system adjust itself to a new value of buoyancy potential.

As a first illustration, take the case of a bare helium-filled balloon. The buoyancy potential diagram is shown in Figure 4. As expected the buoyancy potential depends only on the superheat and is independent of the pressure altitude.

[Also plotted on the diagram, as dotted lines, are what might be typical results of a measurement of the superheat of the balloon gas at each altitude. These lines are taken from the "superheat-profile" shown in Figure 1. The "superheat profile," consisting of a "day" line and a "night" line, is of course a property of the balloon material and of the radiation conditions in the atmosphere, and it would be expected to vary somewhat from day to day, depending on atmospheric conditions. In particular, the night-time curve might be expected to show a seasonal variation, with positive night-time superheats appearing frequently only in the summertime.

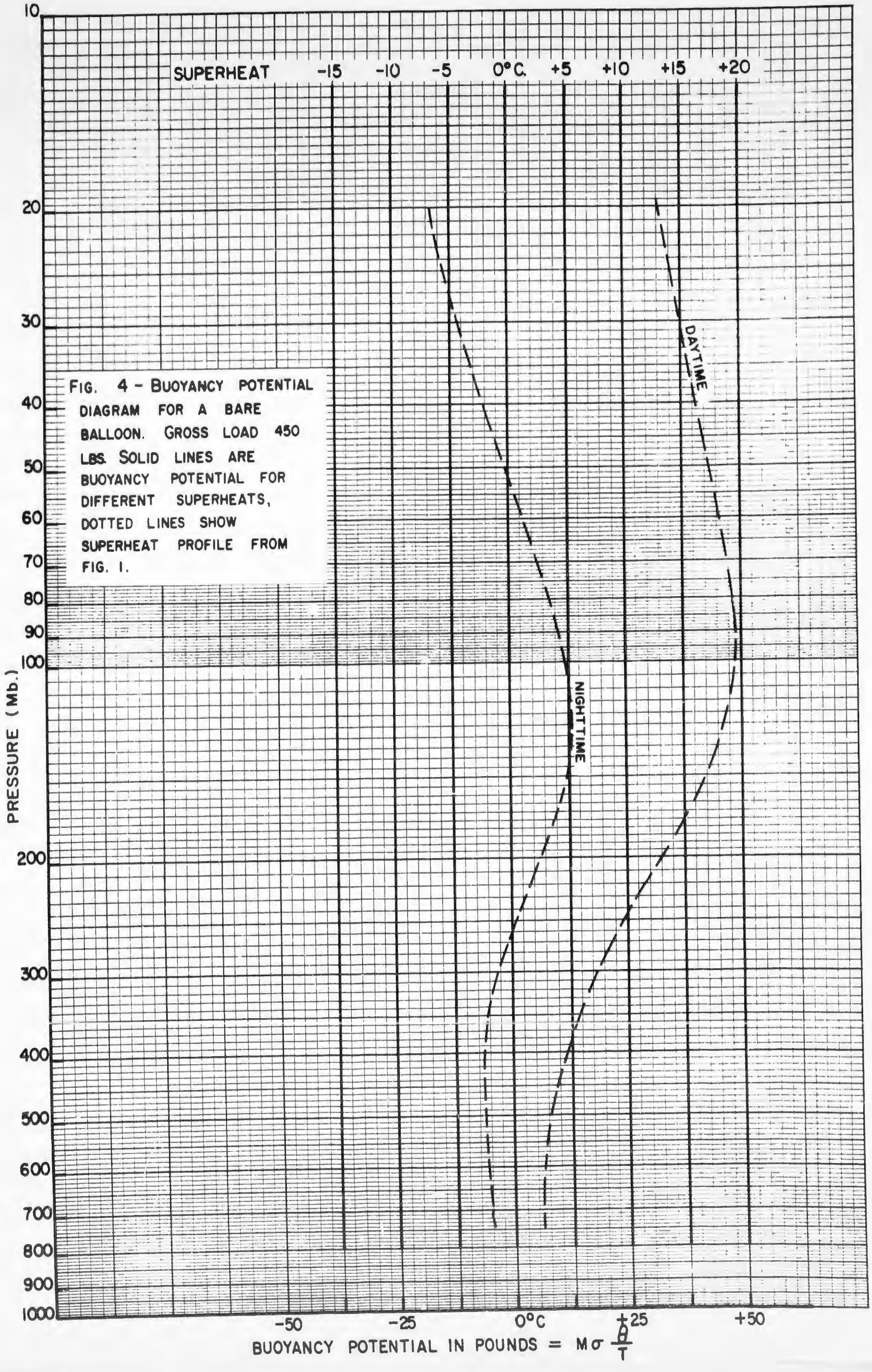

FIG. 4 - BUOYANCY POTENTIAL DIAGRAM FOR A BARE BALLOON. GROSS LOAD 450 LBS. SOLID LINES ARE BUOYANCY POTENTIAL FOR DIFFERENT SUPERHEATS, DOTTED LINES SHOW SUPERHEAT PROFILE FROM FIG. 1.

The superheat profile (which will be the same for all systems made of the same balloon material and operating in the same atmosphere) should be distinguished from the buoyancy potential diagram which is a property of the particular balloon system and is independent of atmospheric conditions. The superheat profile is plotted on the buoyancy potential diagram only to show how a system will act under some particular atmospheric condition.]

It is clear from the diagram that, while the bare balloon at ceiling at night can gain buoyancy potential (lift) by descending, it can never gain enough to get back the lift lost at sunset (i.e., lost in going from the day profile to the night profile). Actually, apart from the effect of aerodynamic drag, the balloon will never change its buoyancy potential. Instead, at sunset for instance, the balloon will merely descend at a rate sufficient to develop a "thermal drag" superheat large enough to restore the buoyancy potential to its original value. The superheat profiles that are plotted apply only to the non-moving situations.

The buoyancy potential diagram for a shrouded balloon is quite different from that for a bare balloon. Since the volume of the system turns out to be always constant, G_t is proportional to p (the pressure altitude), and the buoyancy potential ($P = G_t \frac{\theta}{T}$) will be then just proportional to the product $p\theta$. The buoyancy potential diagram for a typical shrouded system is shown in Figure 5. The dotted lines represent the same superheat profile as before, and it is clear that the shrouded balloon can easily go from the day curve to the night curve by a small descent at constant buoyancy potential.

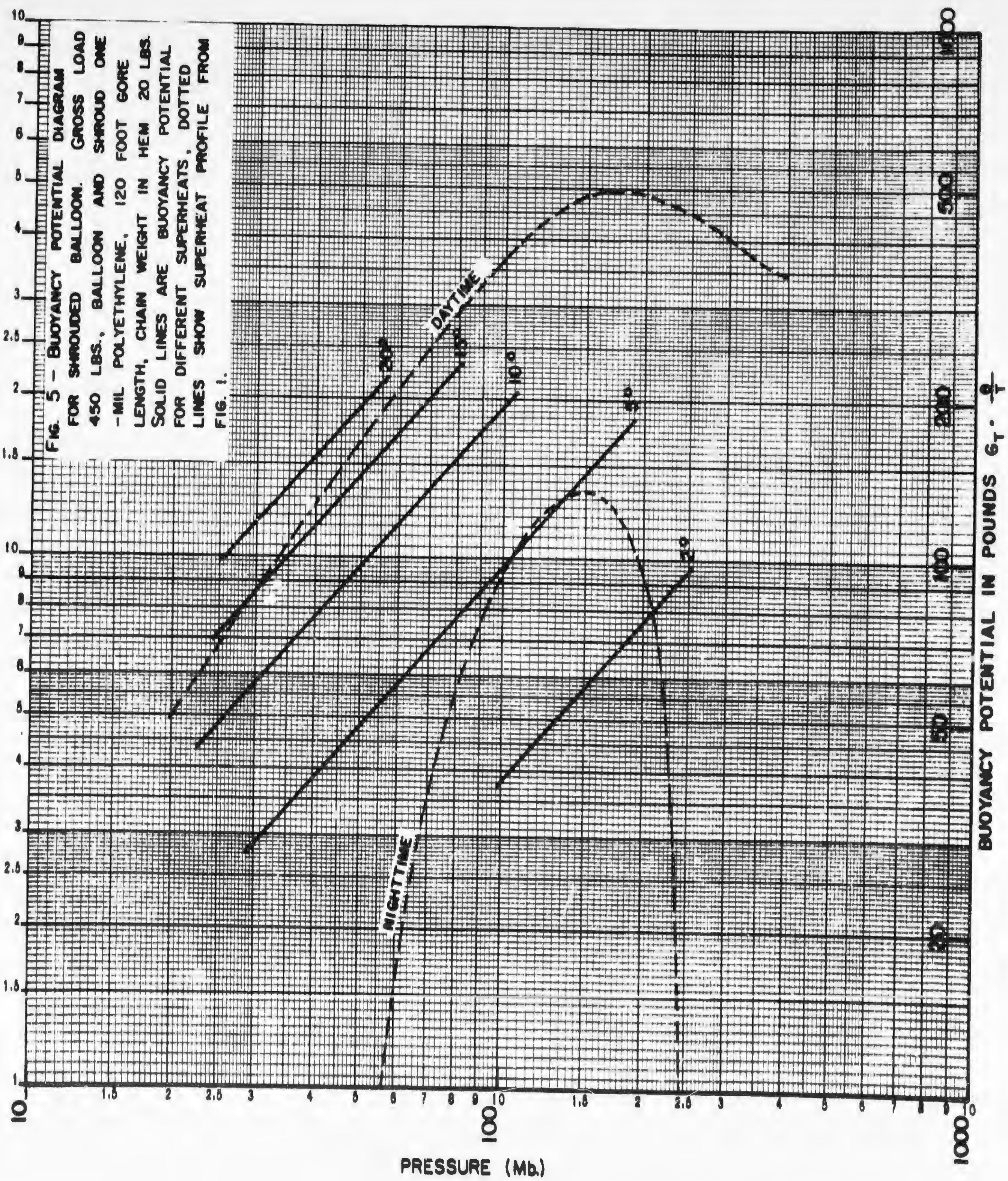

Fig. 5 - Buoyancy potential diagram for shrouded balloon. Gross load 450 lbs., balloon and shroud one-mil polyethylene, 120 foot gore length, chain weight in hem 20 lbs. Solid lines are buoyancy potential for different superheats, dotted lines show superheat profile from Fig. 1.

Only a small range of buoyancy potential has been covered by the solid lines on the plot. The reason for this is that the simple straight line plot holds only for $p\theta$'s of a certain size, namely those large enough to fill out the shroud. The range covered is adequate, however, since the original buoyancy potential is based on the lift that the balloon had when it last valved, i.e., at ceiling during the day. Ballast drops, of course, will change the buoyancy potential, but large drops are somewhat compensated for by the fact that the system will rise to ceiling and valve away the excess lift.

The superheat profiles plotted on the buoyancy potential diagram are intended merely to illustrate a typical situation. The profile will vary from day to day, as has been said, and there will be some nights on which the superheat profile is not positive at any altitude (under this condition the shroud would have nothing to contribute in the way of static stability). The superheat profiles apply, however, only to non-moving situations, and it is possible that even on nights with an all-negative superheat profile the descent of the balloon might cause enough thermal-drag warming of the air under the shroud to fill it out, thus contributing a very large drag force to the system. If the descent rate could be slowed enough, of course, the balloon would still be in the air at sunrise.

With respect to a moving balloon system, it may be said that the system moves at sunset or sunrise along a line of equal buoyancy potential from the day curve to the night curve, or vice versa. For a bare balloon system, this means the balloon tends to keep the same value of the superheat, θ, while for a shrouded balloon system it is the value of the $p\theta$ that tends to stay constant. Thus a bare balloon will stay aloft after sunset at an altitude (if there is one) where the night-time superheat is equal to the daytime superheat at ceiling. A shrouded balloon system will descent at sunset to the level (if any) where the value of $p\theta$ is equal to that during the day at ceiling.

A ballast drop on either system will lower the buoyancy potential along which the system moves.

Response to Ballast Drop

The response of a balloon system to the dropping of an increment of ballast is a convenient measure of the stability of a system. The responsiveness can be expressed as the fractional change in pressure altitude per unit weight of ballast dropped. The less the responsiveness, the greater the stability.

The ballast responsiveness of a bare balloon floating below its ceiling altitude will depend on the superheat profile of the atmosphere. In most cases, however, a small ballast drop is sufficient to send the balloon all the way back up to ceiling, and the system has little stability. This can be seen on the buoyancy potential plot in Figure 4 where the balloon must rise along a superheat profile until it can lose an amount of buoyancy potential equal to the weight of ballast drop. Since these lines are nearly vertical, the stability is very small.

In the case of the shrouded balloon, the lines representing the same superheat profile condition now have a very definite slope. In fact, if the superheat profile is very nearly along a line of constant superheat, the ballast responsiveness will be

$$\frac{\Delta p/p}{\Delta B} = \frac{1}{P} \qquad (3)$$

where $\Delta p/p$ is the fractional change in pressure altitude as a result of a ballast drop, ΔB, and P is the buoyancy potential as read from the diagram ($P = G_t \frac{\theta}{T}$).

During the day, the system is at a higher altitude than at night, but since it is usually not necessary to drop sunset ballast on shroud flights, the system will maintain a constant value of buoyancy potential. Equation (3) therefore shows that shrouded systems have the same ballast responsiveness, day or night. Of course, it is possible that the day and night superheat profiles will not have exactly the slope, and Equation (3) would not strictly hold. Another limitation to the use of Equation (3) is that the air under the shroud may not have the same superheat from top to bottom of the shroud. If, for instance, the air near the bottom of the shroud had less superheat than the rest of the air in the shroud, the system would have to rise further to valve heated-air lift equal to the ballast drop, with the result that the ballast responsiveness would be greater than in the case of a constant superheat distribution within the shroud.

Discussion and Conclusions

The important conclusion to be drawn from the calculation of shroud shapes and volumes is that even with modest superheats a shroud remains full of air even though the inner balloon will be small at the lower altitudes. As can be seen from the buoyancy potential diagrams, this makes the flight characteristics of a shrouded balloon strikingly different from those of a bare balloon. A shrouded balloon without ballast dropping provision may be thought of as having a "day" altitude and a "night" altitude. One would expect a fairly definite day altitude with some variability in the night altitude, particularly in the winter when there may be no night altitude. For purposes of prolonged flight, it might be necessary to provide a ballast drop for those nights on which the night altitude is unacceptably low or missing. Even then, the saving on ballast (and the reduction in the overall gross load of the system) may be quite substantial, since each night that the system stays up without ballast represents a permanent ballast saving.

ADDENDUM TO "SHROUD THEORY"

In the text, a particular shroud was used as an example, and it was found that this shroud would be fully open when $p\theta$ is larger than a certain value $(p\theta)_{min} = 400$ mb°C.

The same analysis applies to any shroud, that is, a shroud with a different gore length and different weight. In scaling up or down the shroud in the text, one would of course find that the minimum $p\theta$ required to completely fill out the shroud would have a different value. It happens that this value, $(p\theta)_{min}$, is a function only of W, the weight of the shroud itself, and $s\lambda$, the gore length of the shroud, in the following way:

In computing the shroud shapes and volumes, it is found that the only significant parameter is the dimensionless number

$$\frac{\beta s\lambda^3}{W}$$

where β is the lift per unit volume of the air under the shroud. The value of β is proportional to $p\theta$ and thus the shape of a shroud is completely determined by the number

$$p\theta \frac{s\lambda^3}{W}$$

The value of $(p\theta)_{min}$ for any shroud will therefore be

$$(p\theta)_{min} = K \frac{W}{s\lambda^3}$$

where K is some constant that can be determined from the example in the text where $(p\theta)_{min} = 400$ mb°C, $s\lambda = 120$ feet, and W = 150 pounds. Putting in these values, one finds that any shroud will be completely filled out when $p\theta$ is such that

$$p\theta > (p\theta)_{min} = 4{,}600{,}000 \frac{W}{s_\lambda^3} \text{ mb}^\circ\text{C}$$

where W is the weight in pounds of the shroud itself and s_λ is the gore length in feet.

To be similar to the example in the text, the total chain weight in the hem should be sealed up according to the weight of the shroud, giving

Total chain weight = 0.134 W.

The actual value of chain weight used is not critical to the computation of volumes and will not greatly alter the value of $(p\theta)_{min}$.

In these considerations it has been assumed that the shroud cylinder has the same gore length of the balloon and is just large enough in circumference to cover the full balloon at the equator. This means that the shroud should have a circumference of $\frac{2\pi}{3} s_\lambda$ for a gore length of s_λ. The volume of the balloon at ceiling will be $0.125\, s_\lambda^3$.

As an illustration, consider a 1/4-mil mylar balloon and shroud with an 80-ft gore length. The weight of the shroud will be 26 pounds, the chain should weigh about 3.5 pounds, and the shroud will be completely full when

$$p\theta > (p\theta)_{min} = 240 \text{ mb}^\circ\text{C}.$$

The mylar balloon itself will weigh 26 pounds and have a volume of 61,500 cubic feet. With a payload of 50 pounds, this system would have a ceiling 20 mb pressure altitude. The buoyancy potential diagram for such a system is shown on Figure 6. Such a diagram, as before, applies only to situations

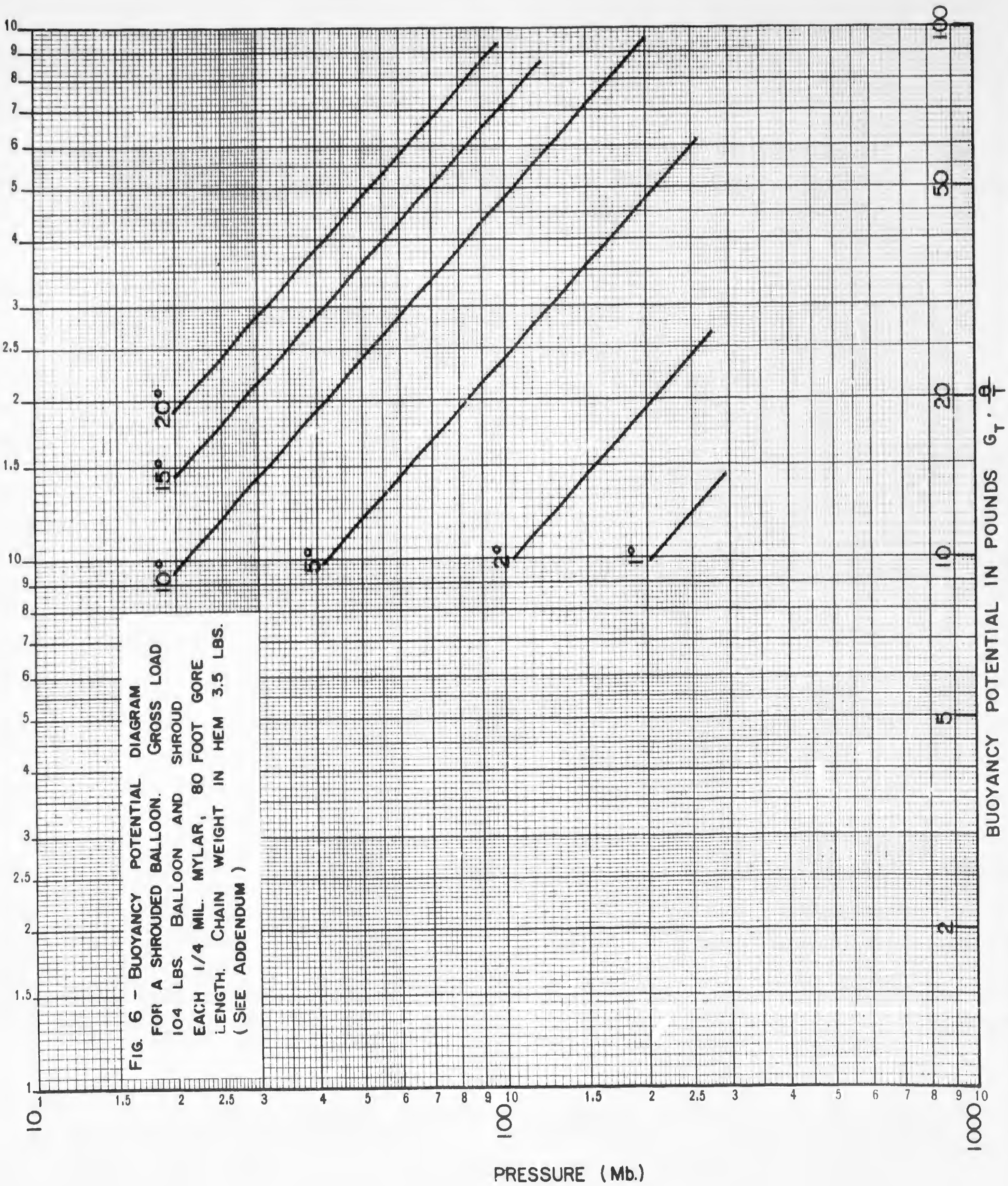

FIG. 6 – BUOYANCY POTENTIAL DIAGRAM FOR A SHROUDED BALLOON. GROSS LOAD 104 LBS. BALLOON AND SHROUD EACH 1/4 MIL. MYLAR, 80 FOOT GORE LENGTH. CHAIN WEIGHT IN HEM 3.5 LBS. (SEE ADDENDUM)

in which $p\theta > (p\theta)_{min}$, as indicated by the fact that the straight lines in this case extend only out from a buoyancy potential of about 10 pounds.

With any shrouded system, the night-time superheat, θ_N, required to level the system without ballast drop at a pressure altitude, p_N, is

$$\theta_N = \theta_D \frac{pD}{pN}$$

where θ_D is the daytime superheat at the daytime ceiling pressure altitude, p_D.