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TETHERED AEROLOGICAL BALLOON SYSTEM

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ABSTRACT. The tethered aerological balloon system (TABS) currently under development at NOTS is designed to maintain a captive balloon and payload at stratospheric altitudes for an indefinite period of time, taking advantage of the region of minimum wind velocity nearly always present at some level in the lower stratosphere. The system consists of (1) a conventional polyethylene balloon fitted with a self-deploying reefing system to reduce lateral drag; (2) an airborne telemetry-command package capable of monitoring up to six aerological or other parameters concurrently (additional packages may be distributed along the tether as needed); (3) a NOTS-developed glass fiber tether having a tensile strength comparable to that of steel, at one-fourth the latter's weight, fabricated in splice-free lengths exceeding 100,000 feet; and (4) a mobile ground vehicle from which all functions subsequent to launch can be performed, carrying a crew, control winch, and equipment to communicate with a ground telemetry and command station; the vehicle can run with the wind to reduce lateral drag loads on ascent or descent. The system is expected to become operational the fall of 1965. Various uses and possible further developments of such a stratospheric moored platform are discussed, including applications to manned systems.

U.S. NAVAL ORDNANCE TEST STATION
China Lake, California
September 1965

U. S. NAVAL ORDNANCE TEST STATION

AN ACTIVITY OF THE BUREAU OF NAVAL WEAPONS

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FOREWORD

This report discusses a portion of the work performed under Project TABS (Tethered Aerolcgical Balloon System) from July 1962 to the present.

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INTRODUCTION

In June 1962, a proposal by Mr. Charles A. Smith, of Aerological Laboratories, Encino, Calif., was brought to the attention of the U.S. Naval Ordnance Test Station (NOTS). In this proposal was discussed the possibility of mooring a balloon at stratospheric altitudes for extended periods of time. The system was originally intended to support a vertical chain of sensors to monitor meteorological parameters continuously, at a single location, over a range of altitudes—hence the acronym TABS (tethered aerological balloon system). The utility of such a system, if feasible, in providing a relatively fixed high-altitude long-duration platform for a wide range of geophysical observations was immediately evident, and Mr. Smith was invited to NOTS for further discussion of his proposal.

BACKGROUND

Meteorological Data

The feasibility of such a system rests upon the observation that temperate-latitude profiles of wind velocity as a function of altitude, such as those illustrated in Fig. 1, almost invariably show a maximum in the troposphere, followed by a minimum in the lower stratosphere. In the region of the maximum, generally between 30,000 and 50,000 feet, the wind velocity exceeds 50 knots nearly half the time and not infrequently reaches 100 knots. At the minimum, however, which usually lies between 55,000 and 75,000 feet, the wind velocity exceeds 20 knots in less than 5% of the profiles studied, and is generally below 10 knots. The wind direction is, as a rule, reasonably constant through the troposphere, but often changes sharply just below the minimum. The altitude of the minimum shows considerable day-to-day variation, and this, coupled with its often rather limited vertical extent, renders its existence much less evident when profiles are averaged over periods of several days, or over successive years at the same date.

Attempts to moor conventional balloons in the troposphere under any but the lightest wind conditions are frustrated by the excessive drag loads imposed, and flights of any significant duration are impractical. The use of high lift-to-drag aerodynamically shaped lifting vehicles alleviates the situation somewhat, but such systems have nevertheless proven unsuitable for flights to altitudes much in excess of 20,000

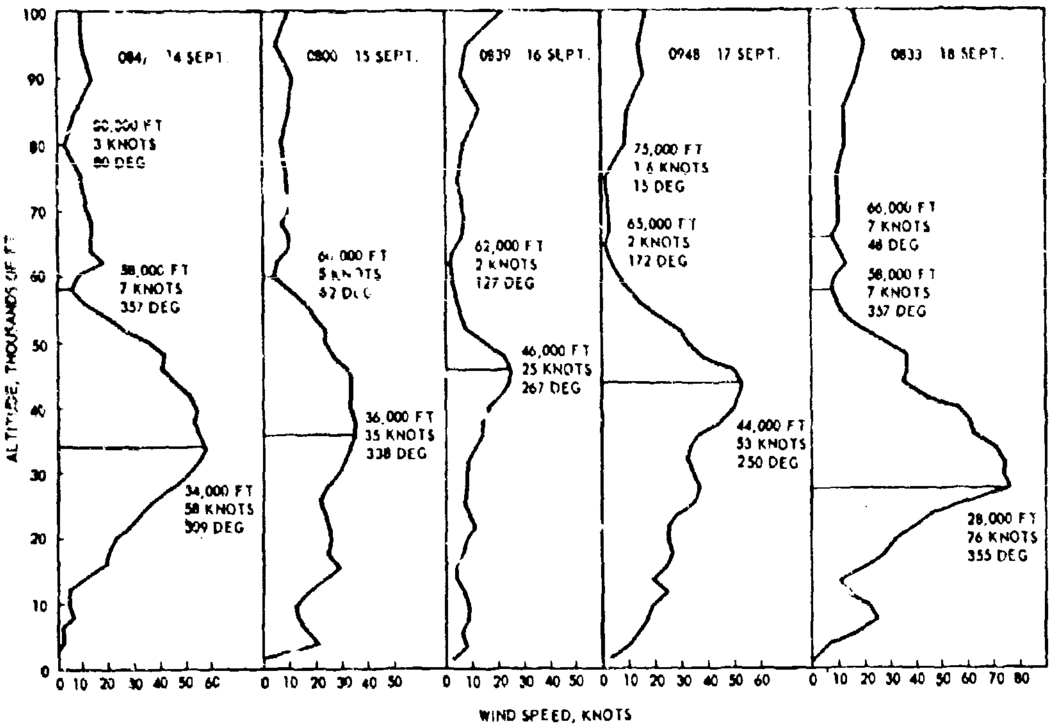

FIG. 1. Wind Profiles, NOTS, Week of 14 September 1964.

feet. If, however, one can place the balloon in the region of minimum winds, the drag on the balloon will be much lower; only the relatively small cross-section tether will be exposed to the high-velocity tropospheric winds, and a minimum total system drag can be maintained by slight adjustments in balloon altitude. It should, therefore, be possible to maintain the system aloft for a considerable period of time, provided that the wind velocity at the balloon remains relatively low, and does not become unreasonably great at lower altitudes.

Balloon and Tether Design and Analysis

Such a system of course requires balloons of suitable design and construction to support the vertical and horizontal loads involved and utilizing materials providing sufficient gas retention and resistance to deterioration under stratospheric conditions to remain aloft for days or weeks at a time. The former requirements appeared to be satisfactorily met by existing natural-shape, taped polyethylene balloons, and while information on the latter problems is as yet relatively sparse, it appears probable that current and projected developments in balloon technology will provide vehicles suitable for flights of at least moderate duration.

It is also necessary to consider the properties of the tether employed. The "classical" material, music wire, has great tensile strength—up to 280,000 psi in diameters near 1/10 inch—and more modern steels are available which are up to 30% stronger. Steel, with a specific gravity of 7.8, is, however, also very heavy, and even the best alloys will support their own weight in lengths only up to approximately 110,000 feet. The total tether length required for a balloon moored at 75,000 feet can easily approach this value, leaving no margin of strength to meet the additional loads imposed by aerodynamic drag and the excess balloon lift required to hold the system erect. One possible solution, that of tapering the tether downward from the balloon, also fails, since with high tropospheric winds the tension in the tether at the ground or at intermediate altitudes may become comparable to that at the balloon.

Since it thus appears that the strength-to-weight ratio of the tether material is a critical parameter, it becomes evident that the solution is to be sought in the direction of the lightweight, high-tensile-strength materials which have resulted from recent technological advances. It was found from preliminary analyses that if a material having a tensile strength of 150,000 to 200,000 psi and a specific gravity of 1.5 to 2.0 could be procured, the stratospheric moored system would become feasible. It appeared that several candidate materials were or would soon become available which might fall within this range.

In order to assess the feasibility of a stratospheric moored balloon system in general, and to ascertain the balloon and tether parameters required to meet specific wind conditions, an approximate method of analysis was worked out (see Analytical Procedure) which involves the balancing of the vector forces acting at successive points from the balloon down along the tether to the ground, the entire system being presumed in equilibrium. The analytical process yields, for a particular wind profile, a balloon of specified lift and weight, an assumed payload, and a tether of given diameter, density, and tensile strength, a set of figures for tether tension and angle to the vertical at successive uniform intervals of altitude. Failure of the system is indicated by an increase in tension beyond the specified breaking strength of the tether or an increase in the tether angle beyond the horizontal (in which case, of course, the tether cannot reach the ground). It is then necessary to increase either the balloon lift (and drag) or the tether strength (and hence tether drag and weight) and repeat the calculation, until either an equilibrium configuration is found or the ultimate capacities of the balloon or tether material are exceeded. In the former case, the given wind profile can be tolerated; in the latter it cannot, and such winds must either be avoided, or countered by improvements in balloon design or tether material.

Ground Station

The ground station from which the system is to be flown must incorporate a winch capable of deploying the system, adjusting its flight altitude as necessary in order to maintain the system aloft, and retrieving the payload (with tether and balloon, if possible) at the end of the flight. The ground station must be provided with data concerning the wind velocity as a function of altitude. These data might be obtained from periodic free-balloon soundings during the flight; a much more satisfactory solution, however, would be to equip the airborne system with instruments capable of measuring the wind velocity at the balloon and at various points along the tether, and continuously telemetering this information to the ground station.

There is a further requirement on the ground station if the system is to be truly operational. Provided that the balloon can be maintained aloft under a given wind profile, the question now arises: Is it possible to launch the system under such conditions? Analysis, and subsequent experience, suggest that the system envisioned cannot be maintained erect if the relative wind at the balloon exceeds approximately 20 knots, at any altitude. If the balloon is to rise slowly, under the control of the winch operator, the system cannot be launched unless the wind is below 20 knots at all altitudes; such conditions are relatively rare, occurring less than 10% of the time. If the system is to be flown under less ideal conditions, other methods must be used.

One possibility is to allow the balloon to rise and move with the wind as if it were free, paying out the tether as fast as it is needed. This has two serious drawbacks: (1) The tether reel-out rate may become excessive for any reasonable winch system. (2) The balloon may be carried so far downwind by the time it comes to altitude that the weight of tether to be supported may exceed the balloon's lifting capacity.

A more attractive solution would be to mount the winch on a mobile land vehicle (or a ship at sea). If the vehicle can then move more or less parallel to the existing winds at speeds up to, say, 40 knots, it should be possible to launch the balloon and allow it to rise under control to altitude through winds up to 60 knots, provided sufficient maneuvering space is available. Even higher winds at specific altitudes might be tolerated by allowing the balloon to rise "free" through the regions in which they occur.

Preliminary Investigation

The system thus proposed appeared to offer sufficient promise to warrant further study by NOTS. A large stock of miscellaneous balloons, acquired in connection with other projects, was on hand; other necessary materials and equipment were readily available; various areas on Station offered airspace closed to civil traffic, lying above relatively flat and accessible desert terrain; and several people were experienced in the handling and launching of balloons. A series of tests was therefore undertaken, using small (18- and 23-foot) balloons, nylon line, and a surplus aerial tow target winch mounted aboard a pickup truck.

No records were established during these tests, although successful flights to relatively low altitudes (approximately 5,000 feet) were made, but a great deal was learned about the handling and rigging of balloons for this type of operation. The mobile-winch technique was tested and found feasible, and the design parameters for the ground vehicle and its equipment were established. A considerable amount was learned about the properties required for the tether and possible methods for its deployment; and finally a great deal of data was acquired against which the analytical technique outlined above could be checked, and from which aerodynamic parameters, pertinent to the analysis, such as drag coefficients, could be derived empirically.

On the basis of these results, it was decided to proceed with a program directed toward the development of an operational system capable of supporting a payload of a few tens of pounds in the lower stratosphere for as much as a week at a time. Funds were solicited and procured from the Atomic Energy Commission and subsequently from the Advanced Research Projects Agency, a contract was drawn up with Aerological Laboratories, and a full-scale developmental program was undertaken. This program has led, during the past 3 years, to a system which is on the verge of becoming operational. The components of the system, and some of the developments leading to their present configuration, will be described in the next section.

SYSTEM CONFIGURATION

OPERATIONAL SITE

During the early stages of project TABS, a number of possible operational sites were considered. The requirement of extensive restricted airspace and terrain permitting considerable mobility limited serious consideration to a few large military reservations in the West, and none of these was found to offer sufficient advantages over NOTS to warrant the more complex logistics involved. The use of a Navy vessel at sea was explored and found both feasible and attractive; again, however, the amount of planning and scheduling involved suggests that such operations should be postponed until a working system has been developed and tested.

Of the areas available at NOTS, the most suitable was found to be the Randsburg Wash test range, an annex to the southeast of the main body of the Station, adjoining and sharing airspace with Edwards Air Force Base and the Army's Camp Irwin reservation. Ground usage of this range is limited, and the airspace is generally available on weekends, and by arrangement at other times.

An existing road, extending eastward for 14 miles in the general direction (approximately west to east) of the summer tropospheric winds, and free of sharp bends or overhead wires, was graded and realigned to permit smooth travel of the winch vehicle at speeds up to 45 mi/hr (Fig. 2). While other, more convenient, areas of the Station

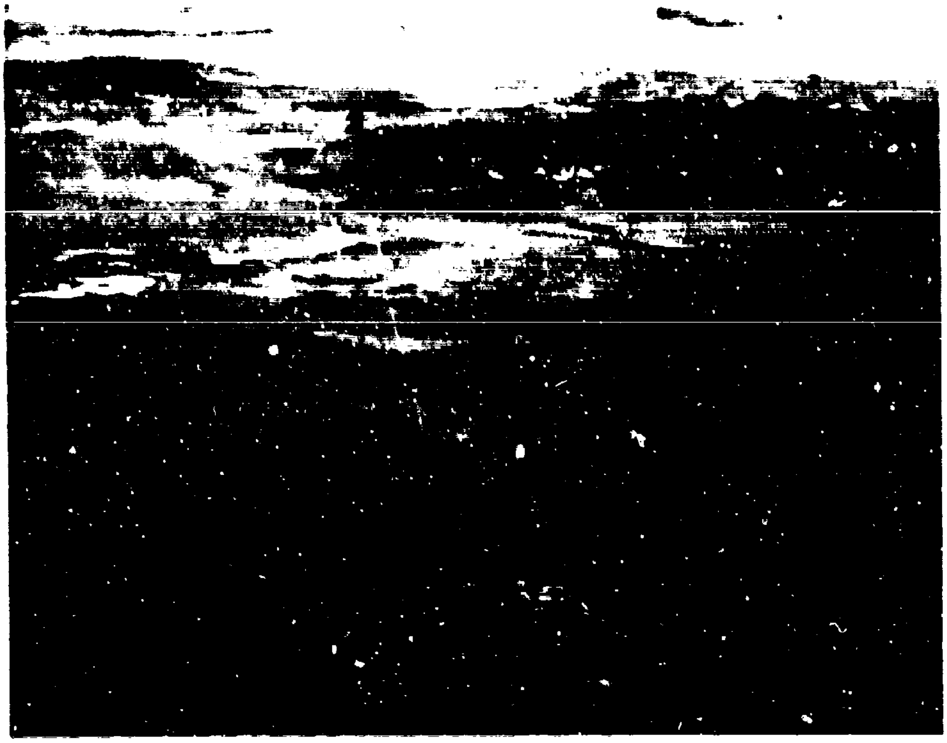

FIG. 2. Balloon Flight Area at Randsburg Wash Test Range. The mobile launch road extends generally eastward (azimuth, approximately 80 degrees) for 14 miles from the balloon inflation site, 1, to its terminus, 2.

have been employed for small-scale tests, Randsburg Wash has been, and will continue to be, the site of major operations.

BALLOON

One of the problems familiar to every balloonist—that of preventing a partially inflated balloon from converting itself into a spinnaker under the influence of a gust of wind—is doubly serious in the case of the tethered balloon. This is so, because while a free balloon, once launched, moves with the wind and thus no longer requires restraint, the tethered balloon may be subjected to appreciable lateral winds all the way to altitude. A surprisingly simple solution to this problem has been found, however: A close-fitting sleeve of polyethylene is slid over the lower three-quarters of the length of the uninflated balloon. Upon inflation, the balloon assumes an ideal "ball-on-a-stick" configuration with a taut bubble which resists deformation under a lateral wind loading and exhibits drag characteristics not greatly inferior to those of a smooth sphere. As the balloon rises to altitude and the bubble expands, the sleeve is forced down accordionwise, offering sufficient resistance to maintain the desired configuration.

This system has been tested with static inflations of the 18-, 23-, and 75-foot balloons employed in this program, with entirely satisfactory results. Figure 3 shows the static inflation of a 75-foot balloon in an

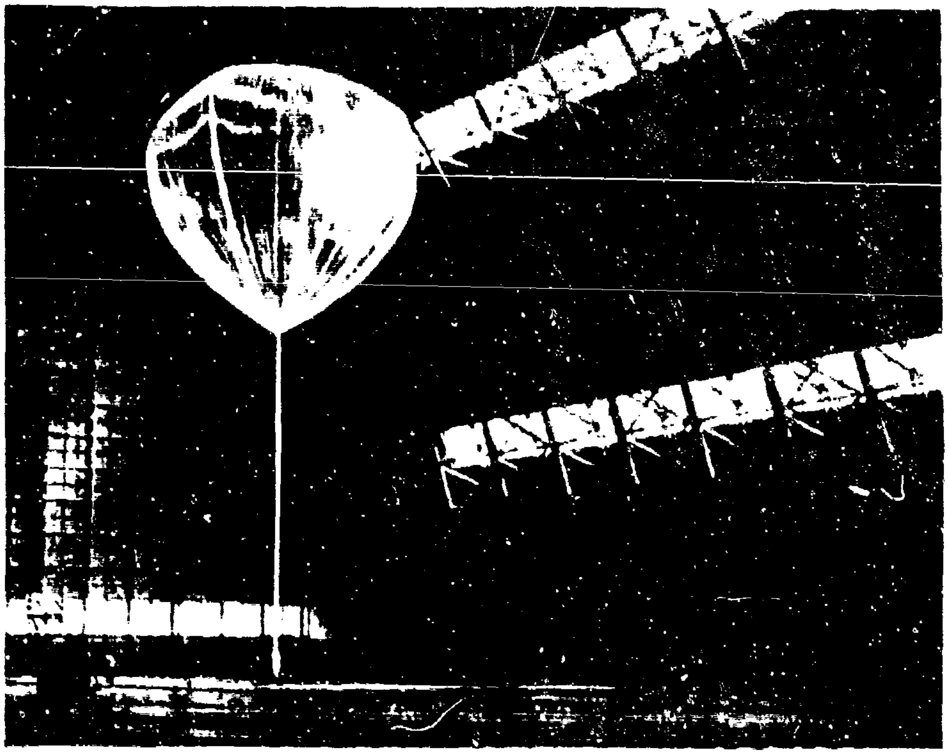

FIG. 3. Static Inflation of 75-Foot Taped Polyethylene Balloon to Test Deployment of Sleeve Clutch.

airship hangar at Santa Ana, Calif. The former two sizes have also been flown tethered to altitudes as high as 15,000 feet with success, using this method (Fig. 7 illustrates a 23-foot balloon so rigged for a low-altitude test flight, with the balloon more than half expanded at ground level). In installing the sleeve clutch it is essential to refold the balloon in such a way that the portion within the sleeve has the form of a fluted column with the load tapes on the outside and the gore panels tucked inward, to avoid pinching the envelope material as it emerges from the sleeve.

A further advantage of this technique is that it provides an appreciable enhancement of the vertical ascent rate. With the large free lifts (often exceeding 60% of the balloon gross lift at ground level) which must be provided in order to support the tether weight as well as wind drag forces when the balloon comes to altitude, the rising balloon, if unrestrained, assumes a variety of extremely unstable configurations which greatly increase its drag and reduce its ascent rate. The sleeve-clutched balloon, on the other hand, takes on a stable, somewhat flattened mushroom shape and ascends considerably more rapidly, with a minimum of billowing and pendulation. This has been verified by radar and phototheodolite observations of pairs, clutched and unclutched, of 18-foot balloons inflated to large free-lifts and allowed to ascend together from adjacent release points. The clutched balloons ascended at a rate up to 15% greater than the unclutched ones, and exhibited vertical drag coefficients of 1.2 to 1.6.

INSTRUMENTATION

As noted in the discussion of the ground station it is desirable to provide airborne wind-speed sensors and telemetry (TM) to relay wind velocity data to the ground. An altitude sensor is also of considerable utility, especially during the ascent phase. If instrumental payloads are ultimately to be carried, TM channels are also desirable for relaying data to the ground. A ground-to-air command system should also be provided, to permit voluntary separation of the payload and tether from the balloon if needed at the termination of the flight, and to allow switching of modes of operation of the airborne instruments to conform to observational requirements.

The package represented by the block diagram of Fig. 4 has been developed to fit these requirements. Powered by silver-zinc alkaline batteries, it provides up to six channels of FM TM on a single VHF carrier (only two channels are currently utilized, for pressure-altitude and wind-speed data) as well as a UHF command receiver for mode selection and balloon cutdown. This apparatus is housed in a glass-resin-covered foam plastic case 8 1/2 inches square and 56 inches high, and is carried in the balloon train, the load being transmitted through a pair of steel stays straddling the package. No particular effort was made to avoid weight; the entire package, with two antennas, weighs somewhat less than 50 pounds. Two identical packages have been constructed and tested; they are shown in Fig. 5.

The ground station, incorporating a pair of helical antennas, a command transmitter, a TM receiver, discriminators for the data channels, paper chart and magnetic tape recorders, and meters for direct pressure and velocity readout, was originally housed aboard the winch vehicle. It has since been found more practical to remove the ground apparatus to a separate location, and it is presently housed either in a fixed instrumentation site for operations at Randsburg Wash, or in an air-conditioned mobile van for use elsewhere. Communication with the winch vehicle is maintained by a radio link.

TETHER

A wide variety of possible tether materials was investigated and tested. Of these, the most promising involved a collimated bundle of glass fibers embedded in epoxy resin, but commercially available specimens suffered from limited flexibility and brittleness and could not be procured in sufficiently great lengths. It was believed that these limitations could be overcome, and the development of a suitable tether was undertaken at NOTS.

A pilot production line was set up, and experiments were carried out using various combinations of glass tether and resin, with highly satisfactory results. Specimens were made in diameters ranging from 0.060 to 0.095 inch, with breaking strengths of 800 to 1,800 pounds. Tensile strengths in excess of 225,000 psi could be achieved consistently

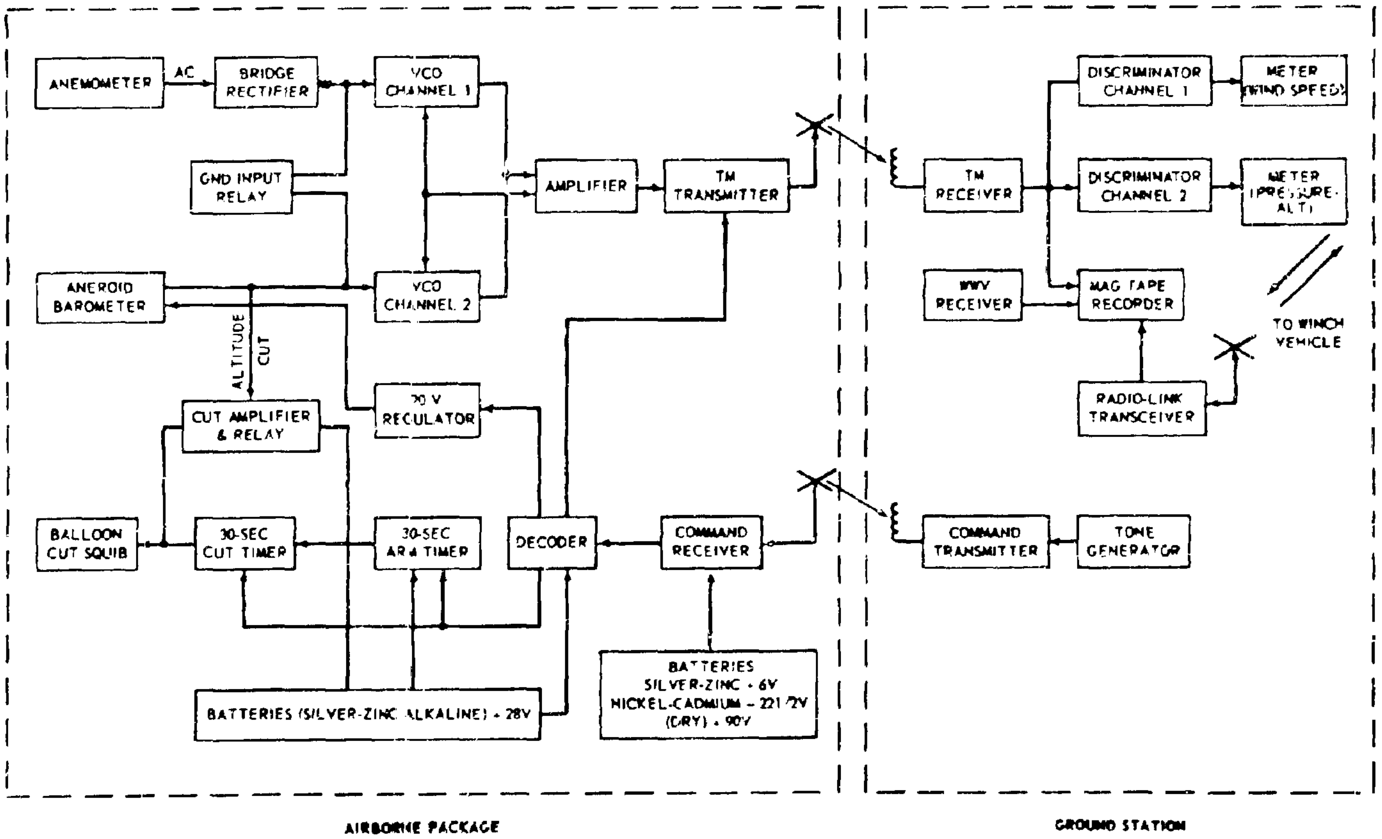

FIG. 4. Block Diagram of TABS Telemetry and Command System.

with occasional specimens running over 300,000 psi. With a resin content of approximately 20% by weight, the samples displayed a specific gravity of 1.6 to 1.7, yielding strength-to-weight ratios and breaking lengths exceeding those of music wire by a factor of 4. All of these

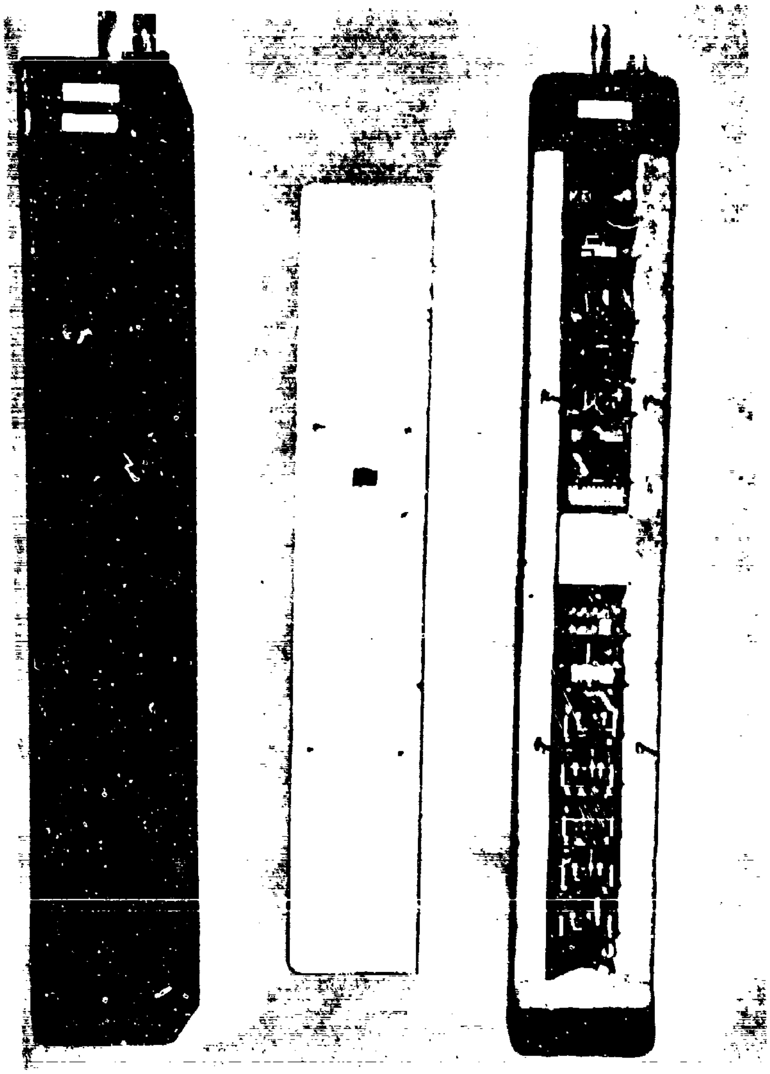

FIG. 5. TABS Airborne Telemetry-Command Packages, Closed and With Cover Removed. The cylindrical-vane anemometer plugs into the large fitting at the top, next to the cut-down squib connector. The aneroid barometer assembly is mounted on the fifth shelf from the top inside the package. The lower six trays carry the silver-zinc and nickel-cadmium batteries. The antenna leads extend through the bottom of the package.

results could be achieved while retaining a high degree of flexibility, comparable to that possessed by steel wire in similar sizes. This portion of the tether development culminated with the production of a continuous splice-free length of material 0.065 inch in diameter and 8,500 feet long, with a minimum break strength of approximately 750 pounds. This specimen was used throughout a series of trial flights and performed in highly satisfactory fashion.

In view of these results, it was decided to set up a full-scale production line capable of manufacturing the tether in lengths of up to 150,000 feet. A 20- by 200-foot area in an existing building was partitioned off and partially enclosed with dust-excluding screening and positive-pressure air conditioning, and the pilot production line was reconstructed on a larger and more permanent scale. For a complete discussion, see Tether Development.

While the new facility was being constructed, Owens-Corning Fiberglas Corporation, which had been supplying the glass roving, offered to manufacture approximately 50,000 feet of 1,500-pound break-strength material of basically similar construction. This proposal was accepted as providing a possibility for conducting intermediate-altitude tests; Owens-Corning was able, however, to produce a total length of 81,000 feet of material of 0.093-inch diameter testing to 1,650 pounds, and the entire quantity was purchased. Approximately one-half of this material has been expended in a series of flight tests to investigate various methods of handling and deploying the tether.

A number of problems remain to be explored with regard to the glass-resin tether. One of the most important concerns the making of attachments to the ends of the tether, which, of course, cannot be knotted. For tensile tests, hollow metal ferrules are potted with epoxy resin to the ends of the test specimens, but the curing process is slow, unless heat is used, and careless handling will allow the sample to break if it is kinked near the mouth of the holder; a new approach providing a rapid, secure connection is needed here. For attachment to the winch drum or the balloon load line, a few turns about a reasonably large-diameter cylindrical surface provide adequate friction to hold the tether end securely, without excessive local stresses (for the attachment to the balloon load line, a large, lightweight but rigid flanged hoop some 24 inches in diameter and 1 inch broad is used, with the flanges extended on one side to hold a shackle pin to which the load line is tied). What is needed, however, is a simple, rapid field technique for making splices in the middle of the line without degrading either its strength or its flexibility to any significant degree. Efforts are currently being made to solve both of these problems (see Appendix).

It has been found entirely feasible to embed one or more copper wires into the tether as it is being fabricated, at only a slight penalty in weight and tensile strength. The possibility of also depositing a conducting outer layer over the tether, to provide a coaxial conductor, is being considered; such techniques would, of course, be of great usefulness for supplying power to and communicating with an airborne system.

LAUNCHER

Initial experiments involving a pickup truck with a hand- or electric-powered tow target winch as a mobile launch platform indicated that a somewhat more sophisticated system would be required. An effective, if unlikely, solution was provided by the acquisition of the surplus amphibious truck illustrated in Fig. 6 and 7. Six-wheel drive and large-diameter tires permit traversal of dirt roads and open desert terrain at adequate speeds with excellent stability; extensive and relatively unobstructed deck space, coupled with a variety of power takeoff points, provided an ideal base for the winch and tether rigging required. The main winch, of 18-inch core and 36-inch flange diameter, 32 inches between flanges, with a capacity of 100,000 feet of 0.125-inch cable, was specially fabricated and mounted on a framework at the stern of the truck. The winch is driven through a four-speed automotive transmission and multiple V-belt by a hydraulic motor. This motor is in turn connected to a variable displacement hydraulic pump driven by the power takeoff originally used for the vehicle's propeller shaft. Reel-in under power, and hydraulic braking of the winch on reel-out may be controlled independently of the truck's road speed by valves at the hydraulic-control operator's position amidships. The tether passes off the winch through a level-wind guide pulley, forward to a second pulley at the bow, and then back to a final fairlead pulley mounted on a welded superstructure over the truck's center of gravity. The bow pulley is supported by a framework incorporating an electromechanical load cell which provides continuous monitoring of tether tension, and is equipped with a footage counter; the fairlead pulley is universally mounted and fitted with a Teflon-bushed lead-out sleeve, permitting the tether to emerge unobstructed in any direction in the upward hemisphere. All pulleys, as well as the drum core and the lead-out shoe, have a minimum radius of 9 inches. Maximum reel-in and reel-out rates under light loads are in excess of 2,000 ft/min, and reel-in can be accomplished at low speeds against a tether tension up to 2,600 pounds.

Adjacent to the hydraulic-control position is a second seat and a console, originally carrying the ground-based components of the TM-command system, but at present fitted with the transceivers for the ground-station radio link and a control panel for the intercom system used by the personnel aboard the truck. These personnel include the hydraulic and communications operators, the vehicle driver, and one observer, who is seated facing backward and upward in the driver's compartment. All personnel are shielded from possible injury in the event of tether breakage by side and overhead screens of wire mesh or clear plastic.

A small auxiliary winch at the extreme stern of the vehicle, together with a guide pulley and lead-out grommet, provide a means for initial erection of the balloon and load train, and for transferal of the load to the main tether. A gasoline-driven 110-volt a.c. generator is also mounted at the stern, to provide power for floodlights during night operations and any additional instrumentation which may be used for a

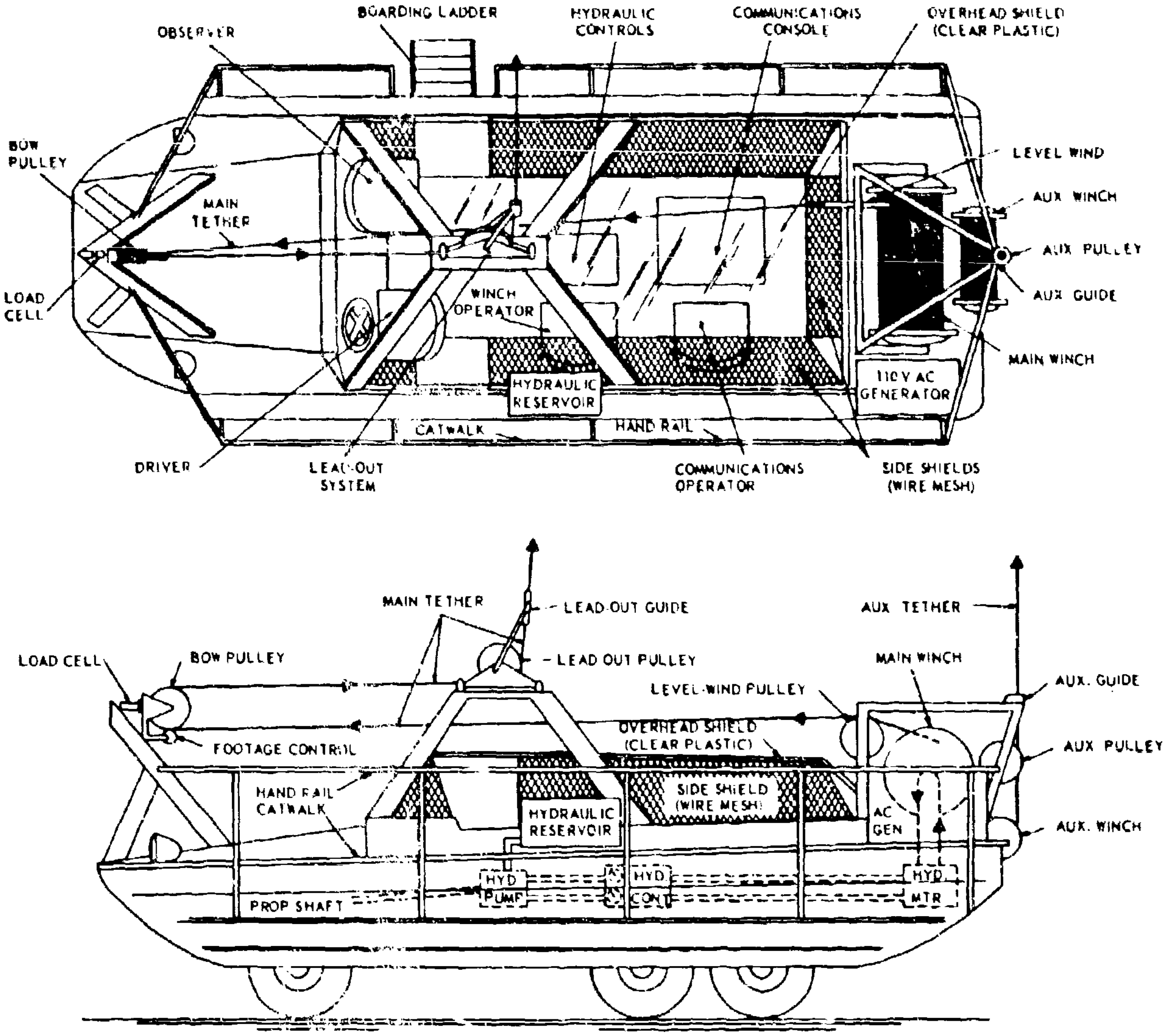

FIG. 6. TABS Mobile Winch Vehicle.

specific operation (all of the basic instrumentation for the flight system is battery-powered). An emergency mechanical braking system for the main winch has controls accessible from several points aboard the vehicle. A catwalk and handrail extend along both sides of the truck, permitting free access to all stations.

TESTING

The present configuration of TABS is the result of a large number of small- and medium-scale flight operations, one of which—a TM test flight to 5,000 feet using the glass tether and a 23-foot balloon—is shown in Fig. 7. Continuous refinements of components and techniques have been made as their need was indicated by practical experience. Flights with the system under full control have been made to 15,000 feet altitude (18,000 feet m.s.l.) using music wire

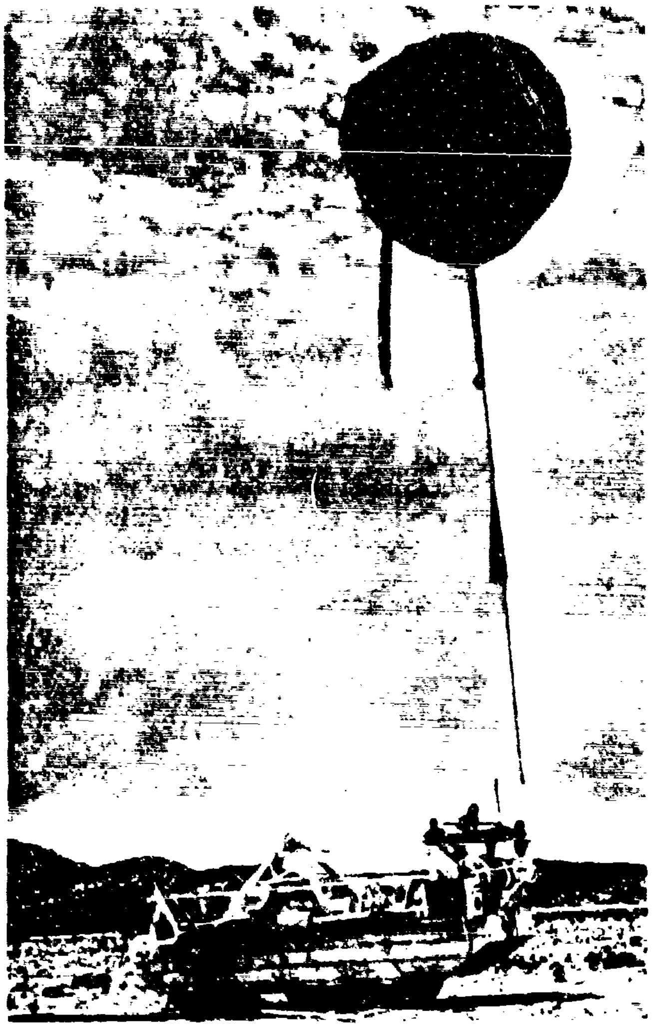

FIG. 7. Final Preparations for 5,000-Foot Telemetry Check-Out Flight Using 23-Foot Sleeve-Clutched Balloon, Glass Tether, and Mobile Launch Vehicle. The balloon is attached to the auxiliary winch by a secondary handling line.

tether, while the glass tether has been used for numerous flights to as high as 10,000 feet, with full recovery of balloon and payload when desired. Analysis of these flights has provided hitherto unavailable data on the aerodynamics of the system, which permit the original analytical technique to be extended with considerable confidence to the full-scale stratospheric flights planned for the immediate future.

The development program is expected to culminate in a series of two or three flights to stratospheric altitudes using the present TABS components and Winzen 225,000 ft^3, 75-foot-diameter taped polyethylene balloons. The first flight will be performed under optimum wind conditions permitting, if possible, a static launch, and will carry instrumentation solely to test the performance of the system itself. This flight will be limited to a few hours' duration.

One or two subsequent flights will be conducted, primarily to test the system under more severe wind conditions requiring a mobile launch, and it is hoped that at least one of these will be of several days' duration. A few tens of pounds of scientific apparatus may be included in the payload for these later flights.

SYSTEM APPLICATION

Plans for the future use of TABS fall into two categories: those utilizing the present system for various geophysical research projects, and those directed toward further development of tethered high-altitude systems.

GEOPHYSICAL-METEOROLOGICAL RESEARCH

The original concept of TABS involved its use as a moored, permanent meteorological station. This still represents one of the most important functions which such a system could fulfill: providing a continuous record of aerological parameters at a fixed point (or series of points, with sensor packages attached to the tether at various altitudes) in the atmosphere. In addition, TABS would make possible the direct measurement of such quantities as vertical wind velocities and precipitation nuclei concentrations which are of interest to the weather modification program at NOTS.

A somewhat related problem is that of atmospheric electricity. Measurements of the atmospheric potential gradient have hitherto relied upon summation or integration of a sequence of short, vertical baseline observations, and have yielded contradictory and nonreproducible results. A tethered system using the glass-resin line with one or more embedded conductors, as mentioned above, would make possible direct measurement of the atmospheric potential as well as its variation with time. Efforts are being made to develop suitable collectors and measuring instruments, and to test various conducting tether configurations The interesting possibility of using the atmospheric electrostatic charge as a source of continuous power is also to be investigated.

TABS could also be used as a platform for photographic, photoelectric, and, ultimately, television observations, both of the ground and clouds below and of astronomical objects above the balloon. The possibility of using wind-vector forces as a simple source of first-order azimuthal stabilization for such instrumentation is of great interest, especially insofar as a stabilized platform would permit relatively long exposures at high resolutions and narrow bandwidths.

The tethered system also provides an ideal vehicle for long-term detection and collection of various atmospheric constituents and contaminants. With a moderate horizontal wind at the instrument, contamination by material associated with the balloon, payload, and tether could be avoided. Suitable collectors and detectors of sufficiently light weight already exist, and will be employed with TABS for study of atmospheric moisture, precipitation nuclei, micrometeorites, and organic material.

UNMANNED- AND MANNED-BALLOON RESEARCH

Since the lift of a balloon increases as the cube of its dimensions while its projected area, and hence drag, varies as the square (similar considerations applying, of course, to tether strength and drag) the efficiency of the system will increase with size. On the other hand, the problems associated with inflating and launching the system, especially under adverse conditions, will at the same time become more severe.

Two approaches to these problems are available. The first, and simplest, is to operate from a vessel at sea, permitting movement in any direction at reasonable speeds. Matching of vessel speed with wind velocity will permit vertical inflation of the balloon from a limited deck space, making a small, fast ship such as a destroyer sufficient for the purpose. It is hoped that this approach can be tested using the present system in the near future.

To operate a larger, all-weather system on land, however, it will probably be necessary to abandon the mobile technique, since the extensive airspace and ground access required will not be generally available, and the larger capacity winching system needed would become somewhat unwieldy. The most direct approach would involve (1) some method of protecting the balloon during inflation and prior to launch (several such methods have been proposed in recent years); and (2) a substantial increase in balloon ascent rate, best achieved by use of a low-drag aerodynamic configuration. If ascent rates of 2,500 to 3,000 ft/min could be achieved, a static launch technique would become entirely feasible, even in the presence of relatively high tropospheric wind velocities. Experiments are to be conducted at NOTS with small, streamlined balloon shapes to determine whether stable ascent can be achieved at such rates, and to develop means for maintaining efficient aerodynamic configurations over the large balloon expansion range needed.

The possibility of mooring balloons at altitudes above that of the wind minimum has also been given extensive consideration. While the strength-to-weight ratio of the glass-resin tether is certainly adequate for flights to the highest altitudes which can be reached by conventional balloons, it is felt that the most efficient system would involve deployment of a high-altitude second stage from a balloon moored at the wind minimum. The upper stage should combine sufficient buoyant lift to support itself and its tether in low winds with aerodynamic lift and control for station-keeping in higher winds. Model studies leading toward such a system could be conducted using the present TABS.

Finally, the tethered balloon system offers an attractive solution to many of the problems hitherto encountered in manned high-altitude balloon operations, especially those involving flights of long duration. The balloon can be confined to a relatively limited region of air space, line-of-sight communications can be maintained, and it might even prove feasible to conduct resupply operations by "flying" a small balloon and payload up along the tether.

ANALYTICAL PROCEDURE

An analytical program has been worked out and refined, which permits determination either of the balloon and tether parameters required to adapt the system to a general class of wind conditions, or of the feasibility of flying a given system under a specific wind profile. The procedure has been simplified to the point where it can be performed by manual computation in a relatively short time following a pibal or rawinsonde sounding, immediately prior to a flight. The vehicle rate profile for a mobile launch can likewise be readily computed on the basis of a last-minute sounding. Examples of such computations for the existing system in a recent, typical wind profile are presented in the following paragraphs.

GENERAL

Figure 8 illustrates the configuration which will be assumed by a tethered system having the parameters indicated on the right in the figure, under the wind profile of 17 September 1964 (see also Fig. 1, where the wind velocity is plotted in knots rather than feet per second). The procedure is as follows:

1. Select balloon flight altitude: h_o = 64,000 feet
2. Select balloon net lift: L_b = 750 pounds
3. Determine balloon projected area at the given h_o, L_b from balloon inflation tables:
   A_b = 4,000 ft^2 (balloon assumed spherical)
4. Determine wind drag on balloon: $D_b = C_{Db} (\rho_o V_o^2/2) A_b \approx 3.5$ pounds
   (C_{Db} = balloon drag coefficient = 0.8
   ρ_o = (atmospheric density at h_o) = 2.0×10^{-4} slugs/ft^3
   V_o = 3.3 ft/sec, both from rawinsonde reduction)
5. Specify payload weight (including TM-command package, antennas, load line, load ring, parachute, squib cannons): W_p = 88 pounds
6. Compute tether angle at balloon by vector resolution:
   $\theta_o = \tan^{-1} D_b/(L_b - W_p) = \tan^{-1} 49.4 \times 10^{-3} \approx 0°17'$
7. Compute tether tension at balloon:
   $T_o = D_b/\sin \theta_o = (L_b - W_p)/\cos \theta_o = 662$ pounds
8. Select first altitude increment: Δh_1 = 4,000 feet
9. Compute tether length in h_1: $\ell_1 = \Delta h_1/\cos \theta_o$ = 4,000 feet
10. Compute tether flat-plate area: $A_1 = 7.85\, \ell_1/1{,}000 \approx 31.4\ \mathrm{ft}^2$
11. Compute tether drag force: $D_1 = C_{Dt} (\rho_1 V_1^2/2) A_1 \approx 0.30$ pound
    (C_{Dt} = tether drag coefficient ≈ 1.2 (mean value from experiment + theory)
    $\rho_1 = 2.25 \times 10^{-4}$ slugs/ft^3, V_1 = 8.35 ft/sec, both from rawinsonde data at increment midpoint, 62,000 feet)

12. Compute tether increment weight: $\overline{W}_1 = 4.75 \ell_1 / 1{,}000 = 19.0$ pounds
13. Compute tether angle at $h_1 = h_o - \Delta h_1 = 60{,}000$ feet
    $\theta_1 = \tan^{-1} (T_o \sin \theta_o + D_1)/(T_o \cos \theta_o - \overline{W}_1) = 0°20'$
14. Compute tether tension at h_1:
    $T_1 = (T_o \sin \theta_1 + D_1)/\sin \theta_1 = 643$ pounds
15. Repeat steps 1 through 14 for successive increments in altitudes of 5,000 feet from 60,000 feet to 5,000 feet, final increment 2,650 feet from 5,000 feet to ground (2,350 feet)

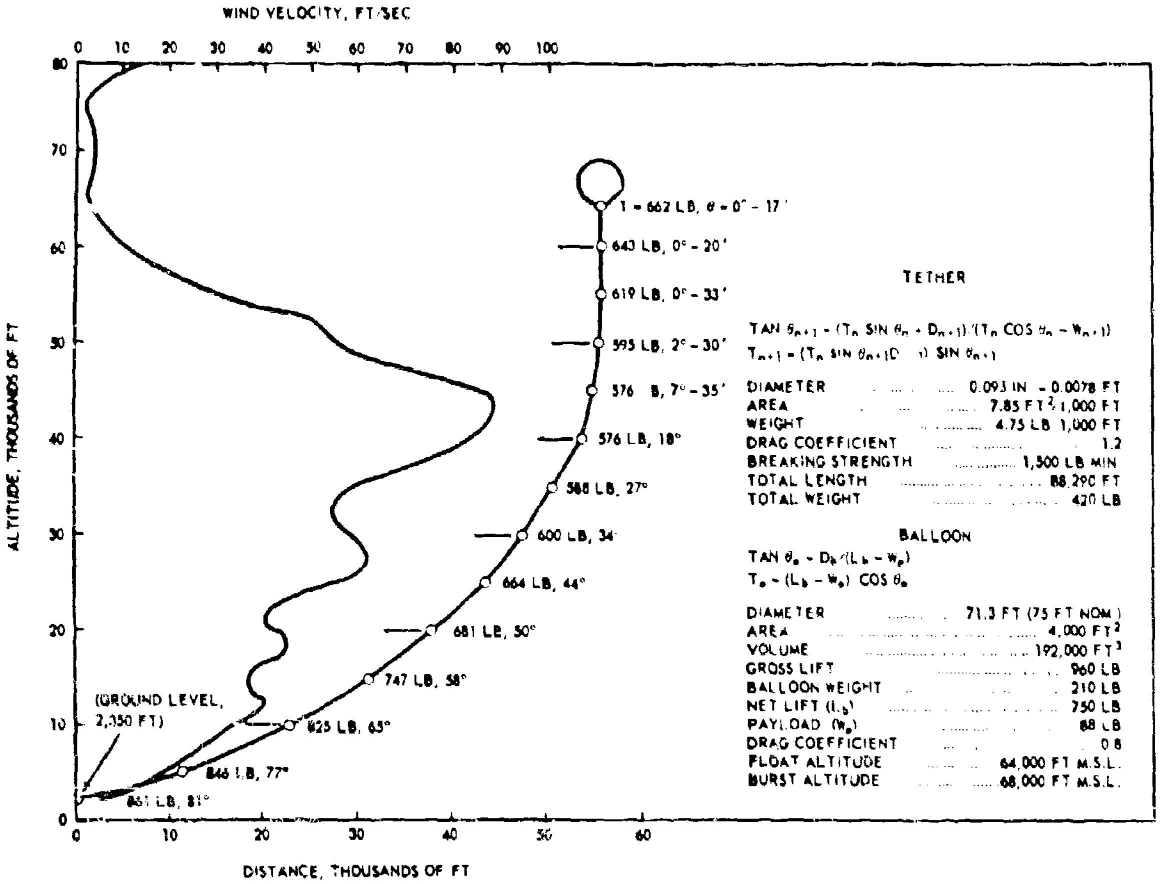

FIG. 8. TABS Flight Configuration (17 September 1964).

From the values of O_n and T_n thus obtained at each altitude h_n, a flight configuration such as that in the center of Fig. 9 can be plotted. If at any point O_n exceeds 90 degrees, or T_n the tether breaking strength (1,500 pounds), the system cannot be flown. In the present case, a previous computation with L_b = 650 pounds showed $\overline{O}$ = 90 degrees at approximately 4,000 feet altitude; the configuration was redetermined for L_b = 750 pounds, with the acceptable results shown in the figure. This profile is, however, close to the maximum which the present system could tolerate; the balloon is very near its maximum inflation, while the tether angle at the ground is dangerously large. The tether tension, however, is at all points well below the specified minimum breaking strength. The total length of tether out is somewhat greater than the presently on hand, but is well within the length scheduled for production at NOTS.

According to the remaining profiles illustrated in Fig. 1, a flight would have been marginally possible on the 14th, since although the velocity at the maximum is somewhat greater than on the 17th, it is relatively less below 20,000 feet, and the altitude of the minimum is considerably lower. The system would encounter no difficulty on the 15th or 16th, and the vertical extent of the low-velocity region could permit flights to considerably greater altitudes. It is unlikely that the present system could have been maintained aloft on the 18th.

In all such calculations the winds are assumed to be constant in direction. This is, in fact, a reasonably good assumption in most cases over the region of moderate-to-high wind velocities, and, further, makes the calculations somewhat conservative since a variation in wind direction with altitude will reduce tether angle to some extent.

Application of the mobile launch technique to the profile of the 17th is illustrated in Fig. 9. If the balloon were to rise freely, with the wind, at a rate of 1,200 ft/min (which should be achieved by a well-clutched balloon having a vertical drag coefficient of 1.5 to 1.6), it would follow the right-hand dashed curve, coming to altitude some 28 miles downwind, and requiring slightly over 30 miles (approximately 160,000 feet) of tether. The weight (760 pounds) of this amount of tether exceeds the lift available, and this launch mode is obviously not feasible.

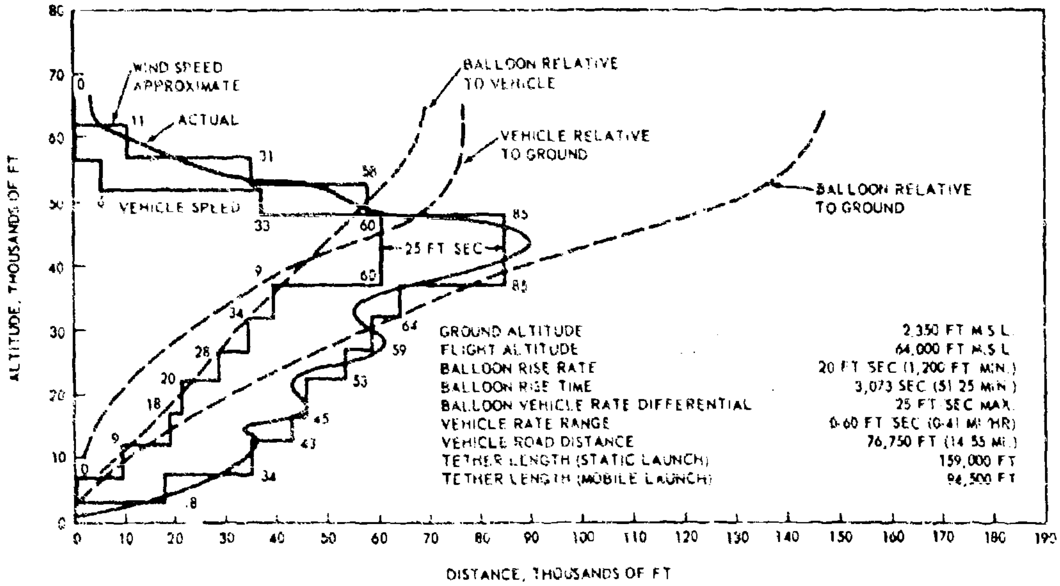

FIG. 9. TABS Mobile Launch-Profile Matching Technique.

If the actual wind profile is approximated by the 5,000-foot-interval stepped profile which overlies it in the figure, and then a conservative vehicle-balloon rate differential of 25 ft/sec (approximately 15 knots) is assumed, the vehicle rate profile indicated by the left-hand stepped curve is obtained. The vehicle is then driven for periods of 4 minutes 10 seconds (equals 5,000 feet divided by 1,200 ft/min) at each of the various speeds indicated in the figure, attaining a maximum speed of 60 ft/sec equals 41 mi/hr and following the central dashed curve. The total road distance covered is 14.6 miles, which is just feasible, utilizing a section of available road lying to the west of point 1 in Fig. 2. The balloon, following the left-hand dashed curve relative to the vehicle, now comes to altitude 13 miles downwind of the end of the road (2, Fig.2), with 18 miles (approximately 95,000 feet) of tether deployed, for a total weight of 450 pounds. This is quite acceptable, and the balloon would gradually drift back upwind, with the tether being retrieved under light tension, until the configuration of Fig. 9 was reached.

Of the profiles in Fig. 1, that of the 14th is too severe; the tropospheric winds are blowing at some 50 degrees to the road direction, giving a cross-wind component of some 40 knots. Even if the wind were blowing along the road, the 58-knot maximum would require excessive vehicle speeds, unless the rate differential were allowed to approach 20 knots. On the 15th the winds, although relatively low, are at some 80 degrees to the road direction, making a mobile launch impractical. Free ascent of the balloon from a static ground point would, however, consume less than 100,000 feet of tether, and would be feasible.

The profile of the 16th offers some choice: The balloon could be let out under control from a static position to 40,000 feet, and then allowed to rise free to approximately 50,000 feet, or the mobile launch method could be used, with the vehicle rate profile matched to that of the wind velocity, the vehicle remaining more or less directly below the balloon during the entire ascent. On the 18th, again, launching would prove impossible.

It can be seen that, during the week under consideration, the system could be launched and maintained aloft over a full three days, from the 15th through the 17th. This is a fairly typical pattern: a recent study indicated that of some 83 days during June through September 1964 on which soundings were made, static launches could be made on six, and free-rise or mobile launches on 22, for a total of 34% of the days considered. Similarly, the system could be maintained aloft on 58, or 70%, of the days studied, many of these falling into groups of a week or more.

DRAG

The various drag coefficients used in these calculations have been derived from analysis of flights to altitudes of up to 15,000 feet (and to 50,000 feet for the ascent rate observations with free balloons). They are at least plausible when compared with theoretical calculations and the limited experimental data obtained elsewhere, and there is no evident reason for doubting their applicability at higher altitudes. The empirical drag coefficients for the balloon, 0.7 to 0.8 lateral and 1.2 to 1.6 vertical, lie between the values for a smooth sphere (0.5) and a circular flat plate (2.0); the higher figure for vertical drag evidently results from the observed flattening of the balloon crown at high ascent rates.

The assumed tether drag coefficient of 1.2 is somewhat more complex. Strictly speaking, an element of the tether should be considered as an inclined cylinder subject to normal and parallel drag forces as well as lift, and three coefficients should be employed. It appears, however, that by using a single drag coefficient and utilizing the total flat plate area (not just the component normal to the wind) of the tether, a reasonable approximation to the actual forces on the tether can be obtained, permitting a great simplification of the calculations; the drag coefficient thus determined falls in the range 1.1 to 1.3. Parallel (skin) drag is found to be negligible except at high tether inclination angles, which in the normal TABS configuration occur only near the ground. Lift forces, which will be negative and thus equivalent to an excess tether weight, are significant principally at intermediate angles, again encountered at relatively low altitudes. Normal drag coefficients based on Reynold's number calculations for the prevailing velocities and tether dimensions range from 2.0 at 10 ft/sec at 80,000 feet to 1.1 at 10 ft/sec and 0.8 at 50 ft/sec at the ground (at 1 ft/sec at 80,000 feet the coefficient can reach a value of 6, but the drag force at such a low velocity and atmospheric density is negligible). The assumption of a drag coefficient of 1.2 applied to the total projected area of the tether results in general in a moderate overestimation of the tether drag force, which offsets the effect of neglecting lift forces upon the derived values of θ at intermediate altitudes, and somewhat overestimates the tether tension. Similarly, near the ground the calculated drag is considerably in excess of the actual normal drag, which probably overcompensates for neglect of parallel drag. The result is a relatively conservative assessment of system capabilities which should suffice for the present; actual high-altitude flight data will ultimately provide more precise information on which a more detailed and accurate analysis can be based.

TETHER DEVELOPMENT

BACKGROUND

The first report on the development of a balloon tether covers the time from early 1963 to the present. The desirability of a very-high-altitude tethered meteorological balloon had previously been indicated, and a region of relatively low winds at an altitude of from 55,000 to 80,000 feet had been identified.

It was estimated that in order to reach this altitude a balloon tether 100,000 feet long would be required. Aerodynamic stability of the balloon indicated a net lift of about 800 pounds, and the balance between aerodynamic drag and tether weight resulted in a relatively constant tension. The usual balloon tether material had been steel wire or nylon cable; however, even the best of these materials can hold their own weights to a length of only about 120,000 feet, to say nothing of supporting the net lift of the balloon. These considerations led to the use of reinforced fiberglass for thether.

PRELIMINARY INVESTIGATION

A request for technical proposals asked that information include the services, labor, and materials necessary to design and fabricate cable of nonmetallic materials, two samples of 100,000 feet each, meeting certain specifications and having a minimum breaking strength of 1,000 pounds.[1] The principal specifications were that the cables furnished have a minimum breaking strength of 140,000 psi, and that the cable support 90% of the load while wrapped around a radius of 100 tether diameters for a period of 72 hours.

Responses were received from three firms. One company was producing a polyester strand rope called NOLARO (no lay, or twist, to the cable); however, the breaking strength of polyester cannot possibly be made high enough to meet outlined requirements. Another firm with no experience at all in this field offered a proposal that would not meet the requirements. The third respondent was the New Plastic Corporation of Los Angeles, Calif., which had been producing a glass fiber-epoxy rod to be used for guy wires for radio antennas.[2] This material NUPLAGLAS, was recommended for the tether. However, although New Plastic Corporation was considered to be technically qualified to produce balloon tether, it was felt that a better material might result from pilot production at NOTS.

In the meantime, several attempts were made at NOTS to make small pieces of tether by pulling glass strands through eyedroppers, impregnating glass strands in silicone rubber molds, and other experiments of this type. None of these efforts was very successful, although some test samples were made by the eyedropper technique. For instance, one setup featured a spool of glass, a small tubular muffle furnace, and a crank that pulled the glass strands through a simple device to impregnate them. Then, because at that time a fast-setting resin was not being used, the resulting strand was hung up to cure.

A sample of collimated B-staged glass epoxy tape with 80 ends of "S" glass was acquired from Douglas Aircraft Co. This tape was doubled to produce 160 ends and pulled through an eyedropper to make a tether. A tensile test of one of these handmade tether pieces yielded a breaking strength of 1,394 pounds. Other specimens having 210 ends

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[1] Letter, U.S. Navy Purchasing Office, Los Angeles, Code OP4:al, Schedule 32114, Serial 6775, dated 22 April 1963.

[2] Memorandum, from Dr. S. D. Elliott, Jr. to CDR T. A. Cassin; subject, Technical Evaluation on PR 5020 1449 Technical Proposals (IFB-123-413-63); dated 6 June 1963.

of glass yielded breaking strengths ranging from 1,130 to 1,556 pounds. However, these were outstanding exceptions to the general rule that it was not possible to make satisfactory tether specimens in the laboratory.

DEVELOPMENT AT NOTS

Initial Facility Setup

NOTS had had previous experience in working with fiberglass and epoxy in the design and construction of small, filament-wound rocket motors, and it had been concluded that a more flexible epoxy would be beneficial as far as the physical properties of these motors were concerned. Early in 1963 a mixture of Shell Epon 812 and 828 was found to produce an epoxy resin of good strength and flexibility. However, it was still not known how to cure this resin at the speed required for high rates of tether production. The Thompson Aeroballistics Laboratory was chosen as the place for producing the tether, because its 650-foot length made it possible to contemplate a feasible production rate. First efforts of production in the Thompson Laboratory were with a completely homemade setup of dies, ovens, and take-away reel. This first tether production line was almost completely handmade, and its design followed several basic concepts.

The most important requirement was that the glass be kept as free as possible from abrasion and bending while it went through the line, especially before it had had resin applied to it. Second, equal tension was to be applied to all strands. Third, the entire line was to be symmetrical; all of the glass fibers would travel the same distance while going through the line and ideally would require a creel on which the spools of glass would be disposed in a circular array, since they are disposed in a circle in the finished rods.

Since the glass being used was in the form of spools having 20 ends per spool, only six or seven spools were needed to provide the amount of glass for the tether. Therefore a simple frame was designed (Fig. 10) in which the spools were set as closely together as possible and in such a manner that the tension in the glass would be provided by the weight of the spool rubbing on a plastic button underneath the spool. From this tension rack the fibers traveled at a slight, downward slope into the impregnation device, which was a tub in which a roller directed the fibers through the resin. From there the tether went into a precuring or preheating oven (this preheating oven as finally built consisted simply of a piece of 2-inch steel conduit with an electric blanket fitted around the outside). Coming out of the preheating oven the fibers went through a sizing die (a hole drilled into a piece of steel) and into a long post-curing oven (again a series of 2-inch steel conduits with heaters around the outside). The take-away reel was mounted on the floor about 50 feet away from the end of the curing ovens.

The first setup utilized the weight of each spool of glass to provide tension by mounting the spool on a relatively easy-turning spindle, with

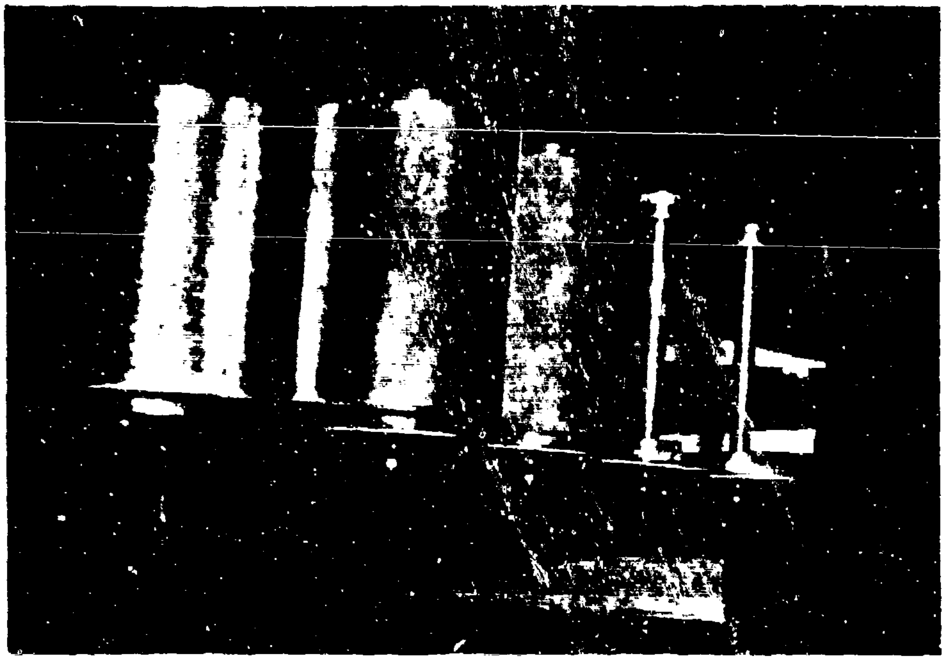

FIG. 10. Arrangement of 20-End Spools.

the spool's weight bearing upon a plastic button. It was soon discovered, however, that an aluminum disk riding on a Teflon, polyethylene, or nylon button created too much drag, and a Teflon disk was interposed between the aluminum disk and the plastic button. The final combination was a Teflon disk riding on a polyethylene button. Problems were still encountered with this arrangement, however, because the glass fibers would spin off the outside of the spool when not under tension and would end up between the disk and the button.

Fiber Handling Methods

Although some of the better samples of tether were made using 20-end roving, continual difficulty was experienced with what is known as catenary, that is, individual strands which made up the 20 ends of roving were not in fact the same length or under equal tension when the roving as a whole was put under tension. This was evidenced by individual fibers actually popping out of the tether after it had gone through the production line. Therefore it was decided to switch over to "single end" glass, that is, each spool of glass has only one end of 204 filaments instead of 20 ends.

The single-end spools are "milk bottle" shaped, larger at the bottom than at the top. The strand of glass is wound on this spool by a device that looks something like the bale on a full-bale spinning reel, which travels from top to bottom all the way around the outside of the bottle. Standard industry practice in applying tension to single-end strands is to take the glass straight off the top of the bottle, unwinding it naturally under no tension. The glass is then run through a tensioning device which may consist of a pair of rollers forming a capstan, or it is led through another device which looks like a wheel split through the middle, much like an adjustable V-belt pulley. When the glass wedges down between the two halves of this split wheel, the tension is applied. These types of tensioning devices were not used at NOTS because they both involve a considerable amount of flexing and rubbing of the glass while it is still dry. Instead, it was decided that the single-end spools would be mounted with their axes horizontal, and a mechanically adjustable brake would be provided.

In fairness to industry, it should be pointed out that the NOTS concept of unrolling the glass directly from the spool also involves a certain amount of abrasion. When the glass is wound on a single-end spool, at least with a fairly close level wind, any tension placed on it will tend to pull the glass down between the other layers of the spool and cause abrasion. No difficulty has been encountered, however; the glass seems to feed off the spool quite smoothly.

When the production line was changed from 20-end to single-end roving, the number of the ends in the tether was increased to 150. In order to provide a more even dispersion of spools around the center of the line the 150 spool holders were arranged on five vertical supports which were then located in the arc of a circle about 30 feet away from the resin applicator. This arranged the spools in a rectangular grid rather than in a circular one (Fig. 11). A tensioning device for single-end spools was developed on the basis of tests conducted on a pilot model. Basically, tension was applied by means of the friction

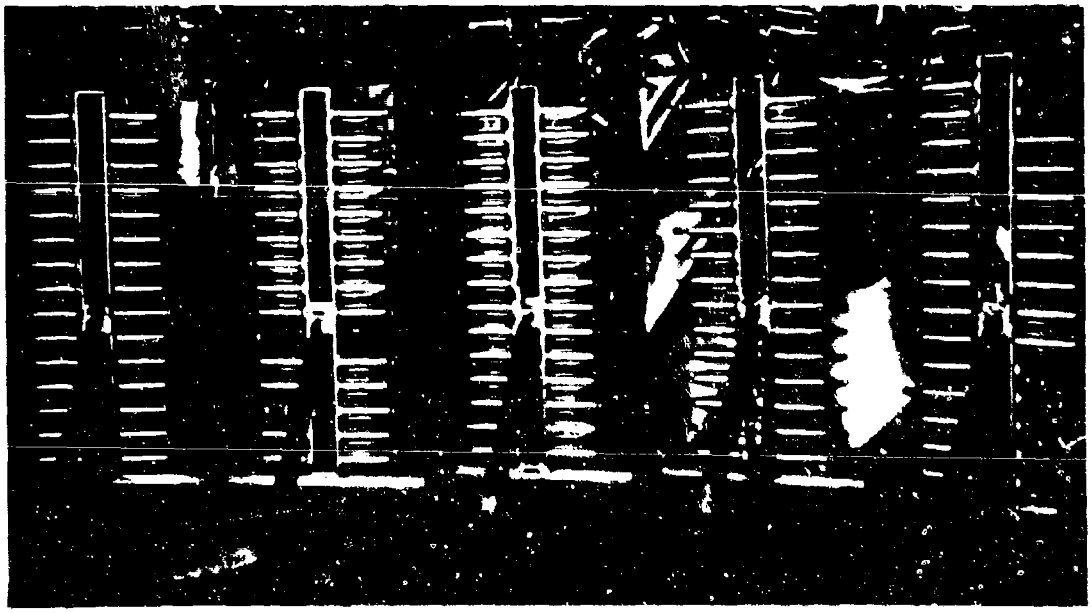

FIG. 11. Arrangement of Single-End Spools.

between a Teflon insert which was pressed into the base of the spool carrier and a felt washer which was compressed beneath this Teflon insert and the aluminum base in which the spool was mounted. A spring bearing on the other end of the spool maintained the pressure. The compression of the spring was regulated by the amount that the central mounting shaft was screwed into the aluminum mounting plate (Fig. 12). The only real difficulty encountered during the installation of these tensioning devices was caused by nonuniformity of spool inside diameter, which caused the Teflon inserts to bind on the shafts. This difficulty was eliminated by hand-reaming the individual inserts after they had been put into the spools.

While it was felt that there were advantages to be gained by using single-end glass in that better tension control was achieved, catenary was eliminated, and in case of a break, minor loss of strength would occur, the prospect of stringing 150 separate ends of glass to a single orifice caused some apprehension. However, no difficulty was encountered; when fiber breaks occurred it was quite simple to start the broken end into the process by merely draping it over one of the other ends which was traveling into the gathering die and then exercising a certain amount of care until the fiber had progressed far enough into the production line so that it was aligned with the other fibers and could pull its own way along.

However, there were some problems connected with the glass itself. For one thing, the first shipment of single-end glass was very poorly packed; the spools were simply put into an open cubicle inside a box and were not protected from impact in any way. As a result,

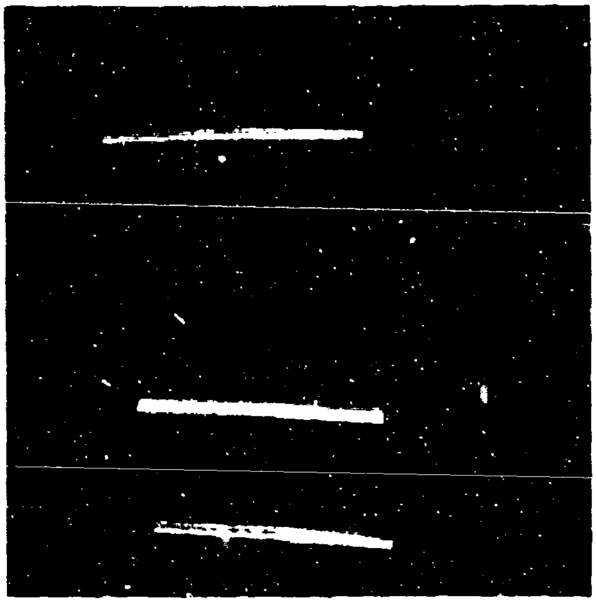

FIG. 12. Single-End Spool Mounting.

many of the spools arrived bruised, dented, torn, or cracked and could not be used. They were all more than 3 months old, and the HTS finish was partly cured.

Fiberglass is presently produced and packaged by methods largely inherited from the textile industry. The 20-end roving is wound onto the spool by having a spool turn, and the individual ends of this roving have a maximum of about one twist per foot of length. This twist simplifies handling in the producing plant. On the other hand, the single-end glass is wound onto the spool by a different process, which results in the glass having one twist per inch. This high degree of twist, besides causing some undesirable properties in the finished tether, has caused continual difficulty in the production of tether, in that these single ends like to twist one upon the other in the area from the spool to the gathering die.

Fiber Impregnation Methods

It was realized that satisfactory impregnation of the glass fibers could not be achieved by simply pouring the resin on the glass as the fibers went by, because the 150 ends of glass contain 31,200 separate filaments. Usual practice in industry is to use a relatively thin resin and to allow a reasonable period of time for the resin to soak its way into the interstices between the glass fibers. Alternatively, the laminate is flexed, rolled, squeegeed, or otherwise mechanically manipulated to force the resin between the fibers. Rather than utilize such mechanical methods, it was hoped that good impregnation could be achieved by applying resin to a rather loose bundle of fibers and then running the fibers through a die to apply pressure.

The first production line had to be assembled as soon as possible, however, and the initial impregnation device consisted simply of a large plastic roller riding in the tub through which the fibers ran (Fig. 13). A modification to this concept, used during the winter of 1963-1964, involved a piece of heavy aluminum foil which was slipped over a steel die so that a pool of epoxy resin might be maintained around the fibers in front of the die. In this way the glass fibers first touched the resin and were coated by it before traveling into the die (Fig. 14). The disadvantage of this method of operation was that the glass fibers were all gathered together into one solid rod before being impregnated or heat-treated. In an attempt to improve this situation, a polyethylene disk with four holes in it was inserted before the gathering die so that the fibers entered the impregnation device in four separate bundles instead of one. Generally good quality tether was made from this, but the polyethylene separator apparently also functioned as a coating device and put a skin of polyethylene around each one of the four separate bundles. The bundles then separated easily after the tether was cured.

The concepts just discussed were feasible for use with the 20-end roving because the tension device, the strands of glass, and the tube or tub which held the resin could all be tipped up from the gathering

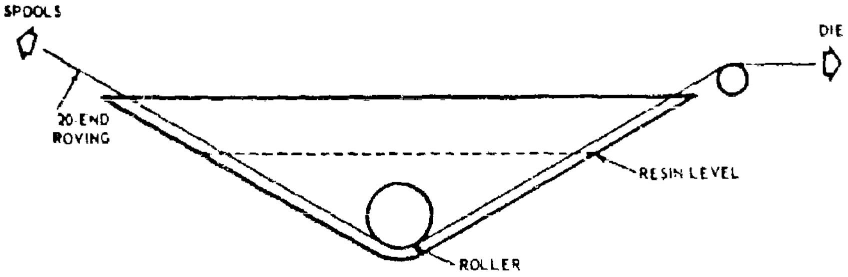

FIG. 13. Initial Impregnation Tub.

FIG. 14. Resin Bath and Die Setup.

die. In this way the resin could be held in the bath. However, the single-end spools were disposed horizontally at the same elevation. The centers of the spools were at the same elevation as the gathering die, and therefore a slanted holder could not be used for the resin pool. To better impregnate the tether material and to remove air and other volatiles by applying a vacuum, a new method, that of separating the glass into many bundles, was attempted. This method utilized a spray ring (Fig. 15) to provide at least a temporary coating of resin on the fibers, a large gathering die into which was interposed a metal spreader, and a tube which would be full of resin and would be closed off on the downstream end by another combination of metal outside die and inside spreader. The vacuum was to be applied in the steel tube which served as a preheating chamber. The glass fibers would be gathered into a rod while in vacuum, thereby minimizing the chance of trapping air or other volatiles inside the rod of fibers. The resin would be pumped from the resin tank by a Zenith metering pump to the ring which surrounded the front of the cone.

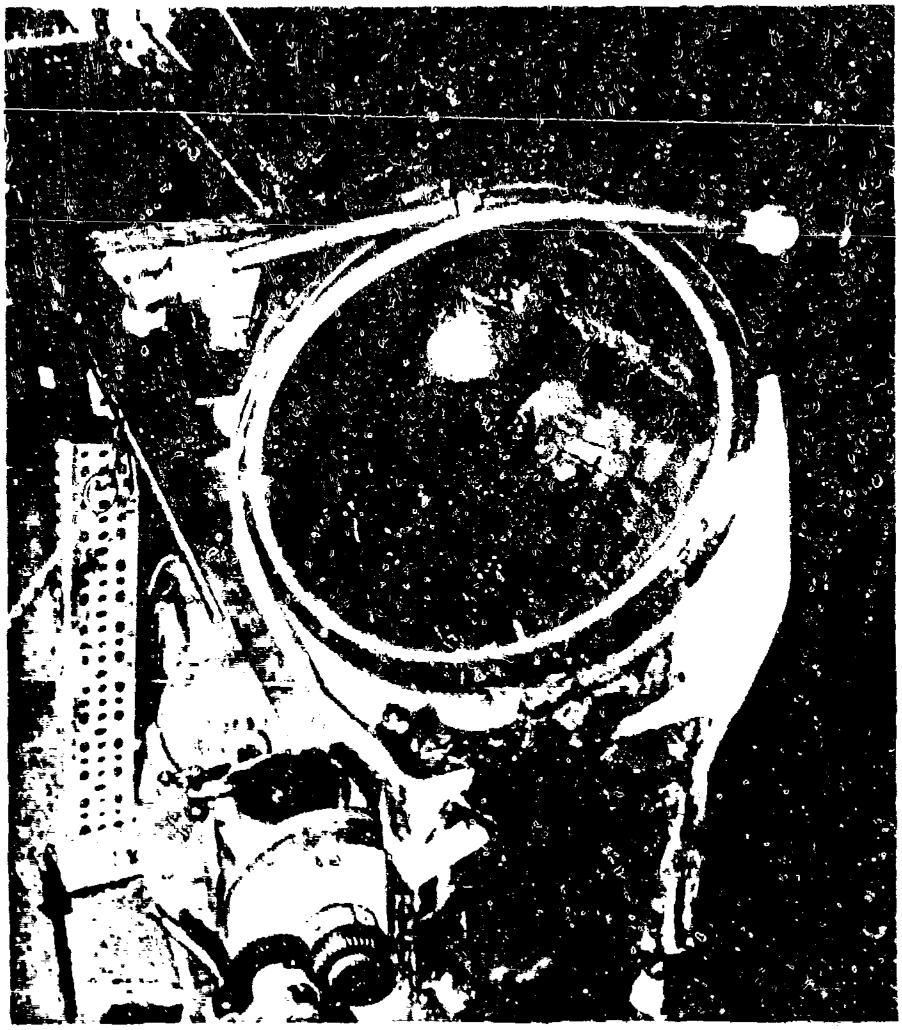

FIG. 15. Resin Spray Ring.

When this concept was tried out, the pump did not deliver enough resin to provide any sort of spray from the spray ring; the heavy, rather viscous epoxy simply ran down the outside of the ring. The resin delivery pipe was then rerouted so that it discharged just above the gathering die. Next it was found to be impossible to seal the upstream end of the vacuum chamber satisfactorily if the spreader and die were used together; this setup was changed to a single round die just big enough to admit the glass so that most of the resin stayed behind in the tank. This system was workable.

However, the tether was still not of acceptable quality, and therefore a third tank was interposed between the resin tank and the preheater oven which was in essence a cold vacuum chamber in which the fibers were spread apart by a rod having an elargement in its center. The idea of this was that half the fibers would be led into one side and half the fibers into the other and they would be spread apart while under vacuum, but in spite of a great deal of care in threading up, the fibers still crossed over from one side to the other, snarled themselves upon the rod, and broke off inside the chamber. This idea then had to be abandoned. The resin tank and vacuum tank were separated to cut down the amount of resin which leaked into the vacuum tank. Fairly satisfactory tether was made with this arrangement. However, the vacuum achieved inside the vacuum tank was still not nearly high enough to achieve good results.

Finally the units of the line were separated so that the resin was applied as the glass fibers passed through a tank on which was mounted an ultrasonic vibrator, and the excess resin was wiped off. The laminate was then preheated in an open oven, passed through a rather small vacuum device in which a high vacuum was maintained, through a coating device to replace the resin which had been sucked off the tether by the vacuum, and then through a sizing die before going through the curing oven. The performance of this vacuum devolatilizer is excellent considering that the tether rod spends only about 0.6 second inside the vacuum. The latest system (Fig. 16) is slightly longer and includes provisions for reapplying resin to the surface of the rod and for a final steel sizing die.

Impregnation Material

First runs were made with a mixture of 100 parts Epon 828, 15 parts Epon 812 (added to make the tether more flexible), and 5 parts catalyst "A." However, even with this relatively slow catalyst a great deal of difficulty was encountered because the resin would set up before it could be made into tether. The second resin system used had the same proportions of Epon 828 and 812, with three parts of a catalyst called boron trifluoride-methylethylamine, or BF_3MEA, also called BF_3-400. This catalyst has the admirable property of having an extremely long pot life at room temperature. With Epon 828 it has a pot life of about 6 weeks, that is, it takes that long for the viscosity to become so high that the resin is not usable. On the other hand, at elevated temperatures the resin cures completely in a matter of minutes.

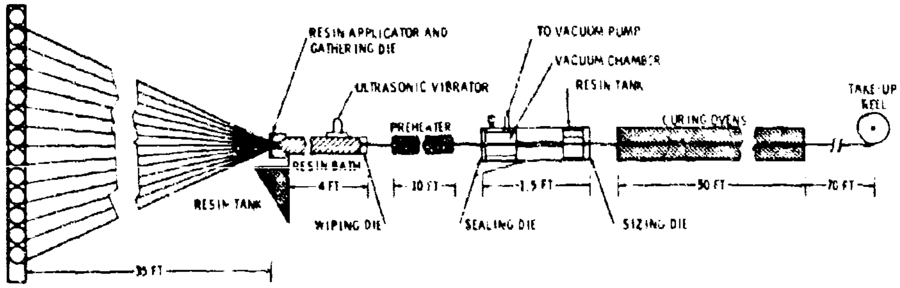

FIG. 16. Final Curing Sequence.

Almost all of the successful running at first was with the 20-end roving and this particular resin blend of Epon 828 and 812; however, it was noticed that with this tether the resin had a rather low heat distortion temperature. It was felt that this lack of heat resistance would lead to trouble when the tether was deployed from a vehicle in the desert sun. At this time, information was received from Shell that Epon 812 in a liquid state is mutually soluble with water, and this raised a possibility that the finished resin would have enough water in it to cause problems with steam evolution during curing of the tether.

For these reasons, three separate resin systems, 100% Epon 828, 100% Epon 826, and 100% Epon 815, were tried with the BF_3MEA catalyst; however, all three systems proved to be too brittle, that is, the finished tether was not flexible enough for practical use. Shell representatives suggested that the addition of Epon 871 (replacing Epon 812) might improve flexibility. After some preliminary experiments a blend of 100 parts of Epon 828, 10 parts of Epon 871, and 3 1/2 parts of BF_3 catalyst was used for the balance of tether runs. The amount of BF_3 was changed several times until a satisfactory balance between cure time and strength was achieved. (Table 1 summarizes run data.)

TABLE 1. TETHER PRODUCED AT NOTS USING S-994 GLASS FIBERS

Glass type, ends	Total no. of ends	Resin type	Mean diameter, in.	Ultimate breaking strength, lb	Date produced
20	140	Epon 828	0.090	1,446 - 1,486	10/63
20	140	Epon 815	.090	1,434 - 1,456	10/63
20	140	Epon 828+812	.090	1,718	11/63
20	140	Epon 815	.090	1,474 - 1,500	12/63
20	140	Epon 828	.090	1,406 - 1,492	12/63
20	100	Epon 828+812	.069	1,120	12/63
20	100	Do.	.065	978 - 1,104	12/63
20	80	Do.	.060	756 - 904	1/64
20	80	Do.	.062	787 - 858	3/64
Single	139	Do.	.084	1,390 - 1,425	9/64
Do.	147	Epon 828	.085	1,464	9/64
Do.	150	Epon 828+871	.088	1,546 - 1,570	11/64
Do.	150	Do.	.085	1,600 - 1,625	12/64
Do.[a]	150	Do.	0.082	1,550 - 1,580	1/65

[a] Production run of 26,000 feet

Curing

The cure time was regulated by changing the pull speed, noting the color difference in the finished tether, and correlating this color with the test results on samples taken from the run. With the present resin blend and with the heater set at maximum temperatures, the best results have been achieved at a production rate of 24 ft/min.

The post curing is accomplished by running the tether through a series of five 10-foot lengths of 2-inch conduit, three of which have electric heating blankets around the outside, and two of which are simply insulated. The temperature in the ovens is kept uniform by means of a small blower which moves air from the upstream end down through the series of heaters and out the back. On a typical run at 24 ft/min, the preheating oven, which is 10 feet long, is set at 400°F, with the post-curing ovens at 450 to 500°F. Resin temperature at the impregnation bath is about 150°F. The finished tether with the Epon 828-871 blend is between a light amber and a straw color. It is wound onto the take-up drum about 60 feet downstream from the end of the curing oven.

The tether is generally started up by manually pulling the dry glass through the resin impregnator and die, that is, before the resin is put in, and then enough slack glass is pulled through so that it can be attached to an old piece of tether or suitable fish tape and connected to the take-up reel.

Tether Size

Initial runs were made with a Teflon sizing die containing a fairly large percentage of graphite; however, this die wore much too rapidly. (The Teflon die at the downstream end of the resin tank which was originally 0.094 inch wore to 0.137 inch during the course of a 24,000-foot run.) Subsequent runs were made with a die of mild steel, and this die was used to make the original long run of 12,000 feet in the spring of 1964. During this run the die increased in diameter by 0.003 inch. Next, BTR (Bethlehem Tool Room) steel was used. This steel was not hardened, but subsequent dies have been made of hardened BTR steel. This hardened steel die has been used for all runs from September 1964 to the present with no measurable wear. It seems safe to conclude that this material will make a satisfactory die, and it is planned to use it in the final setup.

In early runs a phenomenon known as blossoming or blooming, was encountered in which the tether increased in size after it left the sizing die. Most of this increase was caused by the expansion of gases trapped inside the tether, created by the formation of bubbles as the glass fibers moved through the pregnation tank. To solve this problem, heat was applied to the resin tank (currently it is operated at about 150°F), and a small vibration transducer was attached to the outside of the tank. When the vibration frequency is 40,000 cps, blossoming is virtually eliminated behind the sizing die, and the size of the tether actually decreases.

In many runs the sizing die served as a guide, or an applicator of extra resin for the outside of the tether; the size of the tether is really determined principally by the number of ends and the resin content, rather than by the size of the final die. For instance, tether 0.080 inch in diameter has been made from a die having a diameter of 0.082 inch.

Take-Away Drum

The take-away drum for most of the tether runs has been a converted naval winch having a 2-foot core diameter, driven by a variable-speed drive. As originally set up, the unit had a level winding device, but the lead on this level winder was about 5/8 inch per turn. This, coupled with the diameter of the tether, which of course is less than 1/8 inch, resulted in considerable damage to the tether because of crossovers as succeeding layers were wound on. This take-away unit was modified by a small handmade gear box to achieve a minimum lead of 0.090 inch, which gives reasonably good results. The longest run to date has resulted in 12 layers on the drum. In balloon launching, the tension is approximately eight times as much as the tension used in making the tether; therefore the tether may pull down into underlying layers during launching.

Appendix

SPLICING AND END FITTING TECHNIQUES

LAP SPLICE

Ideally, a splice should change neither the size nor the stiffness of the tether and should support the same tensile load. A straightforward way to approach this goal is through the use of a beveled joint, in which the ends of the tether are cut at a shallow angle and glued together. Theoretically, such a joint would develop the full strength of the tether if the bevel were 75 diameters long.

For the first splice a clamp held the tether so that its end could be beveled at an angle of 1 1/2 degrees with a razor blade. This angle, the shallowest feasible to make in a steel jig, produced a lap only about 2 inches long. Furthermore, the thin end did not readily stay in its groove. After gluing, this splice broke at a stress of 770 psi.

In an attempt to strengthen the joining area, extra glass fibers were used; however, joints usually failed in the resin layer between the reinforcement and the original tether. In a few instances the outside "skin" of the tether pulled off, and two of the sample splices were still intact when the tether itself failed. These latter splices were hand-cut to a long taper, and the tether surface was carefully cleaned and reinforced for a distance of 8 inches. The reinforcement was held firmly in place by a sleeve of heat-shrunk plastic tubing.

The minimum length of the skive splice should be 75 diameters on either side of the center (assuming that all of the load is carried by the reinforcing material), or 12 inches for an 0.080-inch tether. With the same amount of glass in the reinforcement as in the tether, the overall diameter will be increased by 41.4%. The 0.080-inch-tether splice, with an 0.020-inch polyolefin tubing, will have a diameter of at least 0.153 inch and a length of at least 12 inches.

Technique for Making Lap Splice (0.080-Inch Tether)

Split the tether about 8 inches from the end, and cut off the thinner half. With the cut surface up, bevel the end of the split about 4 inches and bevel from the split section into the full tether section about 4 inches as shown in Fig. 17. (This will provide a 12-inch lap.) Prepare the other piece of tether to be spliced in the same way. Clean the ends with solvent for a distance of at least 18 inches. (After the tether is cleaned, gloves should be worn for all operations.)

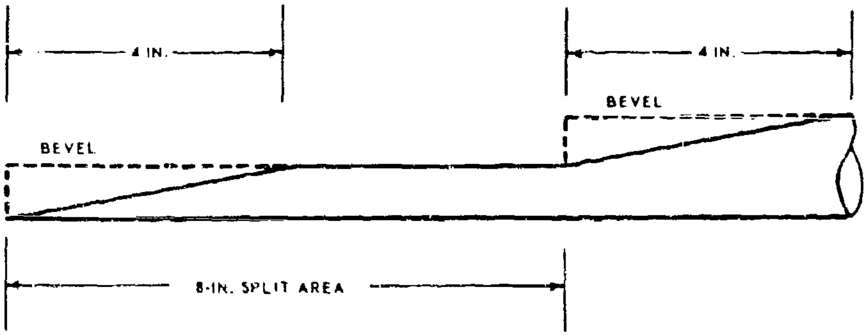

FIG. 17. Tether Preparation for Lap Splice.

Place a short (about 4 inches) piece of shrink tubing over each tether end and slide it away from the splice area. Insert 6 feet of fiberglass ends (about 160 ends) through 24 inches of shrink tubing. Slide this piece of tubing containing the fibers onto one end of the splice. Clamp the tether ends so that the laps match. Coat the cut surfaces with a thin layer of epoxy resin, and bind the laps together with glass thread. Lay the glass fiber reinforcement extending from the 24-inch tubing along the top of the splice joint and soak with resin. This soaked fiberglass should extend at least 6 inches on each side of the splice. Hold the tether and push the tubing over the splice, using a slow twisting motion to distribute the fibers around the spliced area.

Use a heat gun and shrink the tubing from the center toward each end. Trim off any extending ends of glass fibers, slide the short lengths of tubing over the splice ends, and shrink. The total length of the splice area is approximately 24 inches.

Suitable resin systems are (1) Shell Epon 828 with 10 parts Epon 871 and 10 parts DET per hundred; (2) Dow DER 335 with 10 parts DET per 100; or (3) either (1) or (2) with 3 1/2% BF$_3$MEA substituted for the DET. (1) and (2) cure in 8 hours at room temperature. (3) has a pot life of several weeks at room temperature and may be premixed, or it may be cured by application of high temperature (240°F) for a few minutes. The relationship between curing time and curing temperature is exponential.

SPLIT END SPLICE

A splicing technique which relies upon mechanical interlocking has also been developed. This splice, with suitable reinforcing, is shorter than the lap splice and is more reliable. It has exceeded the strength of the tether many times. However, it is also much bulkier and stiffer than the lap splice, and is usually more than twice the original tether diameter. Because of these deficiencies this technique is not being used, although a description follows.

Technique for Making Mechanical Splice

Split each tether end to be spliced into fourths for 8 inches. Bevel the split ends for a distance of 3 inches. Clean the ends with solvent and install reinforcement and shrink tubing as for a lap splice. Spread the cut ends with scrap pieces of tether and clamp the ends to give a total overlap of 13 inches (Fig. 18). Interleave the split ends and bind them with glass thread. Complete the splice using the same method used in the lap splice.

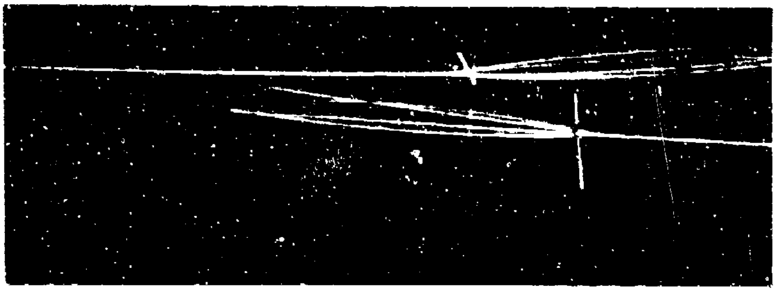

FIG. 18. Tether Preparation for Mechanical Splice.

END FITTINGS

Most of the end fittings used in testing tether samples have relied on a mechanical lock to hold the end of the tether. The tether is led through a small hole in a mild steel fitting, the end is split into quarters, and a wedge is inserted in the split end to prevent its pulling out (Fig. 19). The space between tether and fitting is then filled with epoxy resin. This holder has performed very well for initial testing.

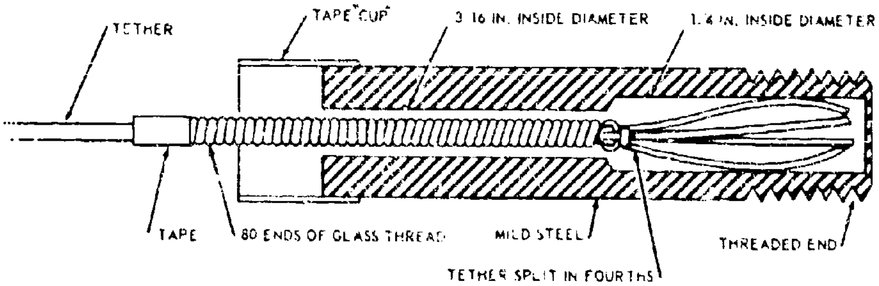

FIG. 19. Tether End Fitting.

When this holder was used for uniaxial fatigue tests, premature failures were accompanied by heating in the center of the holder and evolution of powdered epoxy from the end of the holder. A rough calculation showed that the elongation in the 5-inch length amounted to 0.15 inch. Since the resin thickness at the narrow end of the holder is about 0.023 inch, the resulting shear strain was 700%—far too much. Several holders were modified by enlarging the 1/8-inch hole to 3/16 inch, eliminating the heating problem. These modified holders have since been used for tensile and creep tests with good results, although the resin often cracks at the end, since the shear strain is still about 300%.

Better results and easier specimen preparation result from using 80 ends of glass roving laced through the split ends and wrapped around the tether as it emerges from the holder. A "cup" of tape is then wrapped around the holder, which is filled with resin before insertion of the tether end.

The tether has been subject to breaks at the holder because of the tendency of tether made from all-the-same-twist glass to unwind. The ends of a specimen 12 inches long have been observed to rotate 90 degrees relative to the holder during a tensile test. This places a very high stress concentration where the tether enters the holder.

The holders used in testing have been made of steel, because this metal will withstand the temperature needed to burn out the epoxy resin after each use. Aluminum, having a lower modulus of elasticity, would make a more compliant holder, and a holder made of glass-reinforced epoxy resin would be even better. Such a holder has been used for test work at the University of Nevada. Except for a few failures caused by unwinding, this holder has developed the strength of the tether up to 1,800 pounds.

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The tethered aerological balloon system (TABS) currently under development at NOTS is designed to maintain a captive balloon and payload at stratospheric altitudes for an indefinite period of time, taking advantage of the region of minimum wind velocity nearly always present at some level in the lower stratosphere. The system consists of (1) a conventional polyethylene balloon fitted with a self-deploying reefing system to reduce lateral drag; (2) an airborne telemetry-command package capable of monitoring up to six aerological or other parameters concurrently (additional packages may be distributed along the tether as needed); (3) a NOTS-developed glass fiber tether having a tensile strength comparable to that of steel, at one-fourth the latter's weight, fabricated in splice-free lengths exceeding 100,000 feet; and (4) a mobile ground vehicle from which all functions subsequent to launch can be performed, carrying a crew, control winch, and equipment to communicate with a ground telemetry and command station; the vehicle can run with the wind to reduce lateral drag loads on ascent or descent. The system is expected to become operational the fall of 1965. Various uses and possible further developments of such a stratospheric moored platform are discussed, including applications to manned systems.

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