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Investigation of Various Parameters Affecting Altitude Performance of Tethered Aerostats

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INVESTIGATION OF VARIOUS PARAMETERS AFFECTING ALTITUDE PERFORMANCE OF TETHERED AEROSTATS

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Abstract

Tethered aerostats are lighter-than-air aerodynamically shaped balloons used for surveillance and other missions. There are numerous factors which affect the altitude capability of a tethered aerostat, which may be grouped into three main categories. First, the aerostat has inherent properties which are fixed for a given design, such as hull size, geometry and weight. Next, there are environmental parameters which affect the performance, such as temperature, pressure, and wind. And third, there are operational mission factors and trade-offs which affect the altitude, such as extra lift margin and duration of flight. Numerous parameters in these three areas are analyzed and simulated to evaluate the overall effect and to optimize the system. The aerostat systems range in hull size from 25,000 to 600,000 ft^3, and curves are presented to extend the effects to one million ft^3 and beyond.

Nomenclature

p_o = standard atmospheric pressure
T_g = absolute temperature of the enclosed gases
T_o = absolute standard temperature
V_t = total volume of the enclosed gases
ΔL_p = lift differential due to superpressure
ΔL_t = lift differential due to superheat
Δp = pressure differential of the internal gases over ambient air (superpressure)
ΔT = temperature differential of the internal gases over the ambient (superheat)
ρ = specific weight of air
ρ_o = specific weight of air under standard conditions

Introduction

Modern tethered aerostats have proven to be safe and reliable platforms for mounting of radar and various other electronic payloads. They have been used extensively for border surveillance[1,2] and for communications relay and broadcasting. The standard models range in length from 25 to 71 meters with corresponding volumes of 25,000 to 600,000 ft^3. A typical TCOM 71M™ aerostat in flight is shown in Fig. 1.

New applications include military surveillance[3] and mounting of telescopes on high altitude aerostats for enhanced viewing above the effects of the atmosphere[4,5].

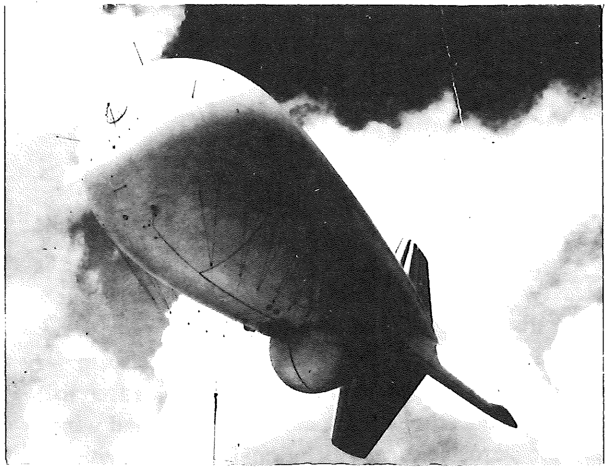

Fig. 1. 71M™ Aerostat

Tethered aerostats rely on excess lift to provide excellent station keeping performance. This lift, along with added aerodynamic lift when there is a wind, allows them to be flown in greater winds and turbulence than other comparable aircraft. The large 71M™ aerostats are designed to be operational in winds up to 70 kt and to survive 90 kt. Since they are unmanned, aerostats have flown through turbulence and lightning storms that a piloted aircraft would avoid.

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Static lift is derived from the Archimedean buoyancy of the envelope which is commonly filled with helium gas. Under standard conditions the buoyant lift of helium is 0.0659 lb/ft^3, or conversely, 15.2 ft^3 of helium is needed to lift 1 lb of weight, which illustrates why the vehicles sometimes must be very large. Air-filled ballonets are also included in the hull to permit air to be expelled as the helium expands in order to maintain a constant hull volume. The envelope must be sized large enough to lift the system safely to the required operational altitude and have additional provision for the air ballonets when all environmental effects are considered.

The first area to be investigated, inherent aerostat properties, includes parameters such as aerostat weight, tether weight and pitching moment. The second area, environmental parameters, includes effects of superheat, pressure, helium impurities and pad altitude. The third area, operational strategies, includes helium fill strategy related to leakage and length of mission, blowdown or downwind displacement, extra margin of lift required, and additional altitude by use of aerodynamic lift.

Some of these concepts have been introduced previously[6], but the analyses are extended in this paper and the effects of additional parameters are considered. The analyses apply to the standard TCOM family of aerostats, and hulls of different configurations may produce varying results.

Technical Overview

The concept of excess lift mentioned above is necessary for the aerostat to withstand turbulence, downdrafts, weight of precipitation from rain, dew, sleet and snow, and to maintain a stable platform for the payload. This excess lift is referred to as free lift, and is defined as the tether tension at the ground winch when the aerostat is at operational altitude with no wind or superheat. It is usually expressed as a percent of the standard gross lift in the aerostat. The standard gross lift is the buoyant lift resulting from the helium fill in the aerostat corrected to standard temperature and pressure. A low free lift enables a smaller aerostat but increases the risk of low tether tension and laying of tether on the ground. On the other hand, a high free lift requires a larger aerostat and raises the tether tension and thus the strength required. Experience has shown that a practical amount of free lift in the aerostat is 15% of the standard gross lift, and the analyses in this report will use this value for all cases.

Another aerostat characteristic is the vent ceiling, sometimes called the pressure height. This is defined as the altitude at which the helium has expanded and filled the entire hull, thus emptying the ballonet. Any further increase in altitude would cause the internal pressure to rise and the emergency helium valves would open to vent helium. Venting of helium is avoided not only for economic reasons but because the amount of helium remaining in the aerostat becomes uncertain.

The optimum altitude is defined as the operating altitude at which the aerostat is at vent ceiling with a given helium fill and free lift. In the examples presented, 25°F day superheat is used in the vent ceiling calculations and 15% free lift is used in the lift calculations, with standard temperature and pressure conditions at the surface. Thus, each time a parameter such as tether weight is changed, the revised altitude reflects more than this single effect. Rather, the new weight results in a revised helium fill calculation and thus a new vent ceiling in order to optimize the performance, and it is this optimum altitude that is presented in the graphs.

Aerostat Properties

The weights of the envelope, rigging, flight hardware, and payload are key factors in sizing of the aerostat, with the weight of the flexible structure envelope being the major component in this case. Modern field-proven laminates have provided the means to make the envelopes much lighter and stronger with improved flex life, environmental resistance, and helium permeation resistance than in the past[7]. The materials are strong enough to support the vehicle with no internal framework and provide a service life of 7 to 10 years.

As the envelope increases in size, the stresses in the material increase also; the hoop or tangential stress in the material is a direct function of the radius of the hull. Thus, the unit material weight will increase with the size of the hull diameter and may reach a limit where the weight of the envelope is excessive. Fig. 2 shows a log-log plot of aerostat weight as a function of aerostat hull volume. Data is presented for the total aerostat weight, which includes rigging, hardware, electrical and pressurization equipment, or alternatively, the entire system without the weight of the tether, payload and internal gases.

The sensitivity of the aerostat systems to weight changes is shown in Fig. 3, where an increase or decrease in weight produces a corresponding change in operating altitude. As mentioned earlier, the helium fill in the aerostat is adjusted to maintain 15% free lift in calculating the new altitude values. The 71M™ aerostat, with a volume of approximately 600,000 ft^3, shows an altitude change of about 1 ft for each pound of added payload.

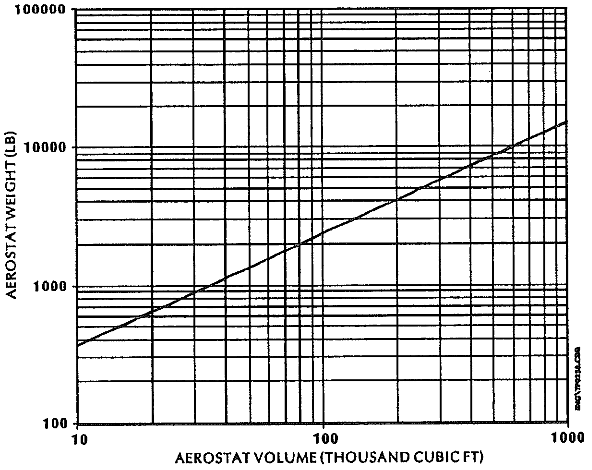

Fig. 2. Aerostat Weight vs Volume

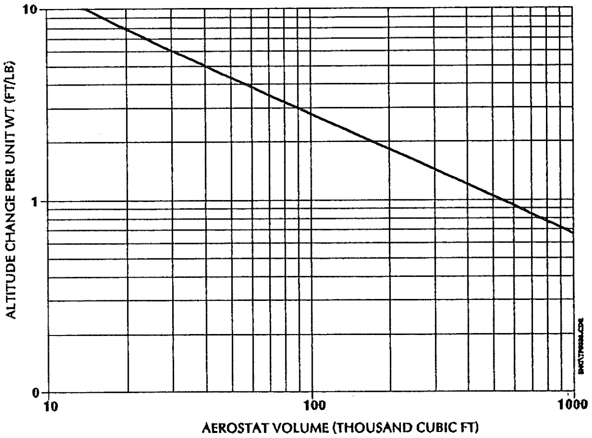

Fig. 3. Altitude Change per Unit Weight vs Aerostat Volume

The tether weight varies with strength required, power throughput, fiber optic capability for data transmission, lightning protection capability, and other factors. Modern tethers are manufactured using Kevlar strength members and fiber optics for data transmission. Nominal tether weights for the range of aerostat sizes of interest is shown in Fig. 4. Tether design and aerostat size are iterative since each is dependent upon the other.

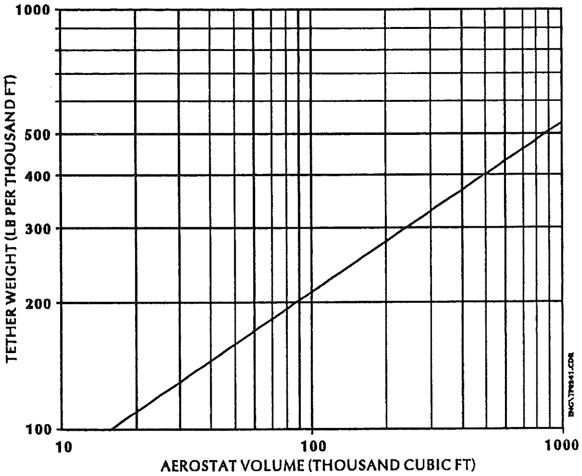

Fig. 4. Tether Weight vs Aerostat Volume

The pitch angle that an aerostat assumes is of great importance when designing the system. The zero wind trim angle is determined by static forces, and the high wind pitch angle is primarily determined by the large aerodynamic forces on the system. Fig. 5 shows the sensitivity of the aerostat system to change in moment as a result of changing weight or its location and the resulting pitch angle change. The 71M™ aerostat requires a moment change of about 10,000 ft-lb to change the pitch angle by 1°.

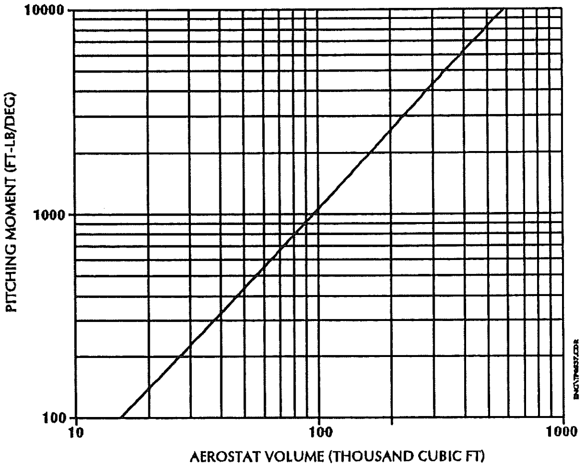

Fig. 5. Pitching Moment Sensitivity vs Aerostat Volume

Environmental Properties

The pad altitude has a significant effect on an aerostat's operational altitude above sea level. However, there is not a one-for-one increase in operating altitude with pad altitude, due to expansion of gas and vent ceiling limitation, and thus a change in helium fill. For example, a 1,000 ft increase in pad altitude results in approximately 400 ft increase in operational altitude above sea level for the 71M™ aerostat. Fig. 6 shows the sensitivity of aerostat altitude to changes in pad altitude for various size aerostats.

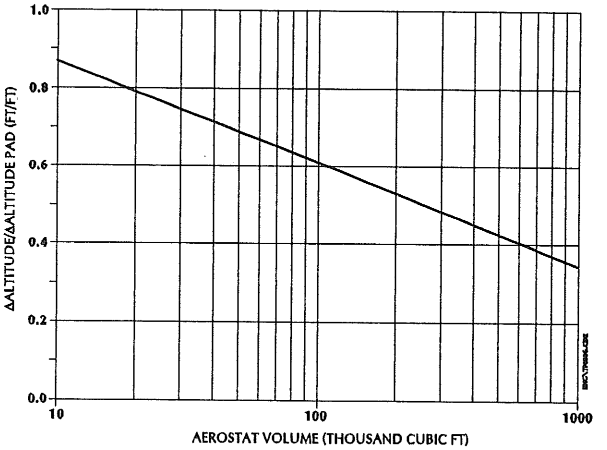

Fig. 6. Altitude Change per Unit Pad Altitude vs Aerostat Volume

Ambient pressure affects the expansion of the helium and thus vent ceiling. The sensitivity of altitude as a function of barometric pressure is shown in Fig. 7 for various size aerostats. For example, the 71M™ aerostat would increase in altitude by 600 ft for a 1 in Hg increase in barometric pressure. This is useful for comparing different site locations where the normal barometric pressure varies between the sites, and therefore the nominal helium fill in the aerostat would be adjusted accordingly.

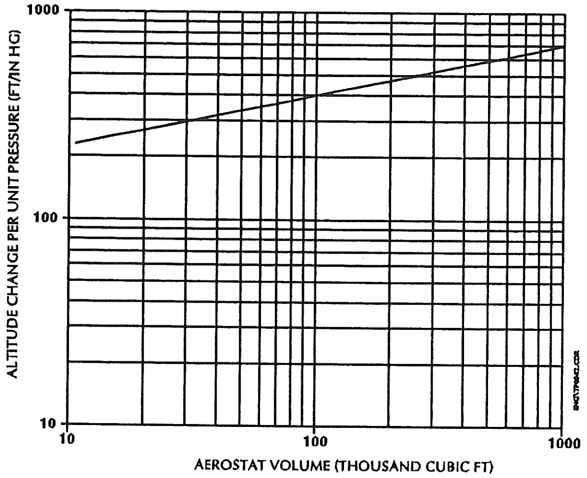

Fig. 7. Altitude Change per Unit Pressure vs Aerostat Volume

Superpressure, defined as the pressure inside the hull relative to the ambient, is another factor to consider. The superpressure must be sufficiently large to maintain the hull shape in static as well as dynamic conditions, with wind gusts. As the wind increases, the internal hull pressure rises accordingly. The internal pressure must also allow the hull to withstand the bending moments along the length of the envelope. Another point to consider is that air and helium have different gas densities, and the columns of air and helium above a pressure sensor, or the hydrostatic head, vary in height as the aerostat changes in pitch. This will affect the pressure reading, and thus the superpressure in the hull must be large enough to avoid being adversely affected by this phenomenon. Aerostats typically operate at 1 to 3 inches water gauge (0.04 to 0.11 psig) above the static pressure and dynamic pressure from the wind. The compressed gases add weight and reduce the buoyancy as follows[8]:

$$\Delta L_p = -\frac{\rho_o T_o V_t \Delta p}{T_g \, p_o}$$

For example, a 71M™ aerostat operating at 15,000 ft with 3 in water gauge pressure and standard sea level conditions would gain approximately 400 lb equivalent weight due to the gas compression.

Superheat, defined as the temperature difference between the interior of the hull and the ambient, is another key factor. Positive superheat expands the gases and thus increases buoyancy, but also reduces the vent ceiling. Negative superheat, sometimes referred to as supercool, has the opposite effect. The change in lift is given by[8]:

$$\Delta L_t = \rho \, V_t \frac{\Delta T}{T_g}$$

For example, a +10°F day superheat in the 71M™ aerostat produces approximately 650 lb additional lift.

Water vapor inside the hull acts in a similar manner as day superheat, where it adds volume to the helium chamber, thus reducing vent ceiling, and it also provides additional buoyant lift, since it is lighter than air. Conversely, water vapor outside in the ambient air has the opposite effect, which means a vehicle entering a moist environment will lose some buoyancy. Water vapor contamination in the helium can cause a miscalculation in the lift loss rate over time[9]. Another effect of external water vapor is the formation of dew on the aerostat hull as the internal gases cool in the evening, which can add a surprising amount of weight to the system, and the formation of rime ice on the fabric and rigging in certain environmental conditions.

Helium purity is another factor which must be considered. Air may enter the helium chamber through small holes in the ballonet or by molecular action through the material, the rate of which is highly dependent on temperature[10], and this has the effect of a reduced vent ceiling. If gas is removed to raise the vent ceiling, then the lift may not be sufficient. Since helium purity changes gradually over a long time span, the helium fill is adjusted accordingly to provide the optimum performance. The sensitivity of aerostat altitude to helium purity is shown in Fig. 8, where a 71M™ aerostat shows a decrease in altitude of 200 ft for a 1% degradation in helium purity. Any gas other than helium, such as water vapor, is sometimes considered an impurity, but this depends upon the definition one uses for the system.

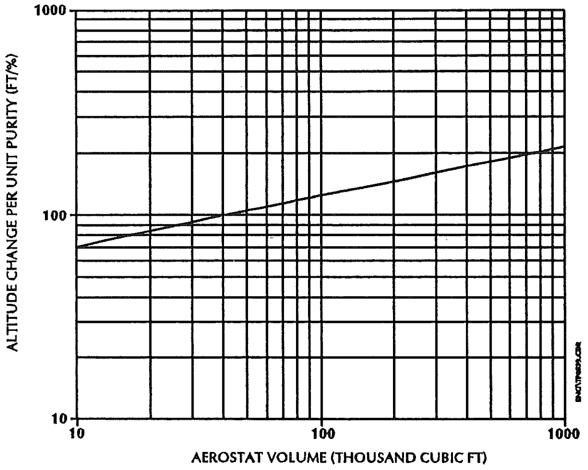

Fig. 8. Altitude Change per Unit Purity vs Aerostat Volume

Optimum Altitude and Operational Strategies

Payload weights range from approximately 700 to 3500 lb on the 32M™ and 71M™ aerostats, respectively. The payload, tether and aerostat weights are used to calculate the operating altitude at zero windspeed with 25°F day superheat and 15% free lift. A plot of altitude as a function of aerostat volume for these standard systems is shown in Fig. 9. Notice that altitude is a linear function when aerostat volume is plotted on a log scale. At field sites, much greater aerostat altitudes have been achieved than shown in the curve by using lighter payloads, tethers, and flying in non-standard conditions.

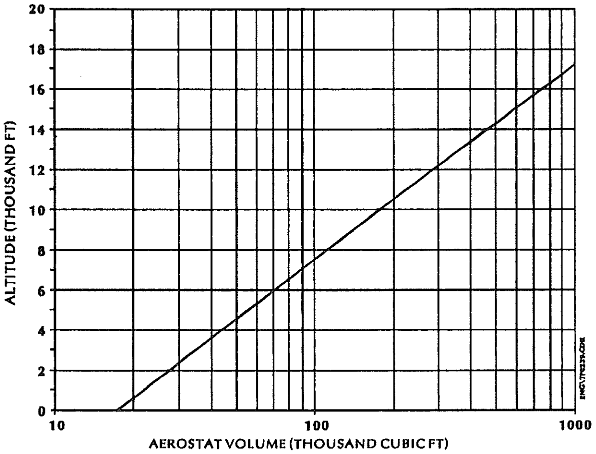

Fig. 9. Aerostat Altitude vs Volume

It is convenient to convert the volumes obtained into a corresponding aerostat hull length. Fig. 10 shows the 71M™ aerostat length and volume projected using a $V^{1/3}$ relationship to calculate these hull lengths.

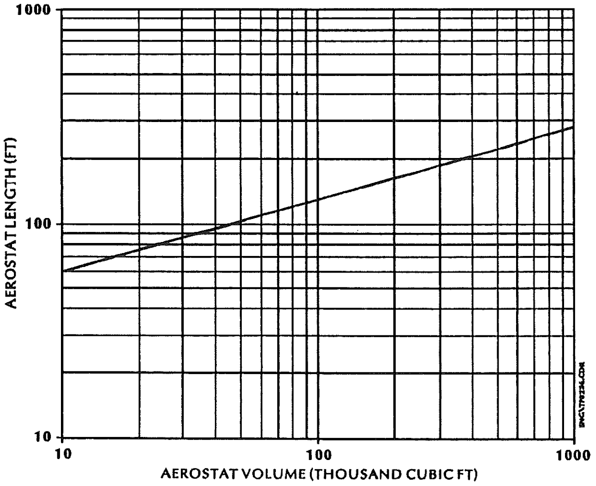

Fig. 10. Aerostat Length vs Volume

A plot of helium fill in pounds of lift is shown in Fig. 11 for the various aerostat sizes. The fill shown is the optimum fill using 15% free lift and 25°F day superheat for a standard day at sea level.

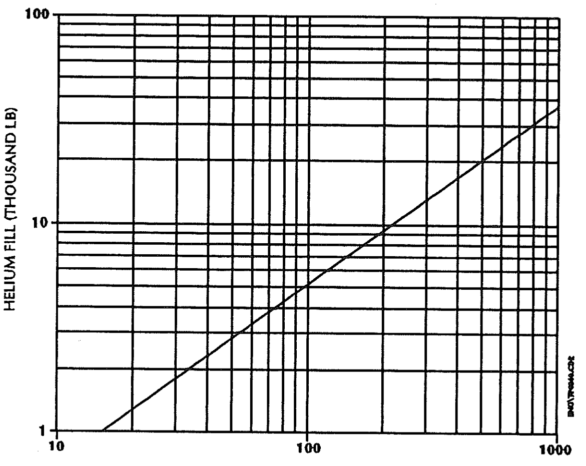

Fig. 11. Helium Fill vs Aerostat Volume

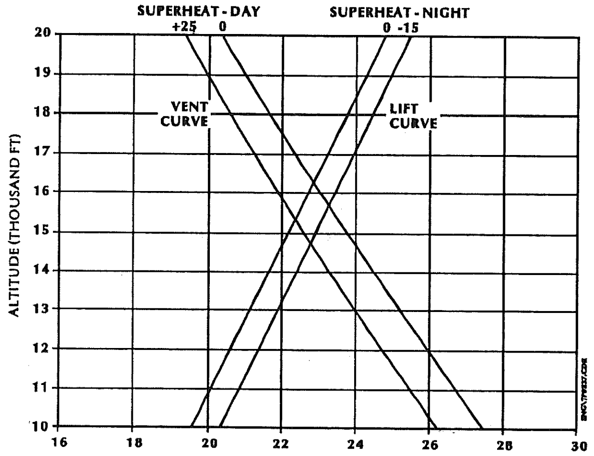

Fig. 12. Aerostat Optimum Altitude

Once an aerostat has been sized, the operating conditions also have an effect on the operational altitude. It is easily seen that in order to increase altitude and thus lift additional tether, helium must be added to the aerostat. This is represented by the positive sloping curve in Fig. 12, the slope of which is the inverse of the tether weight, and is referred to as the lift curve. Performance along the lift curve is adversely affected by night supercool, as shown in the figure. A factor which acts in converse of the lift curve is the vent curve. This curve takes into account the fact that as more helium is added to the aerostat, it will reach vent ceiling sooner, and is represented by the negative sloping line in Fig. 12. Performance along this line is adversely affected by day superheat. The intersection of the lift and vent curves, called the optimum altitude corresponding to an optimum lift, is the highest point at which the aerostat may safely operate[8]. The point is generally calculated using the vent curve with day superheat but the lift curve with no superheat. At night, the actual free lift may fall below 15% in supercool conditions, but it is usually calm at this time and the reduced lift margin is acceptable. A family of curves for the 71M™ aerostat at optimum altitude as a function of payload weight and temperature is shown in Fig. 13.

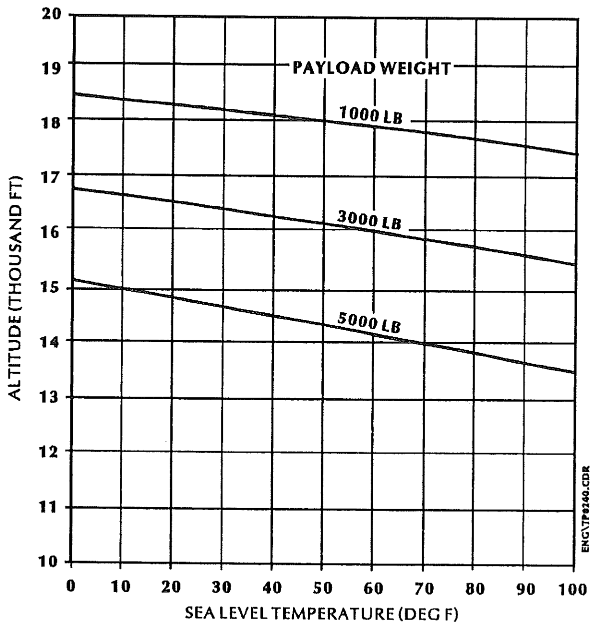

Fig. 13. 71M™ Aerostat Altitude as a Function of Temperature and Payload Weight

Similarly, a family of curves for the 32M™ aerostat is shown in Fig. 14. This particular aerostat contains rugged equipment for flight from a vessel at sea and extra lightning protection equipment. A land based version is lighter and thus achieves slightly higher altitudes.

An overfilled aerostat will be limited in altitude by the vent curve, and an underfilled aerostat limited by the lift curve. The aerostat must be sized large enough to allow for this deviation from the optimum fill and still maintain the operating altitude. Since some helium is lost through leakage and permeation through the

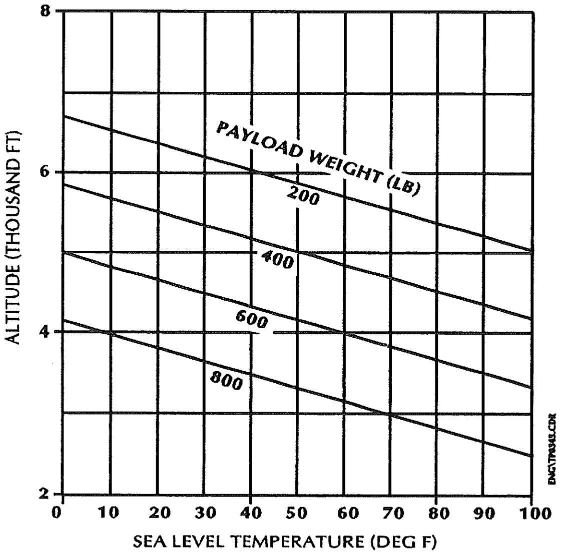

Fig. 14. 32M™ Aerostat Altitude as a Function of Temperature and Payload Weight

material, the operating strategy of overfilling at the beginning of a mission and being underfilled at the end will determine how often the aerostat is temporarily taken out of service to add helium to the envelope. Thus, mission duration is an important factor in determining the aerostat size.

Wind at altitude has an effect on the performance of the aerostat. A common operational strategy is to outhaul enough tether to reach the operating altitude and then secure the tether, commonly referred to as flight at constant tether length. As the wind increases, the aerostat will translate horizontally along the surface and also decrease slightly in altitude, although this altitude decrease is minimized due to aerodynamic lift, and the tether will take the shape of a catenary. A plot of nominal horizontal down wind displacement measured from the mooring system is shown in Fig. 15. This may vary with change in factors such as fineness ratio, confluence point location and pitch angle. In order to minimize the horizontal displacement, the tether tension may be increased by oversizing an aerostat to provide more than 15% free lift at the operational altitude.

Another strategy for operating in wind is to have an operator observe the system and outhaul tether as the aerodynamic lift increases with increasing wind. This method allows the aerostat to maintain its altitude, but a sudden drop in wind may reduce the free lift to unacceptable levels. The safest method is to design the aerostat large enough to maintain operational altitude without the necessity of relying on aerodynamic lift. This approach to flying aerostats has been safely used worldwide accumulating hundreds of thousands of hours of flight time.

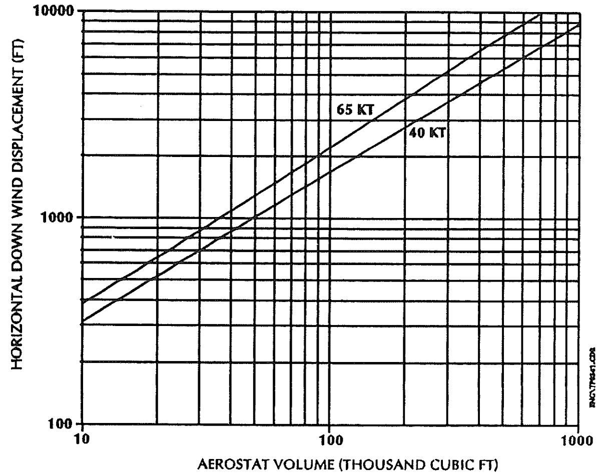

Fig. 15. Horizontal Down Wind Displacement vs Aerostat Volume

Additional operational factors must be taken into account when sizing the aerostat. For example, several parameters may be entered into the definition of the flight envelope. Flight in high turbulence necessitates heavy duty hardware and a strong tether. Sudden sustained downdrafts require extra blowers to keep the aerostat from becoming flaccid, and similarly, updrafts require extra valves to avoid overpressurizing the hull. Flight in areas of high lightning probability requires a heavy duty wire system around the aerostat connected to the tether to safely discharge the currents to the ground. Thus, an aerostat must be sized to accommodate all of these factors.

Summary and Conclusions

Sizing of an aerostat requires an optimization of numerous factors. These may be classified as aerostat related properties, environmental properties, and operational strategies. As a parameter changes, the helium fill in the aerostat may be adjusted in order to achieve optimum performance.

The numerous parameters which must be considered in sizing include such items as weight, material effects, temperature, pressure, and mission altitude and duration.

The current standard aerostat hull sizes range from 25,000 to 600,000 ft^3, and curves are presented to extend the effects to one million ft^3 and beyond. Materials and technology exist today to permit tethered flight to 65,000 ft AMSL and planning is underway to achieve this altitude.

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