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VULNERABILITY OF TETHERED BALLOON  
SYSTEMS

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July 1974

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Naval Facilities Engineering  
Command

A serious look at the vulnerability of tethered balloons indicates that they are difficult to bring down quickly because of the large size, low differential pressure across the skin, and low gas loss because of partial closure when projectiles pass through. With no radar signature, and the soft skin, it is difficult to make any currently available round explode at the right moment to create a catastrophic failure.

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| KEY WORDS                |    | LINK A |    | LINK B |    | LINK C |    |
|--------------------------|----|--------|----|--------|----|--------|----|
| ROLE                     | WT | ROLE   | WT | ROLE   | WT | ROLE   | WT |
| Balloons, Aerodynamics   |    |        |    |        |    |        |    |
| Logistics                |    |        |    |        |    |        |    |
| Balloons, Natural Shaped |    |        |    |        |    |        |    |
| Balloons, Vulnerability  |    |        |    |        |    |        |    |

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## I. INTRODUCTION

To be effective in military applications a balloon system must have a high probability of surviving enemy actions or operational hazards to which the system would be exposed.

This study examines the vulnerability of the individual components and subsystems of tethered balloon systems with emphasis on Balloon Transport Systems (BTS). Comparison is made with the two closest competitors in the ship-to-shore movement of heavy cargo, the helicopter and the crane. It should be noted at this point, that neither of these alternatives are directly comparable to the balloon system, since in the case of the helicopter, current lift capabilities for in-service aircraft are limited to 17 tons, and in the case of cranes, their lift is limited by boom length and lift capability at that radius. [The largest mobile cranes (300 tons) are limited to 24 tons at 120 foot radius.] Cranes would require a sand-filled sheet steel pile or jacked up pier to offload landing craft at the shore. The balloon is limited in lift only by its design size; and operating distances, whether 50 feet or 5,000 feet, make little difference in the system's operation or configuration other than the requirement for larger drums for distances over 1000 feet.

To provide a basis for comparing the vulnerability of balloon systems with other competitive systems, the current vulnerability thinking on fixed wing and rotary wing aircraft is first reviewed. This is followed by an analysis of crane vulnerability and an examination of balloon failure mechanisms and potential threats and hazards. Next possible design modifications, countermeasures and operational tactics which might be adopted to reduce system vulnerability are considered. This is followed by a concluding section of conclusions and recommendations.

A tethered balloon system of substantial interest to the military services is the Balloon Transport System (BTS) used for ship-to-shore transport of military cargo (Figure 1). In this system a heavy lift balloon provides the necessary aerostatic lift to support the lead and the cable system. In addition to the lines connecting the balloon to the payload, two other cables providing both tethering and driving functions are present. These are attached to the Balloon Line and the Load Line at a confluence point part way between the balloon and load. The driving cables are controlled by separate winches on a large device called a yarder. One of these cables, the Main Line, passes directly from a winch to the confluence point. The cable from the other winch, the Haulback line, passes through a block on the far side of the balloon and back to the balloon. Thus these two cables can pull the balloon

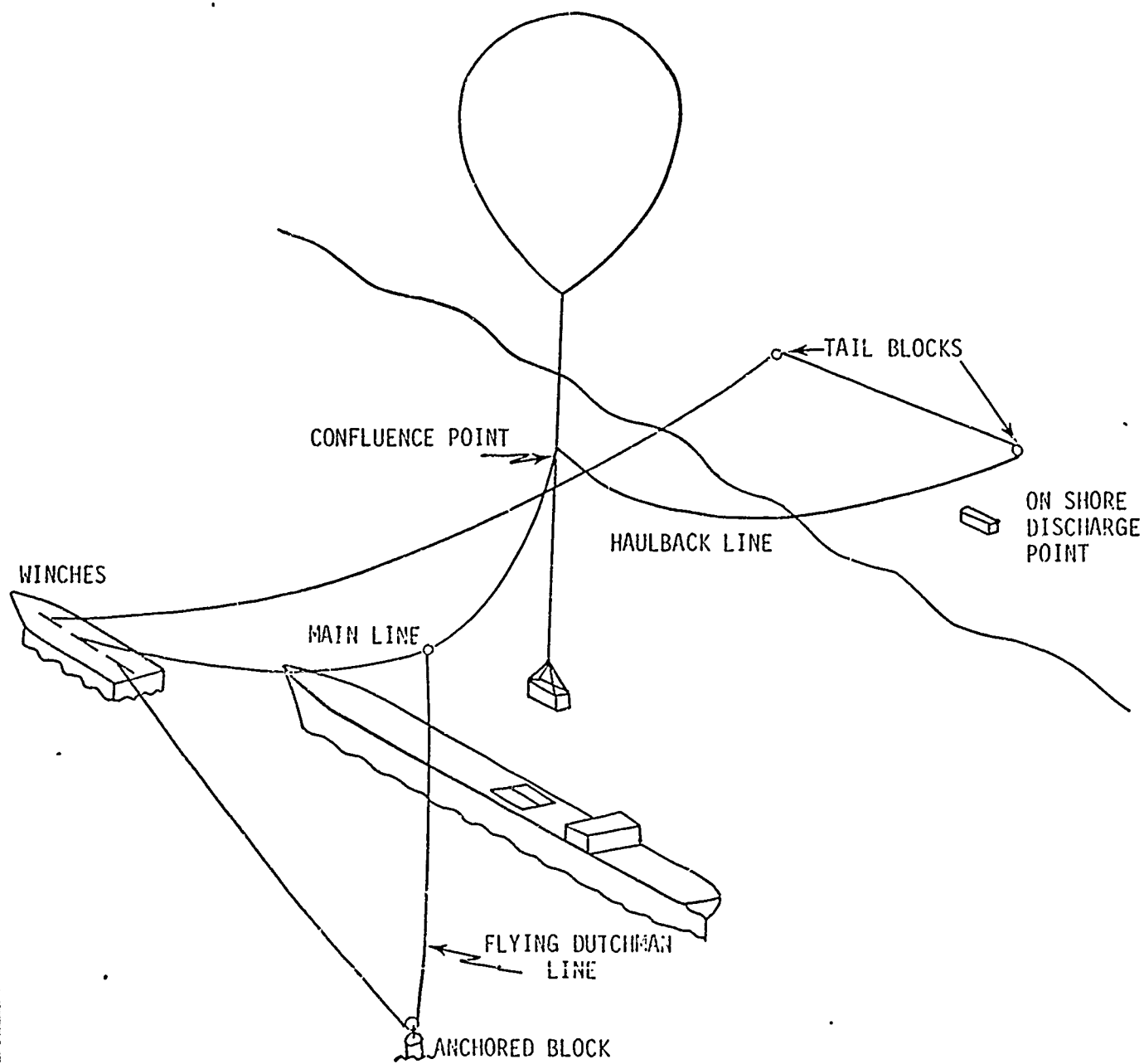


Figure 1. Ship-to-Shore Balloon Transport System

and any attached load back and forth by operating the winches in opposite directions, or pull it up and down by operating the winches in the same direction. Further lateral positioning is obtained using the so-called Flying Dutchman line attached through a block to either the Main line or the Haulback line. The Flying Dutchman also requires a separate winch.

The yarder can be either a single piece of equipment or two similar pieces to reduce size. It can be positioned either on shore or on a workboat -- with the necessary blocks positioned on the opposite end of the offloading track. By proper operation of the winches, the balloon can be placed over the individual holds of a container ship and used to extract the containers from the hold and carry them either to a shore position or to a nearby lighter.

For military ship-to-shore applications the BTS should be capable of handling loads weighing up to 45,000 pounds at velocities sufficient to achieve a discharge rate of 12 containers per hour. To accommodate the frequent change in direction of motion and to reduce the lift fluctuations inherent in aerodynamic vehicles under changing velocity conditions, the natural shape balloon has been adopted. Operations are of course accomplished at altitudes only slightly above sea level.

Major subsystems of the Balloon Transport System are:

1. Lift System - Balloon Envelope

2.. Tether and Power System - Cables, Winches, and Blocks

3. Bed Down System - Central Tether and Side Tie Down  
Lines

The vulnerability of these subsystems against enemy threats and natural hazards will be examined in the following sections.

## II. VULNERABILITY CONSIDERATIONS OF FIXED AND ROTARY WING AIRCRAFT

Substantial research and development work has been devoted to the understanding of aircraft vulnerability and to methods for reducing vulnerability or its converse, increasing aircraft survivability. This previous work gives a strong foundation for examining and evaluating the vulnerability of balloons.

Three types or levels of failure are considered in assessing the vulnerability of military aircraft.

Type A is catastrophic failure in which the aircraft is suddenly and completely lost.

Type B is the situation in which an aircraft is forced to land immediately, but does not necessarily result in the total loss of the aircraft, i.e., the aircraft may be repairable.

Type C is a loss of aircraft capability which requires the mission to be aborted, but the aircraft is able to return to base.

In examining weapon effectiveness and the vulnerability of aircraft, it is necessary to determine both  $p_h$ , the probability of hitting the aircraft, and  $p_k$ , the probability of killing the aircraft after it is hit.  $p_{hk}$ , the probability of both hitting and killing the aircraft is of course the product of the probabilities  $p_h$  and  $p_k$ .

In addition to being a function of the total aircraft cross section area,  $p_h$ , the probability of hitting the aircraft, is also a function of the observables. These include the radar cross section, the optical cross section in both the visible and the infrared wavelengths, acoustic cross section and the response to other sensing media.

$P_k$ , the probability of killing the aircraft after it is hit, is related to the proportion of vulnerable area to the total aircraft cross section area, the characteristics of the specific vulnerability and the characteristics of the weapon or possibly the natural hazard.

It should be noted that striking or penetrating the skin of fixed or rotary wing aircraft is generally insufficient to create damage of the aircraft serious enough to abort the mission, let alone cause the loss of the aircraft. Instead it is necessary to impact or sever critical components.

Aircraft losses sustained in the wars from World War I through the Southeast Asia conflict have been primarily due to fuel subsystems damage, with pilot incapacitation as the second largest source, and damage to flight controls as the third.

In the case of rotary wing aircraft, damage to the rotor can set up vibrations which can lead to loss of the helicopter.

Finally, of course, the aircraft structure can sustain only a certain amount of damage before failure of one of the three types will occur.

The threat against aircraft ranges from small arms fire to sophisticated Ground-to-Air Weapon Systems including Anti-Aircraft Guns and Surface-to-Air Missiles as well as Aircraft Weapon Systems which include Air-to-Air Missiles and Aircraft Guns.

Damage mechanisms of these conventional arms are penetration, fire and blast. Each of these mechanisms has been examined in detail for each weapon and each aircraft.

To minimize the vulnerability of future aircraft an effort is being made to minimize the vulnerable area of the critical subsystems. Vulnerable area can be reduced by applying the following principles:

1. Protection of critical components
2. Redundancy and separation
3. Isolation of potential sources which by themselves may not be vulnerable but in the proximity of other components may create vulnerable combinations.

Initial effort to reduce aircraft vulnerability was concentrated on the application of ballistic protection (armor) around critical components; principally the pilot and fuel tanks. Leakproof and self-sealing fuel tanks were also developed. Later it was recognized that reduction of the probabilities of detection, acquisition, and hit provided additional methods for obtaining higher aircraft survival. Employment of evasive maneuvers, improved tactics, flak suppression, escort aircraft, chaff and other electronic countermeasures have enhanced aircraft survivability.

Tables 1 and 2 present data on the vulnerability of helicopters in several weight classes to weapons of several sizes. It may be noted that for the larger weapons the vulnerable area scales almost directly with the weight of the helicopter. Thus, although vulnerability data on heavy lift helicopters was not immediately available, the vulnerable area of these helicopters in the 25,000 pound class would probably be 70% larger than the tabulated vulnerable areas of the 15,000 pound helicopter.

The probability of kill,  $p_k$ , for the several types of kill can be considered as the ratio of the vulnerable area to the presented area for each aspect. Having determined the probability of hit,  $p_h$ , under the specific conditions of the observables, electronic countermeasures and tactics applied,  $p_{hk}$ , or probability of both hitting and killing can be computed by taking the product of  $p_h$  and  $p_k$ .

TABLE 1

VULNERABLE AREA OF THREE HELICOPTER SIZES AGAINST SMALL ARM FIRE

| 1) Characteristics of the Threat Weapon                  |   |            |  |  |             |  |  |  |  |
|----------------------------------------------------------|---|------------|--|--|-------------|--|--|--|--|
| Max effective range                                      | - | 1000 M     |  |  |             |  |  |  |  |
| Detect to fire                                           | - | 6 sec      |  |  |             |  |  |  |  |
| Rds/1 sec burst                                          | - | 10 Rds     |  |  |             |  |  |  |  |
| Delay between bursts                                     | - | 10 sec     |  |  |             |  |  |  |  |
| Magazine capacity                                        | - | 50 Rds     |  |  |             |  |  |  |  |
| Ballistic error                                          | - | 5 mils     |  |  |             |  |  |  |  |
| Range - M                                                |   | <u>300</u> |  |  | <u>1000</u> |  |  |  |  |
| Remaining vel-M/sec                                      | - | 489        |  |  |             |  |  |  |  |
| Time of Flight - sec                                     |   | .45 (est)  |  |  | 1.6         |  |  |  |  |
| 2) Helicopter Presented Area ( $A_p$ ) - m <sup>2</sup>  |   |            |  |  |             |  |  |  |  |
| Helicopter Approximate Weight (lb)                       |   | 3,000      |  |  | 10,000      |  |  |  |  |
| Front (m <sup>2</sup> )                                  |   | 2.85       |  |  | 4.54        |  |  |  |  |
| Side                                                     |   | 9.92       |  |  | 20.29       |  |  |  |  |
| Rear                                                     |   | 2.87       |  |  | 4.54        |  |  |  |  |
| 3) Helicopter Vulnerable Area ( $A_v$ ) - m <sup>2</sup> |   |            |  |  |             |  |  |  |  |
| Helicopter Approximate Weight (lb)                       |   | 3,000      |  |  | 10,000      |  |  |  |  |
| Remaining Velocity - M/sec                               |   | >305       |  |  | 152         |  |  |  |  |
| Type Kill                                                |   |            |  |  |             |  |  |  |  |
| Aspect                                                   |   |            |  |  |             |  |  |  |  |
| Front (m <sup>2</sup> )                                  |   | A          |  |  | .01         |  |  |  |  |
|                                                          |   | B          |  |  | .11         |  |  |  |  |
|                                                          |   | C          |  |  | .32         |  |  |  |  |
| Side                                                     |   | A          |  |  | .19         |  |  |  |  |
|                                                          |   | B          |  |  | .70         |  |  |  |  |
|                                                          |   | C          |  |  | .44         |  |  |  |  |
| Rear                                                     |   | A          |  |  | .07         |  |  |  |  |
|                                                          |   | B          |  |  | .26         |  |  |  |  |
|                                                          |   | C          |  |  | .04         |  |  |  |  |

TABLE 2

## VULNERABLE AREA OF THREE HELICOPTER SIZES AGAINST 50 mm GUNS

| 1) Characteristics of the Threat Weapon -- 50 mm Gun     |           |         |        |                                       |
|----------------------------------------------------------|-----------|---------|--------|---------------------------------------|
| Fire Control                                             |           | Optical | Radar  | Aiming error - mils                   |
| Max effective range - M                                  |           | 4000    | 6000   | Optical 8.75 + .000136                |
| Detect to fire - sec                                     |           | 7-10    | 6-15   | Radar 8.75 + .000136                  |
| Rds/burst                                                |           | 8       | 8      | ( $\delta$ = slewing rate - mils/sec) |
| Delay between bursts - sec                               |           | 2       | 2      | Ballistic error 5 mils                |
| Magazine capacity - Rds                                  |           | 4       | 4      |                                       |
| Reload delay - min                                       |           | na      | na     |                                       |
| Rds on station                                           |           | 200     |        |                                       |
| Halt time - sec                                          |           | 60      |        |                                       |
| Range - M                                                |           | 1000    | 1500   | 2000                                  |
| Remaining vel-M/sec                                      |           | 898     | 849    | 801                                   |
| Time of Flight - sec                                     |           | 1.1     | 1.6    | 2.2                                   |
| 2) Helicopter Vulnerable Area ( $A_v$ ) - m <sup>2</sup> |           |         |        |                                       |
| Helicopter Approximate Weight (lb)                       |           | 3000    | 10,000 | 15,000                                |
| Remaining Velocity - M/sec                               |           | >305    | 152    | >305                                  |
| Aspect                                                   | Type Kill |         |        |                                       |
| Front (m <sup>2</sup> )                                  | A         | 2.53    | 1.27   | 3.24                                  |
|                                                          | B         | .02     | .01    | 1.62                                  |
|                                                          | C         | .30     | 1.57   | .23                                   |
| Side                                                     | A         | 8.51    | 4.26   | 1.20                                  |
|                                                          | B         | 1.06    | .53    | .61                                   |
|                                                          | C         | .35     | 5.13   | 7.96                                  |
| Rear                                                     | A         | 2.33    | 1.17   | 15.91                                 |
|                                                          | E         | .22     | .11    | 2.89                                  |
|                                                          | C         | .30     | 1.57   | 1.45                                  |
|                                                          |           |         |        | 1.49                                  |
|                                                          |           |         |        | 1.75                                  |
|                                                          |           |         |        | 2.58                                  |
|                                                          |           |         |        | 1.92                                  |
|                                                          |           |         |        | 3.84                                  |
|                                                          |           |         |        | 1.29                                  |
|                                                          |           |         |        | 3.58                                  |
|                                                          |           |         |        | 1.79                                  |
|                                                          |           |         |        | .63                                   |
|                                                          |           |         |        | .32                                   |
|                                                          |           |         |        | 1.40                                  |
|                                                          |           |         |        | .70                                   |

### III. VULNERABILITY CONSIDERATIONS OF CRANES

Unlike the research which has been done on helicopter failure mechanisms, there is virtually no work that has been done on cranes in advanced areas of the sizes needed for off-loading 22.4 ton containers, simply because there have been no cranes of this size used in amphibious warfare to date. A detailed assessment of these failure mechanisms is not necessary, however, to make a meaningful comparison between a crane and a balloon system, since a delineation of similarities and differences will lead to the logical conclusions desired.

Regardless of the configuration of the yarder, be it one or two large track mounted winches, or two truck mounted winches, the vulnerability of this component of the balloon system is relatively the same as any piece of heavy equipment now in inventory. The same precautions would have to be taken in design and manufacture for safeguarding hydraulic lines, critical controls, etc., as in the case of militarized versions of civilian equipment. Damage to this subsystem, as discussed under the "Tether and Power" section of "Balloon Failure Mechanisms" would most likely be limited to repairs which could be accomplished in field with a minimum of downtime. The effect on systems operational capability could be limited if all three winches (two for the yarder, and one for the Flying Dutchman) were of the same type. If one were catastrophically lost, the Flying Dutchman mode could be suspended

without serious impairment of the primary ship-to-shore movement of cargo. In like manner, if the balloon system were to be the primary logistics support, it would be supposed that there would be more than one system at the site, and interchangeability of components and subsystems would further reduce the possibility of cessation of operations due to the loss of one winch truck, or other subsystem. Comparing the other components of the balloon system such as the main and haulback lines, blocks, buoys, anchors, balloon envelope, etc., is meaningless, since there are no comparable components in a crane system. The added components add complexity and greater opportunity for enemy action.

It follows logically then, that if the crane and balloon system are to be compared solely on the basis of vulnerability, without taking into account the differences in capability, the balloon system is more vulnerable. It is not possible to quantify this difference simply because of the nature of the difference in components involved.

#### IV. BALLOON FAILURE MECHANISMS

##### A. LEVELS OF BALLOON SYSTEM KILL

Three types or levels of balloon system kill may be defined similar to the three levels of aircraft kill.

Type A kill is the sudden and catastrophic kill resulting in the complete loss of the balloon system capability. Since the system components are separated it may be possible to salvage some of the components, e.g., the winches if the balloon envelope is lost.

Type B kill is a rapid degradation of capability requiring an immediate halt in operations and repair of the damaged component.

Type C kill is a slow degradation of capability in which the balloon system can continue operations at a reduced level of performance until a convenient time for repair.

##### B. BALLOON ENVELOPE PUNCTURE

Clearly the component of initial interest in the examination of balloon system vulnerability is the balloon envelope itself. If this envelope is punctured by enemy action, by improper handling, or by natural causes, the buoyant gas will escape and the balloon will lose its support. However, for small punctures, the gas release is not a sudden rush, but rather a slow flow and slow loss of buoyancy. Thus the degree of damage under most circumstances would be classified

as Type C or slow degradation of capability or at the most a Class B damage if the holes are large enough. This means that the balloon would have to be brought down to be patched when convenient (Class C) or patched immediately (Class B). In either case, the damage leads to inconvenience and loss of time, but is not a permanent loss of capability.

#### 1. Gas Flow and Buoyancy Loss Rate

The rate of gas flow through a punctured envelope is primarily dependent upon the pressure differential across the envelope and the size of the holes. This flow rate may be expressed as follows (1):

$$Q = A C_D \sqrt{\frac{2g \Delta p}{\rho_{HE}}} \quad (5.2)$$

where:  $Q$  = flow rate ( $\text{ft}^3/\text{sec}$ )

$A$  = area of hole ( $\text{ft}^2$ )

$C_D$  = discharge coefficient (0.60 for clear sharp-edged orifice)

$g$  = acceleration of gravity ( $32.2 \text{ ft/sec}^2$ )

$\Delta p$  = difference between internal helium pressure and external atmospheric pressure (inches  $\text{H}_2\text{O}$ )

$\rho_{HE}$  = density of helium ( $.01039 \text{ lb/ft}^3$ )

---

(1) Goodyear Aerospace Company Report 1TTFL64411-1, August 13, 1963, "Balloon-Borne Counter Insurgency Communications Relay."

The above relations assume that the holes are not sufficiently small that viscosity must be considered.

For zero pressure balloons (balloons whose internal pressure at the balloon bottom equals the external atmospheric pressure) the pressure differential across the envelope at any point equals the weight of a column of air of unit area extending from the balloon bottom to the point of interest less the weight of a similar column of gas. Even at the top of a 100 foot high balloon the pressure differential would be only:

$100 \text{ ft} \times (0.075 - .010) \text{ lb/ft}^3 = 6.5 \text{ lb/ft}^2 = 1.25 \text{ in. H}_2\text{O}$   
 where the specific weight of air and helium under normal temperature and pressure conditions are  $0.075 \text{ lb/ft}^3$  and  $0.010 \text{ lb/ft}^3$  respectively. The gas flow under the above pressure differential would be:

$$Q = A \times 0.6 \sqrt{\frac{2 \times 32.2 \times 1.25 \times 5.2}{.010}}$$

$$= 122.7A \text{ ft}^3/\text{sec}$$

A hole area of 0.1 square feet corresponds to 73 - 9 mm bullets each punching two full cross section holes in the envelope or one 2.75 inch rocket punching two full sized holes.

Mass flow through this hole area for a 100 ft diameter balloon with all holes at the top would be  $122.7 \times 0.1 \times .0104 = .1276 \text{ lb/sec}$ . Since each pound of the buoyant gas provides 6.25 pounds of lift, the 0.1276 lb/sec loss of gas corresponds

to a bouyancy loss of 0.8 lb/sec. This calculation is considerably exaggerated, however, when compared with actual occurrences under operating conditions for the following reasons:

a. It assumes all holes are at the top of the balloon envelope which is clearly not possible when being fired from the ground or an aircraft. If the average hole were in the center (50 feet up the column) gas loss would be reduced by 50%.

b. It assumes that the hole made by the projectile is the same size as the projectile. Except in the case of a flat-nosed projectile (please see Appendix A for a complete analysis of hole mechanisms), this is not the case, and a closure representing 50% of the projectile size is much more likely to be the case, thereby reducing gas loss by 50%.

c. It is assumed that full pressure is maintained on the envelope as gas leaks out, however, as the gas escapes, the volume contained by the balloon envelope is necessarily reduced. The balloon changes shape and sags at the periphery. In addition, air flows in at the bottom which reduces the effective gas column and pressure differential across the envelope. Under the resultant lower pressure differential, the gas velocity and flow also decrease.

Under these considerations, a curve, Figure 2, shows the anticipated loss in lift in pounds per minute for varying cumulative hole sizes, (curve A). Curve B indicates the time to lose lift capability for 44,800 pounds versus cumulative hole size.

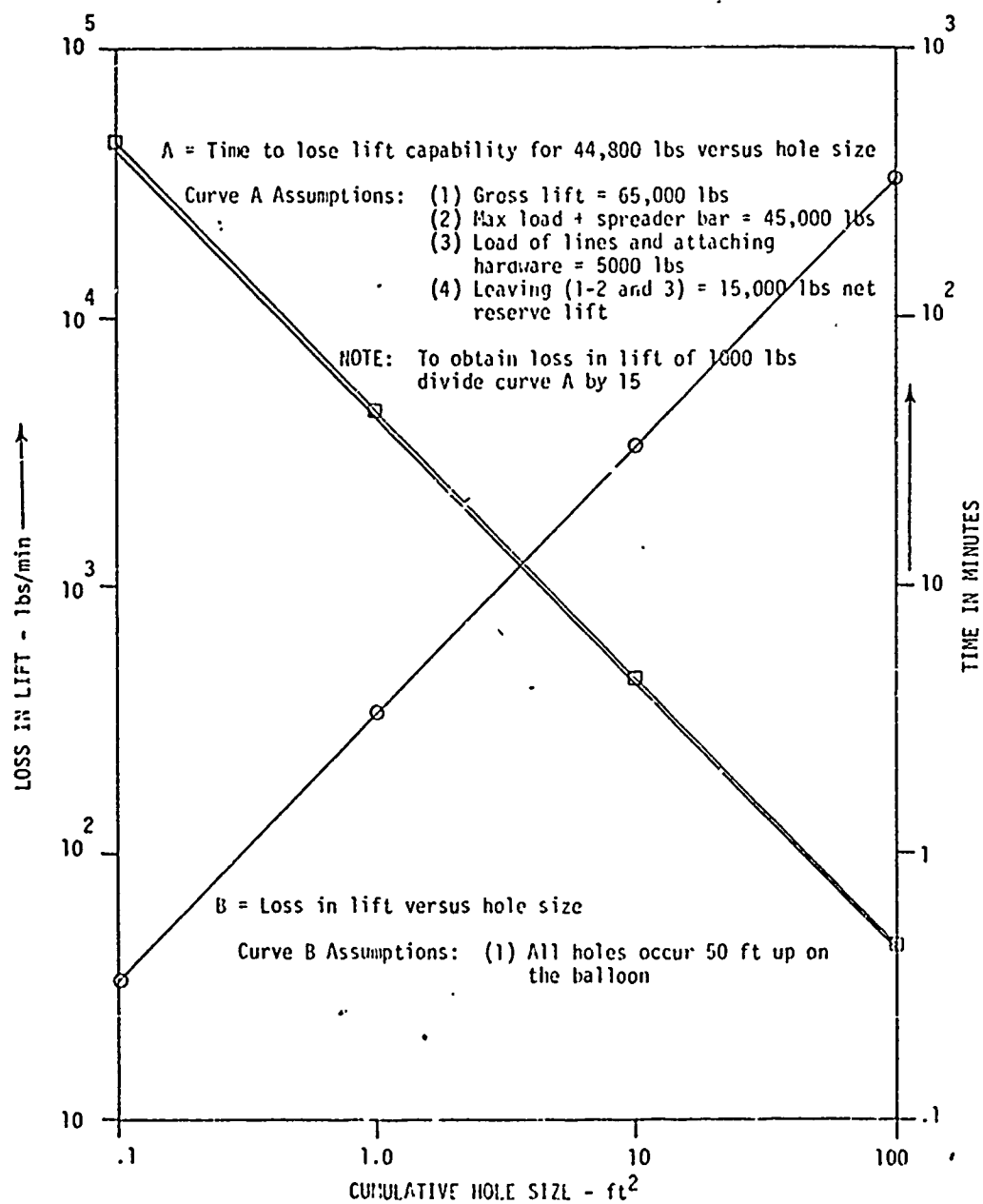


Figure 2. Loss of Lift Resulting from Multiple Holes

With this data, a loss of 1000 pounds of lift for a hole size of  $.1 \text{ ft}^2$  would occur in 1/2 hour. Assuming the fabric holes are 1/2 the projectile size because of natural closure, the previous example of 73-9mm shells or a 2.75 inch rocket would lose 1000 pounds of lift in 1 hour. This in turn would degrade the lift capabilities of the balloon to where it could not carry the full 22.4 tons in 15 hours. In addition to losing lift, loss of gas leaves the balloon in a less taut condition, and more susceptible to wind effects.

Control of the splitting action as a projectile passes through is extremely important in keeping the hole size and loss of gas to a minimum. First, it is highly desirable to keep the splitting crack from propagating any excess distance and second, the splitting cracks under ideal conditions should be in a single direction to enable closure of the envelope behind the projectile. Development of envelope materials with these specific characteristics in mind would be useful in increasing balloon survivability. Another helpful characteristic would be a low friction condition between the envelope and the projectile. In this case the material laid over the nose cap would start sliding outwards under a lower stress condition leading to higher stresses towards the center of the cap and failure at a smaller diameter.

A projectile carrying an explosive charge would be able to open a large hole in the balloon envelope if an effective means for triggering the explosive charge were available.

While it is impossible to predict what will become available in the enemy arsenal, including soft-impact fuzes and laser guns, there is currently no operational capability for destroying the balloon in either of these modes.

The balloon envelope itself is non-metallic, and therefore transparent to radar. It is not anticipated that a pressurizing balloonnet and associated pumps will be used in the military system (these components ordinarily would be radar and infrared reflective) since they add complexity, powering and maintenance problems, and gas loss is higher with increased pressures. In addition, the container will be 250 to 300 feet below the balloon, so that a radar homing device would seek the container. Depending on what is in the container, and the power of the device, such an attack could create significant damage.

There are saturation techniques used by aircraft which would create holes in the envelope in large numbers, however, referring to Figure 2, it can be seen that even with a full load of 22.4 tons, and a full two minutes required for movement of cargo from the ship to shore (this would be in a 1 mile offshore situation) that it would take a cumulative 21 square foot hole to down the balloon before reaching shore. In a like manner, any large projectile or schrapnel device would have the same effect depending on the cumulative size of the hole produced. The shorter the transit time between ship and shore, and the lighter the load being carried, the

larger the cumulative hole would have to be to bring the balloon down before reaching shore. As discussed in the section on balloon failure mechanisms, with proper design of the fabric and envelope, gas losses can be significantly reduced over a non-military design.

Special weapons such as knives or hooks would also open large holes with rips in several directions. However, it would be difficult to reach the balloon with these weapons under normal operating conditions.

Natural hazards such as tree limbs, building projections, power line towers, or snags on the ground can rip holes if the balloon is allowed to be blown against them with sufficient force. While the envelope materials used in current balloons are comparatively tough and can resist considerable abrasion and penetration, care must be exercised in preventing contact with these hazards.

Load lines spaced around the balloon transfer the lift from the envelope to a load ring or attachment region below the balloon. Since simultaneous failure of several of these load lines could be disastrous, it is desirable to provide several forms of redundancy in this area such as multiple connection points and multiple sets of load lines or a net of load lines.

#### C. TETHER AND POWER SYSTEM

##### 1. Cables

Releasing the balloon by severing the cables tethering it

to the ground would create a catastrophic Type A kill. However, redundant cable arrangements in the Ship-to-Shore Balloon Transport System would reduce the probability of cable severing to a very small figure. First the connection between the balloon and the confluence point is accomplished with two cables in parallel, each of which can retain the full lift of the balloon. A third cable can easily be added with a low weight penalty and the three cables separated by sufficient spacing to require individual actions against them. Each additional cable in parallel reduces by another power the probability of hitting all cables. Although the balloon in the Balloon Transport System operates at a relatively low altitude, the balloon to confluence point cables are still high enough above ground to present a difficult target. Each cable therefore has a low probability of hit. Even if these cables were struck by small arms fire, the probability of damaging the 1 inch steel cables is vanishingly small. Explosives or incendiary fire would be required to actually sever the cables. Thus the probability of both hitting and severing is extremely small.

Below the confluence point the retention forces are divided between two lines. The Main Line passes directly to the Yarder; the Haulback Line after passing through a block on the other side of the operating area also returns to the Yarder. While in the air, the wide separation of these two lines keeps the probability of hitting both to a small value.

Near the ground, however, the possibility of an infiltrator severing a line is much greater. For reduced vulnerability, therefore, the inverted skyline should be used in which the Haulback Line returns from the tail block through a block supported by the balloon. This holds the Haulback Line well above ground except at the tail block and the Yarder winches. Guards may be required at these two ground points to protect the cable and guide equipment. Even if the Haulback Line were cut at the tail block, the Main Line would be able to retain the balloon. Further if both the Main and the Haulback lines were cut near the Yarder, an emergency braking device could be used to stop the Haulback cable at the tail block.

Finally, a barometrically activated valve could automatically open and release the buoyant gas at a preset altitude should the balloon be released or escape. This would allow the balloon to be recovered and probably repaired.

## 2. Winches and Blocks

Winch storage and driving drums are as vulnerable as most heavy equipment now in inventory, as discussed in Section III. The winch power and winch control systems are vulnerable in the same manner and areas as automotive equipment. The exposed fuel lines and hydraulic lines can be attacked by small arms and rocket fire. Armor plate over these lines, rerouting the lines behind less vulnerable components and other measures normally

taken for automotive equipment can be used to improve the survivability of these systems against small arms.

Considerable damage could be accomplished by an infiltrator if he were able to gain access to the winch equipment. Sand in the hydraulic fluid, lubrication and bearings, ripped out ignition wires, damaged controls as well as severed cables on the drums could be accomplished quietly. A guard placed near the winch or alerting instruments to call in security forces would be necessary to prevent these actions.

Even if the winch equipment were damaged by small arms fire or by infiltrators, the damage would probably not be a catastrophic Type A kill. Repair or replacement of the damaged parts could probably be accomplished relatively quickly and the equipment brought back into operation.

The tail blocks and other blocks used to guide the cables are also relatively immune to damage, but should be guarded to prevent impairment through a clandestine attack.

#### D. BED DOWN SYSTEM

For long time storage, or for protection during very high wind conditions, the balloon should be bedded down in a prepared location. Tie down lines are installed on the side of the balloon for this operation. Care must be taken to firmly secure both the central balloon line and the peripheral tie down lines during this storage. If not, wind conditions may occur which could generate large scale oscillations of the balloon leading

to failure of some of the lines and major damage to the balloon as it is pounded against the ground.

#### E. BUOYANT GAS

Over a long period of balloon development, hydrogen and coal gas (a mixture of hydrogen and methane) were the only lighter than air gases readily available for balloon buoyancy. Both of these gases are inflammable and explosive--leading to serious vulnerability characteristics. The entire cross section area of a World War I Observation Balloon was therefore vulnerable to catastrophic Type A kill by tracer bullets.

The discovery of sizeable quantities of inert helium in natural gas deposits has solved this vulnerability problem. Helium with a buoyancy only 8% less than hydrogen has been used in the majority of U. S. military balloon applications since then.

Unfortunately helium was not released by the U. S. Government in the 1930's to the German operators of the dirigible Hindenberg. At the time practically all of the helium resources were in the United States and under the control of the U. S. Government. The disastrous burning of the Hindenberg, whether accidental or by sabotage has left in the mind of the public a vivid impression of a vulnerability which no longer exists.

## V. POTENTIAL DAMAGE SOURCES

### A. ENEMY THREAT

Containership discharge operations, it should be recognized, would not be accomplished under assault conditions. The beach would be expected to be secured, and the threat against it would be limited to those weapons which infiltrators might be able to carry into the region--small arms of the 9 mm class, rocket weapons, knives and explosives--or aircraft-mounted weaponry.

A determined infiltrator would most likely attempt to gain access to the winches or to the tail block where he would try to sever the cables or damage the winch power or control components using his knife, axe, or explosives. Guards at these locations would hopefully be the best preventative against such actions.

Concern has been expressed that the height of the balloon during transport operations would reveal its position and draw fire from a distance. At mid trajectory in a one mile ship-to-shore operation the balloon would rise to an altitude in the order of 1500 feet. The line of sight from the balloon to a sea level horizon may be determined from the relation:

$$x = 89 \sqrt{h} \quad \text{where } h \text{ is in miles}$$

or

$$x = 89 \sqrt{\frac{1500}{5280}} = 47 \text{ miles}$$

Since the balloon is not reflective to radar, it would be necessary for enemy artillery to be trained optically. If this visible distance constitutes a problem the transport operations could be limited to the night period.

Attack from the air would probably be with 25 mm size projectiles or 2.75 inch rockets.

Although 50,000 cubic foot balloons were used for several purposes during the recent Southeast Asia conflict, no data has been found to date indicating loss of any of these balloons or even any bullet holes due to enemy action. One balloon system which malfunctioned and drifted out of control, was chased by U. S. fighter aircraft who failed to force the balloon down.

Back in the States, however, bullet holes in advertising balloons are fairly common events and cause no great problems other than to find and patch the leaks. The known bullet holes sustained in balloons during the Southeast Asia period include:

1. Bullet holes in the Macy parade balloons and in a balloon used at a state fair to support an antenna for a local radio station.
2. Bullet holes in the Goodyear blimps.
3. Bullet holes in logging balloons during deer hunting season from hunters who could not resist the temptation.
4. Bullet holes in a set of test balloons accomplished for a special study.

5.. Bullet holes in the previously mentioned Vietnam balloon which drifted away and was unavailable for examination.

Small arms, artillery and aircraft have been used against balloon systems in previous wars. The outstanding example of this was the World War II duel between a depth charge carrying U. S. airship and a German submarine mounting 5 inch guns. Instead of submerging in the customary manner when the airship flew toward it, this submarine stood its ground and fired 5 inch shells into the airship. The airship dropped its depth charges (unarmed unfortunately) before settling into the water. This was the only airship casualty to enemy action during World War II.

In World War I, of course, many hydrogen-filled observation balloons were shot down in flame by tracer bullets from aircraft.

A cannon ball was reported to have passed through the gondola of a U. S. Civil War observation balloon.

The Premier of France was shot in the hand while escaping by balloon from Paris during the Franco-Prussian War.

While the balloon envelopes of Civil War and Franco-Prussian War balloon systems must have been struck by numerous bullets, there is no report of these balloons having been forced down by this gunfire.

Several of the above situations are described in the section on the History of Balloon Losses.

## B. NATURAL HAZARDS

### 1. Wind

High wind is the major natural hazard in the operation of the Balloon Transport System. The large size of the balloon together with the comparatively large coefficient of drag combine to create large drag forces under moderate to high wind conditions. These forces could reach a level where they exceed the tether or the power system capabilities and the balloon breaks completely away or the balloon is blown down into trees or projections where the envelope is punctured.

Figure 3 shows the results of drag tests conducted in November, 1973, and are extrapolated for higher wind velocities as well as two balloon sizes--a single  $1.3 \times 10^6 \text{ ft}^3$  balloon and two  $680,000 \text{ ft}^3$  balloons in tandem.

### 2. Snow and Freezing Rain

The second major natural hazard, and one for which a satisfactory solution has not been found, is the accumulation of snow and freezing rain on the balloon.

A 1/4 inch shell of ice over the upper hemisphere of a 125 ft diameter balloon ( $1.3 \text{ million ft}^3$  volume of the type anticipated for a military BTS) weighs approximately 36,000 lbs. Thus a layer of ice not only degrades the capability of the system, but soon can reach a thickness sufficient to force the balloon to the ground or upon trees or other projections where it may be seriously damaged.

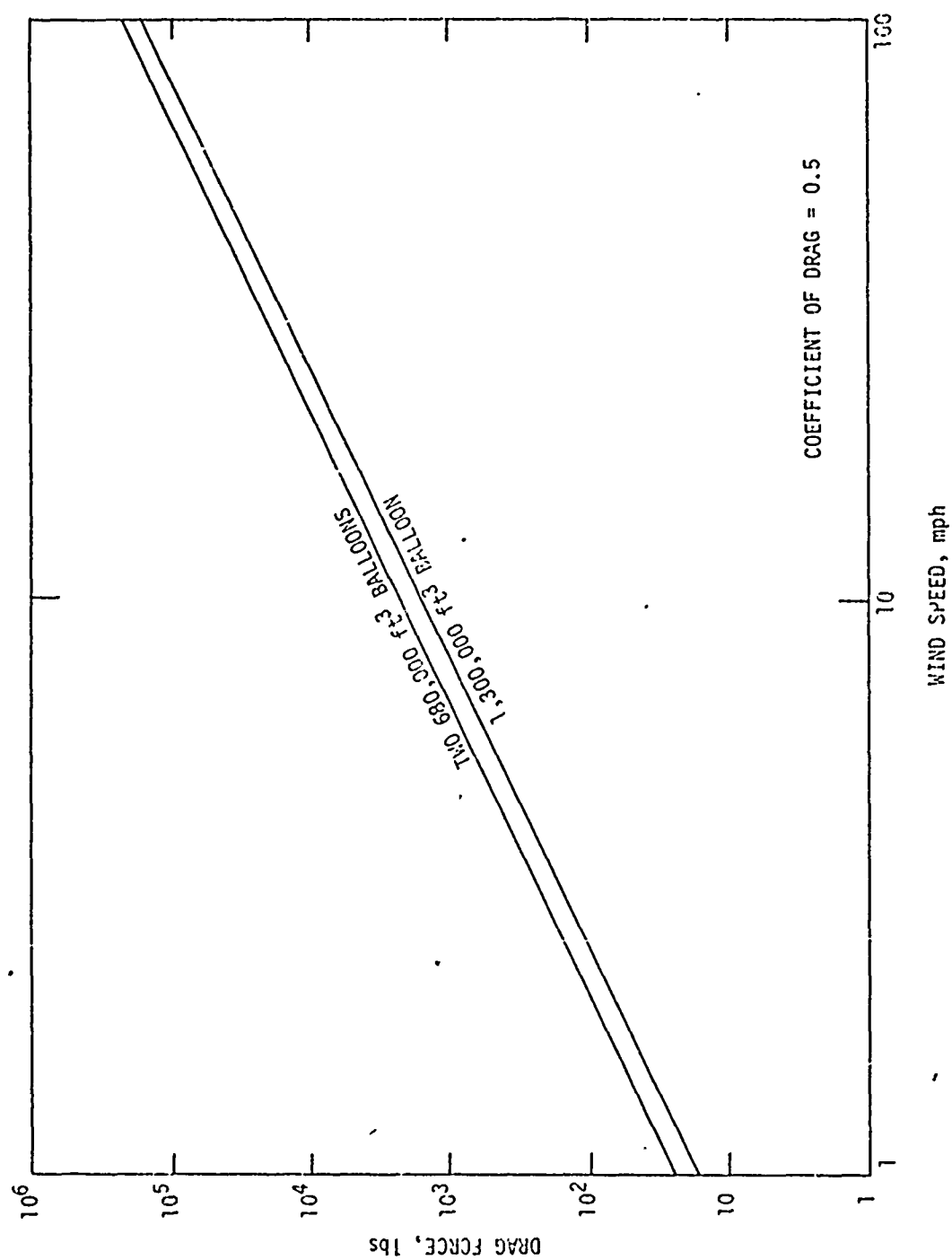


Figure 3. Drag Force on Stationary Balloons in Various Winds

Snow buildup has been a serious problem in the operation of logging balloons in the Pacific Northwest. The logging companies have found it necessary to place personnel on top of the balloon to sweep the snow from the surface. This, of course, is a dangerous operation with the possibility of a section of snow cascading from one side followed by the balloon tipping to the other side.

Jerking the balloon down to one side to loosen and remove the snow has also been tried. In one case the balloon after discharging its load of snow shot upward and lifted a caterpillar tractor on end.

Various thermal and chemical methods have been investigated for the prevention of snow and ice buildup. To date, these techniques have not proved successful. Mechanical methods will continue to be used until better methods are developed.

Icing is believed to have been the cause of the loss of one of the heavy lift balloons. In this case a logging balloon was found one morning on the treetops punctured by tree limbs. Meteorological data indicated that there had been icing conditions in the mountain region which had not been noticed by maintenance personnel in time to take protective action.

Another form of ice found at all latitudes is hail. No serious problems are anticipated from this source--the hail just bounces off the balloon envelope.

### 3.. Lightning

Tethered balloons with their direct connection to ground are particularly vulnerable to lightning. Unfortunately there is inadequate knowledge of lightning characteristics and actions to specify with certainty whether the tether should be conductive, non-conductive or partially conductive. Current thinking leans toward the last situation.

The one inch steel cables of the Balloon Transport System are expected to be able to take a lightning strike without melting and parting.

During the development of the heavy lift balloon, lightning struck a 240,000 cubic foot balloon, resulting in a series of half dollar size holes. It was determined that these holes were created by the melting of an interior wire strung through the balloon which in turn condensed and formed a series of projectiles which punctured the balloon. A lightning rod system was then developed and installed on the balloon. No strike or damaging effects have since been reported for this family of balloons.

The ARPA Family II Balloon tethered at 10,000 ft over Cudjoe Key, Florida, with a non-conductive cable received a lightning strike which jumped to ground through the winch. Evidently a conductive layer of salt and moisture had built up on the cable. While the winch operator was somewhat "shook" at first, he returned to bring the balloon down with no adverse effects to the balloon or tether.

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The ARPA Family J1 Balloon tethered at 10,000 ft over Cudjoe Key, Florida, with a non-conductive cable received a lightning strike which jumped to ground through the winch. Evidently a conductive layer of salt and moisture had built up on the cable. While the winch operator was somewhat "shook" at first, he returned to bring the balloon down with no adverse effects to the balloon or tether.

In the observation balloons of World War I, the principal concern was the possibility of lightning igniting the hydrogen gas. Instructions were provided by the Bureau of Aeronautics and the Army Air Service governing actions to be accomplished at the approach of dangerous conditions as indicated by increased "atmospherics" on the radio telegraph. Observers were to be immediately landed, instruments removed, grounding connection and special dischargers attached and the balloons reflown at altitudes which would "insure their falling clear in case of being struck and fired."

The replacement of hydrogen by helium between the two world wars solved the problem of burning, but brought the question of tether integrity and safety to the forefront.

Numerous lightning strikes were taken by the barrage balloons of World War II. Primary advice for operation of these balloons was to ground them well and--stand back.

## VI. CONCLUSIONS AND RECOMMENDATIONS

### A. CONCLUSIONS

The Balloon Transport System has two competitors for off-shore discharge of cargo, the helicopter and the crane. Neither of these two alternatives have the capability of the balloon system, for the helicopters are incapable of lifting loads greater than 34,000 pounds, and the crane is limited, even in its largest mobile sizes of 300 tons, to reaches of 120 feet with the required lift of 44,800 pounds. The balloon system can lift any load up to its design size, and over any distance from a few feet up to 1 mile with little change in configuration other than adding more cable for the long distances (over 1000 feet).

In comparison to helicopters, the balloon system is less vulnerable, with almost all failures being of a class "C" type - that is a load cycle or cycles would be completed before having to be returned to the beach for repairs.

In comparison to cranes, the balloon system is more vulnerable, with only the winching subsystems being directly comparable, and the other components adding complexity and greater opportunity for enemy action.

The balloon envelope is of such a nature as to lose lift slowly when punctured, usually giving time for the operator to complete a cycle or more depending on the nature and number of punctures. Self-sealing fabric, and fabric which would show some coloration when punctured would aid in locating leaks,

and reducing gas loss. In like manner, crossing of load tapes on the balloon itself would provide redundant support if one or more of the tapes were severed in a single location. The winching machinery is as vulnerable as heavy equipment such as bulldozers and trucks, and should have the same design safety features incorporated as these types of equipment. Redundancy of load lines from the balloon to the confluence point would reduce the chance of loss should one be severed. The lines, blocks, buoys and attaching devices offer very small cross sectional area to small arms and rocket action, and would be most susceptible to infiltrator destruction. The best defense against such action is patrol guards near these vulnerable components.

#### B. RECOMMENDATIONS

In order to reduce the vulnerability of the Balloon Transport System, the following actions are recommended:

1. A design analysis should be conducted addressing fabric sealability, coloration-upon-puncture, bonding and load transfer capabilities to reduce the envelope vulnerability.
2. A design analysis should be conducted to determine what safety features should be designed into the winching subsystems.
3. A study should be undertaken to determine configurations for line attachment at the confluence point to reduce the chance for balloon loss should one or more lines be severed.

## APPENDIX A

### HOLE SIZE DETERMINATION AS A FUNCTION OF PROJECTILE SHAPE

The size of the holes punched in a balloon envelope by a moving projectile is a function of the projectile shape, size and velocity as well as the material elasticity, strength and surface characteristics. Interestingly, these holes are generally smaller than the projectile cross section.

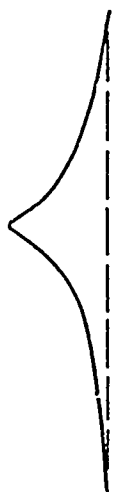
In a broad sense, as a projectile penetrates the balloon, the envelope material stretches around the projectile and after the projectile breaks through, the envelope material snaps back to a smaller size.

The detailed physics of the punching process is as follows:

At the location where the projectile first contacts the balloon envelope, the envelope membrane has initial biaxial tensions depending upon the internal pressure, load and envelope curvature. As the projectile moves through the envelope region the envelope is depressed in a curved indentation, (see Figure A-1). The curved cross section of this indentation is of course due to the two dimensional characteristic of the envelope membrane which allows the tensions created to be diffused in two directions.

It may be shown that the strain and the stress at any point is proportional to the slope of the envelope membrane at that point. Maximum slope and thus the maximum stress will

A-1a SHARP POINTED  
PROJECTILE



A-1b ROUNDED NOSE PROJECTILE



A-1c FLAT NOSE PROJECTILE

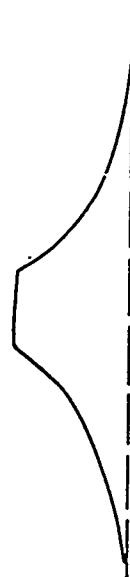


Figure A-1. Balloon Envelope Curvature for  
Various Projectile Shapes

occur at the edge of the region of contact. Initial failure of the envelope can therefore be expected to occur at this edge.

The shape of the projectile has considerable influence on the contact edge location and therefore the size of the resulting hole. If the projectile has a sharp pointed nose (Figure A-1a), the membrane slope and stress will rapidly rise and the material strength will be exceeded in a small region. The projectile point will pierce the envelope and the envelope will probably split far enough to allow passage of the projectile. If the split is essentially in one direction, the envelope will close like a curtain after the projectile has passed, leaving only a small hole area for the escape of balloon gases.

If, however, the projectile has a rounded nose as illustrated in Figure A-1b, the stresses are not as concentrated. Although the slope, and therefore, the stresses are maximum at the edge of the contact region, the material is more distributed and the slope is lower than for the pointed projectile situation. As previously indicated, the membrane at the initial point of contact has zero slope and minimum stress. Each successive circular strip laid down around this initial point has an increasing stress corresponding to the membrane slope at the instant it was laid over the projectile nose. This stress condition is frozen in and the envelope prevented from sliding laterally over the nose by friction between the envelope material and the projectile. Finally the envelope attains

a slope and a stress condition which exceeds the material strength. At this point the material yields and a circular section of material corresponding to the cap over the nose of the projectile is torn from the envelope. This circular section is generally less than the projectile cross section. However, as the projectile continues through the envelope, the envelope material stretches further, or splits to allow passage. Following the projectile's passage the elastic characteristic of the envelope material reduces the hole somewhat, and, if the split is only in one direction, the effective hole is not too large. If, however, splitting actions occur in two perpendicular directions, the effective hole can be much larger.

Figure A-1c illustrates a third type of projectile nose --a flat face with abrupt edges. In this situation the envelope material is laid over the face of the projectile with essentially no stretching. In addition, the abrupt edges create a rapid increase of slope to the critical stress condition. The flat face therefore creates a cookie cutter effect in punching out holes the shape and essentially the size of the projectile.