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LDF POWERED BALLOON PROGRAM

Arthur O. Koran, et al

Air Force Cambridge Research Laboratories
L. G. Hanscom Field, Massachusetts

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Arthur O. Korn
Richard C. Leclaire, 1st Lt, USAF
Catherine B. Rice *

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13. ABSTRACT

This report describes POBAL, a test flight to demonstrate the feasibility of accomplishing station-keeping by powering a 711,000-ft^3 free balloon against the wind in the minimum wind field near 60,000-ft altitude. The propulsion system, fabricated from "off the shelf" components, incorporated a 35-ft diameter helicopter rotor and an 8-hp electric motor powered by Ag-Zn batteries. Line of thrust was controlled by a 9-ft high rudder, steerable either by radio command or by autopilot. POBAL was flown from Holloman AFB, New Mexico in September 1972. System Components, flight results, recommendations and feasibility studies for a long duration POBAL system are discussed.

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1. INTRODUCTION

Several organizations within the Air Force and other governmental agencies, such as NASA and the U.S. NAVY have expressed an interest in a capability to suspend a payload high above selected points on the ground for long periods. A.O. Korn of Air Force Cambridge Research Laboratories (AFCRL) developed the concept of a powered balloon (hereafter known as POBAL) to fulfill this requirement. AFCRL has studied (both in-house and contractually) the feasibility of providing a propulsive force on an unmanned, free balloon to accomplish a high-altitude hovering or loitering mission. Our studies show that such a system is feasible at altitudes near 60,000 ft over a number of areas at selected times of the year. Work was funded under the AFCRL Laboratory Director's Fund to build a system for demonstration using conventional free balloons and existing hardware and launch equipment. The demonstration system was designed to carry a useful payload of 200 lb to an altitude of 60,000 ft for 24 hr, with capability for 12 hr of powered flight (50 percent duty cycle) at 15 knot airspeed.

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2. HISTORY

2.1 Minimum Wind Field Studies

The entire concept of powering a free balloon in order to station-keep is dependent upon the existence of minimum wind fields. Figure 1 shows a simplified pattern of the winds in the summer in the Northern Hemisphere, which causes this phenomenon. Strong westerly winds below strong easterly winds result in a transition region where the winds are a minimum. Within this layer are levels where the winds are essentially zero. For several years, the Aerospace Instrumentation Laboratory has been flying unpowered balloons in this minimum wind layer to study its structure and to see if it is possible to keep a balloon flight system over a point on the ground for extended durations without propulsion. While the balloon is flying, rawindsonde data are used to find a desired wind region. By ballasting or valving to the optimum wind field, the flight direction can be controlled. These tests have been encouraging in that we have been able to keep a balloon within a

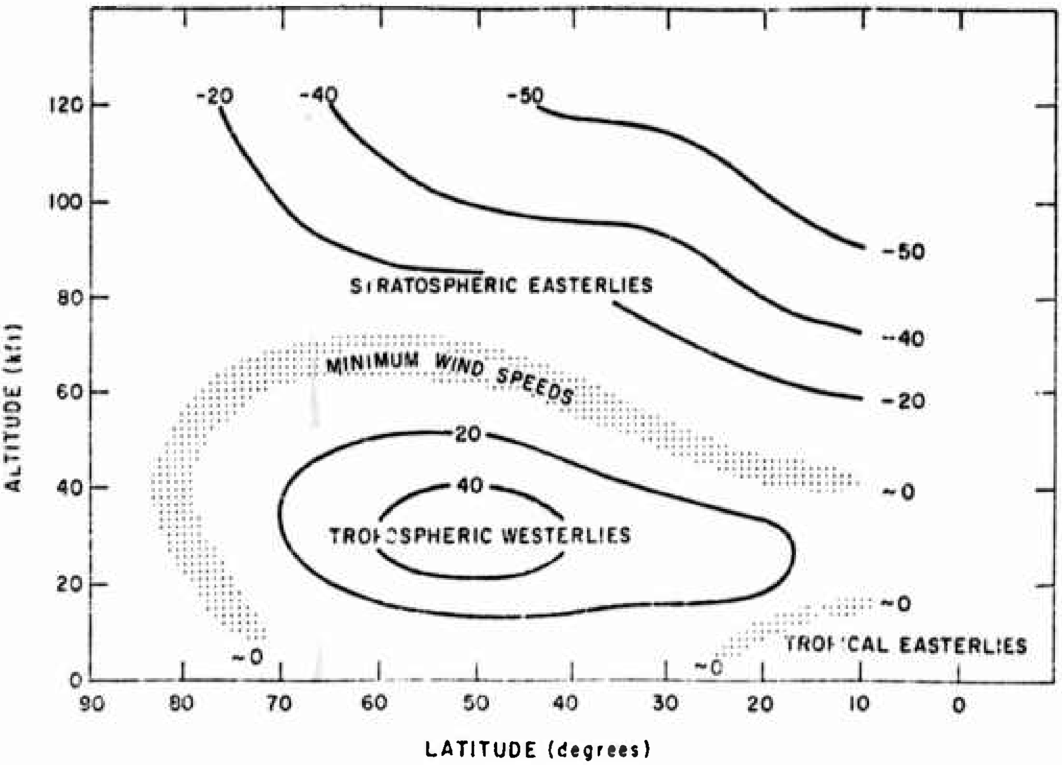

Figure 1. Minimum Wind Fields

100-mile radius for up to 100 hr.[1, 2, 3] For significantly longer durations, the ballast required becomes prohibitively heavy.

2.2 General Concept

The general concept of a powered free balloon is shown in Figure 2. The flight system is launched in the conventional manner and ascends, unpowered,

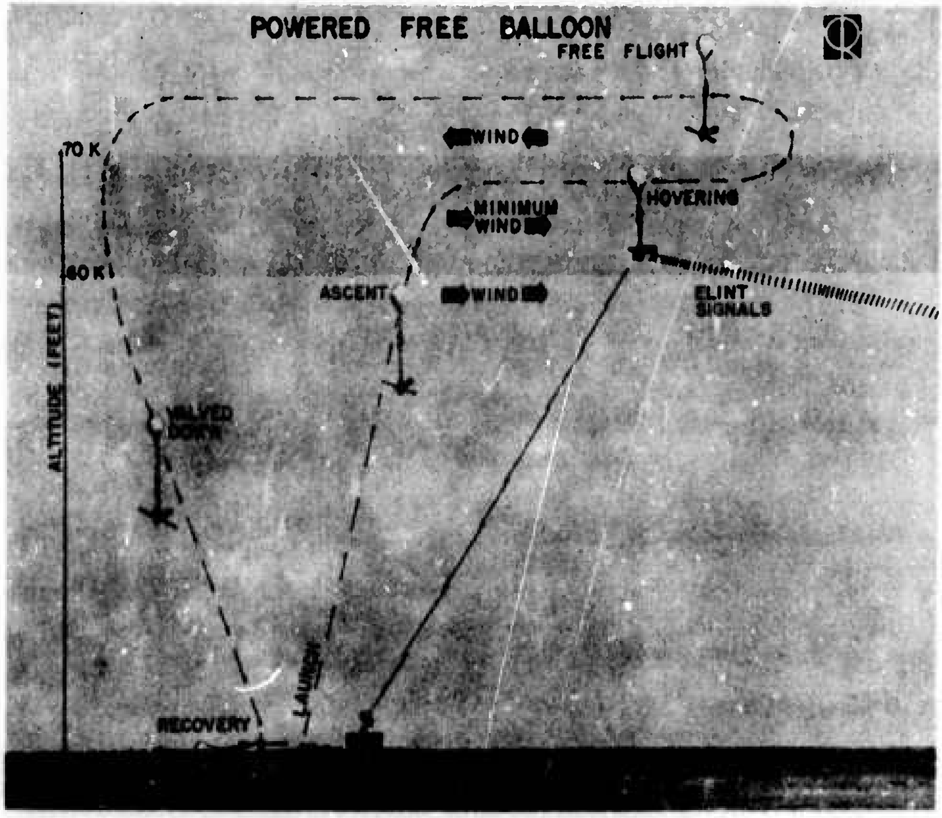

Figure 2. Powered Free Balloon Concept

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[1] Nolan, G.F. (1964) High Altitude Minimum Wind Fields and Balloon Applications, AFCRL 64-843.

[2] Nolan, G.F. (1967) A Study of Mesoscale Features of Summertime Minimum Wind Fields in the Lower Stratosphere, AFCRL 67-0601.

[3] Nolan, G.F. (1969) Meteorological considerations for tethered and hovering free balloons, Symposium Proceedings, Earth Observations from Balloons, Am. Soc. for Photogrammetry.

to float in the minimum wind field. The propulsion system is then used to station-keep by providing thrust to oppose the wind drag force on the balloon. It might also propel the system to another location where station-keeping would again be accomplished. Upon completion of the mission, the balloon either floats or is powered to a recovery area, valved down and recovered.

2.3 Goodyear Feasibility Study

Starting in 1966, in conjunction with Goodyear Aerospace Corp. we studied both streamlined (blimp) and natural shaped (round) balloon configurations with reciprocating engines, turbines, and electric motors as candidates for balloon propulsion. For electrical power sources, we considered solar cells and batteries. Operational altitudes were between 60,000 and 100,000 ft. The results of the Goodyear feasibility study[4] were as follows:

(1) Air breathing engines are most useful below 30,000 ft. The Continental T-65 and Airesearch T-76 were considered.

(2) The best power source above 50,000 ft is an electric motor driven by batteries and recharged by solar cells.

(3) The streamlined balloon concept, though theoretically better (lower drag) than the round balloon, is very costly and difficult to launch. Recovery is also difficult.

(4) Microwave power transmission to a balloon for propulsion is too expensive and a large ground installation is involved.

2.4 Goodyear Parametric Study

Because of the funding limitations, it was decided in 1967 to study further a system that could be built to demonstrate the capability of station-keeping using a powered balloon.

A parametric study[4] was accomplished for the following ranges of parameters:

Balloon Volume	-	500,000 to 100×10^6 ft^3
Altitude	-	60,000 to 100,000 ft
Airspeed	-	15, 30 and 45 knots
Duration	-	12, 24 and 96 hr
Payload (User)	-	100 to 500 lb

In summary, the study established the following conditions for which missions can be accomplished with natural shaped balloons of sizes comparable to those that have been flown. Three electrical power sources provide workable systems for 24-hr flights at 15 knots airspeed over an altitude range of 60,000 to 100,000 ft:

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4. Vorachek, J. J. (1968) Investigation of Powered Lighter-Than-Air Vehicles, AFCRL 68-0626.

primary batteries, secondary batteries and battery/solar cells. Primary battery-powered balloon systems are significantly lighter than secondary battery-powered systems for a given mission, and battery/solar cell-powered systems are even lighter than primary battery-powered balloon systems. The battery/solar cell-powered systems also provide a flight capability for 96 hr at a 15-knot airspeed. A limited number of solutions are available for 30-knot airspeed. A 45-knot speed capability is not feasible for the natural shaped balloon.

3. SYSTEM DEVELOPMENT

3.1 Requirements for a Demonstration POBAL System

The demonstration system using off-the-shelf components was designed by Goodyear Aerospace Corp. with the following general requirements:

(1) System Capabilities:

Altitude - 60,000 ft MSL
Speed - 15 knots airspeed
Useful Payload -200 lb
Duration - 24 hr, 12-hr powered flight
Ballast Capacity - 10 percent of gross weight.

(2) The gondola to be of sufficient strength to withstand parachute opening shock of 10g and ground impact of 5g. Top suspension cables to terminate at single point for attachment to the base of a recovery parachute. Provide space for payload of 200 lb with a size 2 ft × 2 ft × 1 ft high. Provide for honeycomb or equivalent impact attenuator.

(3) The motor to be of sufficient power to maintain required balloon system speed. Blower to be of sufficient capacity to prevent motor overheating, and be thermostatically controlled so that motor temperature does not exceed +400°C.

(4) The rudder assembly to be positioned at rear of gondola in propeller slip stream and be servoed so that gondola azimuth heading can be controlled.

(5) The propeller shall be a high-efficiency lightweight design but not over 40 feet in length, and shall be economical to replace in case of ground impact damage. A horizontal positioning device can be provided if deemed necessary.

(6) An autopilot shall be provided using a gyro, gyro compass, magnetic compass or magnetometer type of reference. This autopilot will be coupled to the rudder servo and must be able to maintain the thrust axis at a desired heading. The autopilot must be able to accept selectable command headings from the ground station in increments. It must maintain the selected heading within ±3°.

(7) Sensors must be provided to monitor the following parameters: motor rpm, rudder position, heading reference, altitude, airspeed, motor temperature, battery temperature, magnetic heading, pitch of gondola, motor voltage, and motor current.

3.1.2 PROPULSION SYSTEM

The propeller was required to provide enough thrust to overcome the drag on the balloon in a 15-knot wind at 60,000 ft MSL. At 15-knot airspeed and 60,000-ft altitude, the calculated drag force on the 711,000-ft^3 natural-shaped balloon was 108 lb. To generate this thrust, the FH 1100 helicopter rotor was selected from among commercially available propellers. This two-bladed rotor has a diameter of 35.4 ft, a chord of 10.22 in., blade twist of 0.571 deg/ft, and blade tip angle of 12 deg. At 196 rpm, the predicted thrust at altitude was the required 108 lb.

This output rpm was achieved using a Lear-Siegler starter generator motor and a gear reduction unit with a ratio of 17.28/1. At this gear reduction, the motor must run at 3387 rpm. The motor requires 35.2 V and 220 A.

All of the required power was provided by silver-zinc rechargeable batteries: a bank of 368 Electric Storage Battery 2-1000 cells for propulsion, and 30 Yardney BB 405 cells for housekeeping functions and system electronics.

The directional control was supplied by an 8.75-ft high, 21.9-ft^2 rudder placed 11.5 ft to the rear of the propeller. The rudder could be rotated $\pm 25^\circ$ from neutral position by autopilot, or $\pm 32^\circ$ manually from a ground-based radio command system.

In addition to the propulsion system, the 2800-lb gondola load included 600 lb of ballast and 139 lb of instrumentation for command, control, and telemetry. It was suspended 300 ft below the balloon on a 293-lb (100-ft dia) parachute system which was flown fully extended and unopened as is conventially done on free balloons. The total weight of the flight system including the balloon was 4637 lb.

The demonstration system design is more completely described in the Goodyear design evaluation report[5] and the Goodyear final report.[6]

3.2 Ground Tests

3.2.1 1/16 SCALE MODEL

During 1 November 1971 to 15 January 1972, a 1/16 scale model of the anticipated POBAL system was made and tested at AFCRL (Figure 3). The model was

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5. Goodyear Aerospace Corp. (1972) R&D Design Evaluation Report, Free Balloon Propulsion Payload, GER 14076, Contract F19628-72-C-0072.

6. Vorachek, J.J., McGraw, E.W. and Bezbatchenko, J.W. (1973) Development of a Free Balloon System, Final Report Contract F19628-72-C-0072, AFCRL-TR-73-0123.

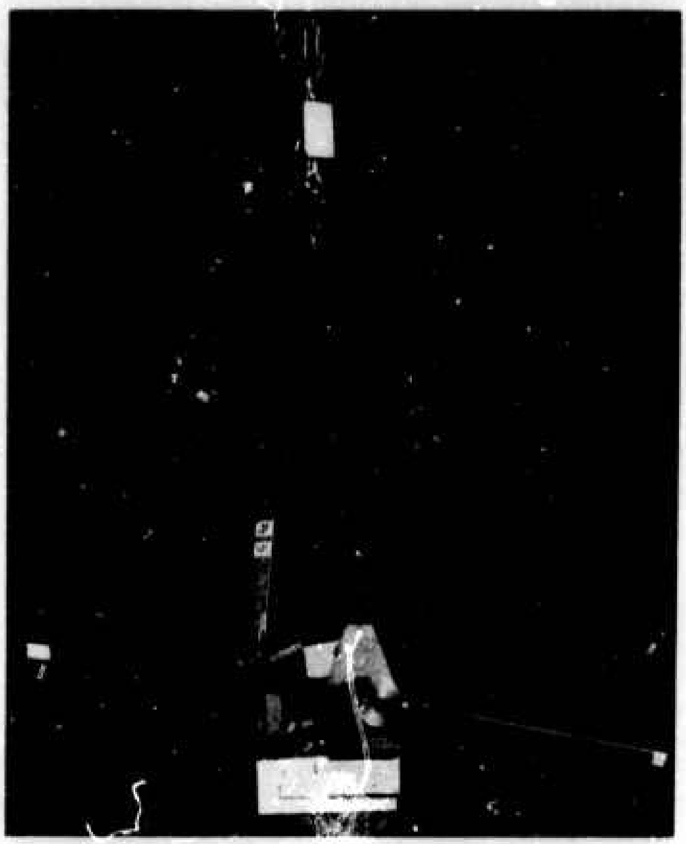

Figure 3. AFCRL Scale Model - POBAL

used to study the effects of gyroscopic moments induced by the propeller, and the effects of parachute length and rudder size on the system.

A scale factor of 1/16 was chosen so that the model would be small enough for convenience, yet large enough to give worthwhile data. The scaling relationships are determined by dimensional analysis. Dynamic similarity between scale model and prototype will be obtained if the following expression is satisfied:

$$\frac{F_1 t_1^2}{m_1 L_1} = \frac{F_2 t_2^2}{m_2 L_2} \tag{1}$$

where:

F = force
t = time
m = mass
L = length
subscript 1 refers to the model
subscript 2 refers to the prototype.

A scale factor, λ, is the ratio of a model quantity to its corresponding prototype quantity. Then, from Eq. (1) the scale factors are related by:

$$\lambda_L = \frac{\lambda_F \lambda_t^2}{\lambda_m} . \tag{2}$$

The rigidity of the gondola is effectively infinite for both the model and the prototype.

It was not possible to scale all factors properly, but most of the improperly scaled quantities were not critical. Among these were air density, temperature, suspension bridle, and support cable. The air density, though important, was not critical for the scale model tests because we were interested in general trends rather than high accuracy. The primary effect of air density was on the rudder control, as mentioned later in this section. Temperature had little effect on the quantities we were measuring.

The model was suspended from a fixed support at an arbitrarily chosen length. Power was applied to the motor very slowly and the propeller started revolving. The angular velocity of the propeller was monitored with a Strobe-O-Tac. Power was slowly increased and the model was visually observed. Regions of instability and the corresponding velocity of the propeller were noted. The speed of the propeller was raised beyond the design value (784 rpm) scaled. Propeller speed was then returned to 784 rpm, and directional control was attempted. The rudder control unit was used to turn the rudder to demonstrate the control available. The motor was then gradually slowed down and any unstable regions at decreasing rpm were observed. This procedure was repeated with several different lengths of support cable.

The results of the scale model test were as follows:

(1) The design of the propeller shaft hub was critical. The hub absorbs a great deal of energy due to the gyroscopic moment of the propeller, and it must be constructed to deal adequately with these loads.

(2) The length of the support cable greatly influenced the stability of the gondola. By varying this length, one could change the instability mode. It would be necessary to determine the proper cable length to prevent excessive vibration in the gondola over the rpm range of the prototype system.

(3) The risers had a great deal of resistance to turning.

(4) The rudder size was insufficient. This was probably due to the resisting torque in the risers. Also involved was an incorrectly scaled air density which affected the thrust developed by the propeller and thus limited the control available.

3.2.2 ALTITUDE CHAMBER TEST

On 24 and 25 May 1972, the actual propulsion system (without propeller) was tested in an environmental chamber to ensure that it would operate at POBAL pressure-altitude and to determine the power available from the batteries.

A torque stand was used to apply known torque loads at the output shaft of the propulsion unit gearbox. The torque stand had an industrial brake, a calibrated load cell, and a pressure gauge which indicated the torque applied to the input shaft of the brake. Pressure was applied to the brake unit by a hand-actuated pump until a load-cell pressure reading was attained which corresponded to the desired test torque load on the gearbox output shaft.

The following criteria for stopping any particular portion of the test were used:

(1) Battery temperature of +150°F or higher.
(2) Propulsion motor brush temperature of 375°F or higher.
(3) Gearbox oil temperature in excess of 375°F.
(4) Propulsion motor current in excess of 300 A.
(5) Battery stack voltage below 27 V.

Also, if battery temperature dropped to 0°F, the system would be started up. Table 1 shows the test sequence and conditions.

Table 1. Test Sequence and Conditions

Run No.	Chamber Air Temp. (°F)	Altitude (ft)	Torque Load Ft Lb		Power Cycles Duration Min.		Remarks
			Start	Run	On	Off	
1	-90	65,000	0	210	50	63	Note 1
2	-90	65,000	0	210	51	61	Note 1
3	-92	65,000	0	210	47	63	Note 1
4	-90	70,000	0	130	60	93	
5	-70	60,000	110	210	42	119	Note 1
6	-67	60,000	110	210	44	62	Note 1
7	-58	60,000	0	210	40	61	Note 1
8	-55	60,000	110	210	41	48	Note 1
9	-50	60,000	110	210	40	29	Note 1
10	-49	60,000	110	210	36	27	Note 1
11	-48	60,000	110	210	38	26	Note 1
12	-45	60,000	110	210	24	---	Note 2

Note 1: Test stopped due to propulsion motor brush temperature reaching limit of 375°F.

Note 2: Test concluded due to propulsion battery voltages dropping to 26.1V.

The results of the altitude chamber test were as follows:

(1) The discrepancy between the design value of propeller speed (196 rpm) at a 210 ft-lb. load and the actual speed (220 rpm) during the altitude chamber test was due to the motor speed-voltage characteristics. The curves given by the manufacturer, Lear-Siegler, are low by 10 percent. This was verified by no-load tests on the motor. The field resistor of the motor was adjusted to bring the motor speed-voltage characteristics in agreement with the original design numbers.

(2) The remaining systems met the predicted design characteristics.

(3) Temperatures were in the proper ranges. The motor brushes showed little wear, and the system components interfaced well.

3.2.3 AIR DOCK SUSPENSION TEST

Air dock suspension tests of the prototype balloon-propulsion payload (the gondola system), Figure 4, were conducted during the period 15-19 July 1972. These tests were conducted to evaluate dynamic interactions of the payload and suspension, propeller characteristics, and steering and autopilot functioning. Minor modifications dictated by the airdock tests were immediately incorporated

Figure 4. Demonstration Prototype, POBAL Propulsion System

and functional tests were successfully completed on the modified system. Specific objectives of the airdock tests were as follows:

(1) Interface with AFCRL van systems and conduct functional test of gondola system.

(2) Determine whether gyroscopic forces cause pitching or vibration. Measure vertical dynamic resonance.

(3) Measure propeller rpm, motor current and thrust to verify aerodynamic curves.

(4) Operate propulsion system, rudder and autopilot controls

(5) Measure dynamic pressure on tail and compare with anticipated value to determine rudder power and effectiveness.

(6) Measure gondola turning rates.

(7) Determine autopilot gain and bandwidth for correlation with altitude performance.

(8) Determine weight and center of gravity of the system.

The 1/16 scale model test had indicated a potential problem in system dynamics. The vertical frequency of the balloon propulsion payload interacting with the parachute suspension system was experimentally determined to be 0.8 Hz (48 rpm). This frequency is sufficiently removed from the propeller forcing frequencies to ensure that no resonance frequencies would cause difficulty. The propeller frequencies including starting steps are approximately as follows:

Step 1 - 0 to 139 rpm
Step 2 - 139 rpm to 179 rpm
Step 3 - 179 rpm to 197 rpm

During motor start-up the propeller passed through the critical rpm range so rapidly that no unusual motion was observed.

Once it was determined that the propulsion system operation was satisfactory, the next task was to monitor the gyroscopic effects of the propeller on the pitching motion of the gondola. Two tether lines were attached to the back of the gondola, and the gondola was manually rotated in both directions to detect any gyroscopic effect. There was no evidence of pitching motion when the propeller was rotated at maximum rpm or at the intermediate rpm, but during shutdown the pitching motion was noticeable at approximately 50 rpm, which is the natural vertical frequency of the parachute suspension.

Predictably, the gondola rolled to balance propulsion system startup torque.

Initial steering tests with the gondola suspended on the parachute indicated that the 12.5-ft^2 rudder was more effective in performing left turns than right turns and that steering power was not as great as desired.

The propeller slipstream dynamic pressure was measured at three points on the vertical rudder. The low magnitude pressures were difficult to measure, but the measurements were indicative. The data for the 12.5-ft^2 rudder indicated a core of low dynamic pressure in the propeller slip stream, and even outside of this core the dynamic pressure was lower than predicted. This dictated the necessity of increasing the rudder area to recover the design value of rudder power. The new rudder area was increased 75 percent to 21.9 ft^2.

The gondola turning rates with the larger rudder were measured. The propulsion system was operated at maximum rpm and the system was allowed to run until a steady-state condition was reached. With steering in the manual mode and the rudder servo operated to place the rudder at maximum for the left-turning direction, the actual turning rate of the gondola was measured. Then the rudder servo was operated to place the rudder in the maximum right-turning direction and the actual turning rate of the gondola measured. Slopes of the magnetic and command heading trace were taken at various intervals along the traces for these measurements. It was noted that the slopes were higher when taken around the center of the magnetic and command heading trace. Also, the slopes were different depending upon which direction the gondola was turning. This was interpreted as an error in the actual setting of the rudder zero position. Zero rudder mechanical position is not the zero rudder aerodynamic position. On one portion of the trace a turning rate as high as 4°/sec was measured. Most of the slope measurements resulted in maximum turning rates of approximately 1.0 to 1.5°/sec.

The conclusions from the airdock tests were:

(1) The system is compatible with the AFCRL telemetry van.

(2) The propulsion motor will produce sufficient torque at the required rpm to achieve an airspeed of 15 knots.

(3) The motor current was higher than was estimated.

(4) The time required for the gondola to settle on a new command heading depends on several factors. First, if the turn is made in manual mode, the operator must learn to anticipate the gondola motion and apply reverse rudder prior to turn completion. Secondly, the relative quietness or turbulence of the air at flight altitude will affect the heading behavior. If wind variations occur at frequencies above 0.15 rad/sec, the autopilot is unable to correct quickly enough to maintain the command heading. As a result, some constant hunting may occur due to wind-level changes.

3.2.4 FLIGHT TEST OF FULL-SCALE MODEL

A full-scale model of the gondola was flight tested prior to flying the actual POBAL System. The mock-up gondola was fabricated by Air Force personnel at Detachment 1, AFCRL, Holloman AFB, New Mexico. This mock-up was not powered, but all dimensions and its weight were correct. This balloon flight had two purposes:

(1) To determine a launch procedure.

(2) To verify that the polyethylene balloon could carry the heavy payload.

To prevent the payload from swinging and rotating during launch, a rigid arm was extended from the crane to the front face of the gondola. A pin was attached to this arm and a cross brace was attached perpendicular to it. These pieces were attached to the gondola body to keep it in the proper orientation.

Two other potential launch problems were investigated. Since the parachute risers slacken at payload release, they might hit the 9-ft tall POBAL rudder. Also, the danger of the very large propeller hitting the ground upon payload release had to be determined. In fact, the gondola was released from the crane attachment without difficulty and there was no damage to the propeller or rudder during launch. The balloon reached float altitude and was successfully tested.

4. POBAL FLIGHT TEST

4.1 Purpose

AFCRL Flight H72-57 was the first flight test of the natural-shaped powered balloon, POBAL.

This demonstration flight was the first opportunity to observe the performance of the propeller-propulsion unit while actually towing the balloon within the wind fields for which it was designed. Specifically, the flight was planned to assess the capability of:

(1) The autopilot to steer a fixed course.

(2) The propulsion system to achieve and sustain design airspeed, 15 knots.

(3) The combined rudder-propulsion unit to effect a turn in the balloon trajectory.

4.2 Test Procedure

After the balloon reached the 60,000-ft float level, the direction and speed of the local wind was determined from the radar track of the balloon without power. POBAL was then powered on during cycles in the following sequence:

	Time	Power	
		ON (minutes)	OFF (minutes)
Run No. 1	14:14 to 14:57	43	
	14:57 to 15:08		11

	Time	Power	
		ON (minutes)	OFF (minutes)
Run No. 2	15:08 to 15:43	35	
	15:43 to 16:01		18
Run No. 3	16:01 to 16:15	14	
	16:15 to 16:26		11
Run No. 4	16:26 to 16:36	10	
	16:36 to 16:48		12
Run No. 5	16:48 to 17:13	25	

Note: After Run No. 4, range-tracking observers reported that an object had fallen from the system. From the performance of the gondola during powered Run No. 5, this object was identified as the rudder (see Appendix A).

Radar 'skin' tracking[*] gave POBAL locations at 1-sec intervals. Wind vectors were determined by rawinsonde and also, more accurately, from the trajectory of the POBAL balloon itself during the most recent unpowered intervals of the flight test.

4.3 Propulsion System

4.3.1 PROPELLER RPM AND PROPULSION SYSTEM MONITORING

At power turn-on, the propeller rotation rate generally rose to 193 rpm and leveled off at a steady 185 rpm.[**]

Motor current, battery temperature and propeller rpm values at the start and end of the powered runs are listed in Table 2. Changes were gradual unless otherwise noted. Motor current was somewhat higher than expected; otherwise, the results of system monitoring are normal.

Table 2. Propulsion System Monitoring

	Run No. 1		Run No. 2		Run No. 3		Run No. 4		Run No. 5	
	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	
Battery Temp.	70°F	86°F	86°F	104°F	106°F	114°F	114°F	114°F	--	
Motor Current	300A	294 A	294A	294 A	300 A	294 A	294 A	294 A	294A	
Prop. rpm[a]	193	185	193	185	185	185	185	185	185	

[a] The values of propeller rpm are derived from the measured values of motor rpm, corrected by the gear ratio.

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[*] The more accurate transponder was not flown due to its weight.

[**] At 1703 hr, when ballast was poured in preparation for flight termination, motor current increased beyond 300 A and propeller rpm dropped to 176.

4.4 Airspeed

The most useful evidence of the POBAL performance is considered to be airspeed (speed relative to the wind) sustained while the gondola motion was essentially linear. If it were possible to detect changes in airspeed during known time intervals, at constant windspeed, the acceleration data would yield a better measure of thrust and drag forces; but POBAL accelerations, by design, are small, and in most instances, airspeed acceleration cannot be detected from among the random, natural fluctuations in windspeed. Also, by design, POBAL airspeeds are of the same order of magnitude as the windspeeds in its environment. Windspeed fluctuations also limit the accuracy to which airspeed could be determined on this flight.

4.4.1 DETERMINATION OF AIRSPEED

Measurements of airspeed were obtained by telemetry from a cup anemometer suspended beneath the balloon, and by computation based upon wind and ground speed data.

4.4.2 ANEMOMETER READOUT

There is some question concerning the validity of the calibration of the anemometer for operation at 60, 000 ft. The computed airspeed values are considered more accurate than the anemometer data; therefore, all results presented in this report are computed values.

4.4.3 COMPUTED AIRSPEEDS

Airspeed values were obtained by vector subtraction, using a vector triangle with the known groundspeed vector as diagonal and the directions of windspeed and airspeed as sides. The procedure for analyzing the data was to scan the trajectory for intervals when the gondola held a reasonably steady course. For those intervals it was assumed that the direction of POBAL airspeed is the same as the heading of the gondola, and that the wind was maintaining the same direction, but not necessarily the same speed as evidenced during the most recent unpowered run. On this basis it was determined that POBAL airspeeds ranged from 6 to 12 knots. The data are discussed in the Appendix A.

Alternatively, Vorachek[6] assumed that in the short interval following unpowered flight the wind had remained steady both in magnitude and direction, but that the airspeed direction was unknown (the system was moving in yaw). By subtracting the wind vector from the ground vector, Vorachek obtained airspeed values up to 14 knots.

In an independent analysis of the trajectory and wind data, B. Gildenberg[7] has concluded: "...there are a number of places indicating airspeeds of 5 to 7.5 knots and one 10.5 knot interval..." (Runs No. 1 and No. 2).

4.5 Estimated Thrust

In principle, POBAL thrust can be computed either from (1) simultaneous acceleration and velocity data (POBAL mass times acceleration plus drag force), or (2) from airspeed at zero acceleration (total drag force computed at maximum airspeed).

(1) The 210-slug mass of the POBAL system requires a thrust of 5.9 lb for each knot/min linear acceleration. As explained in Section 4.4, in general, meaningful acceleration measurements cannot be detected from the data. There is one instance, however, during Run No. 1, from 14:34 to 14:36, where there was a reversal in groundspeed direction at 5-knot average speed. This reversal would require about 10-knots/min average deceleration. If this deceleration was achieved solely by POBAL propulsion, the useful thrust at the time was 59 lb, plus 11- to 25-lb drag force during the same period. Total thrust then would be about 70 to 85 lb.

(2) Thrust was determined from maximum airspeed using the computed total drag-force data shown in the graph, Figure 5. The balloon drag coefficients are taken from wind tunnel data on a natural-shaped balloon.[8] At the lower airspeeds the Reynolds number achieved for the balloon is in the critical and subcritical range, and the drag coefficients are substantially increased. The parachute is considered to be a 100-ft long cylinder of 1-ft diameter, with $C_D = 1.2$. The thrust corresponding to the highest computed airspeed, 11.6 knots, is about 70 lb.

4.6 Autopilot

POBAL was operated by autopilot during the first 18 min of powered flight, from 14:14 to 14:32 hr during powered Run No. 1. Figure 6 illustrates the autopilot-rudder action. The telemetry records show that the autopilot responded as it was designed, detecting the deviation of the gondola magnetic heading from the command heading and deflecting the appropriate rudder to correct the error.

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[7] Gildenberg, B. (1972) Private Communication from B. Glidenberg, Chief, Flight Control Analysis, AFCRL Det. 1, Holloman AFB, to A.O. Korn, 13 October 1972 and 30 November 1972.

[8] Sherburne, P.A. (1968) Wind Tunnel Tests of Natural Shape Balloon Model, Goodyear Aerospace Corp, AFCRL-68-0123.

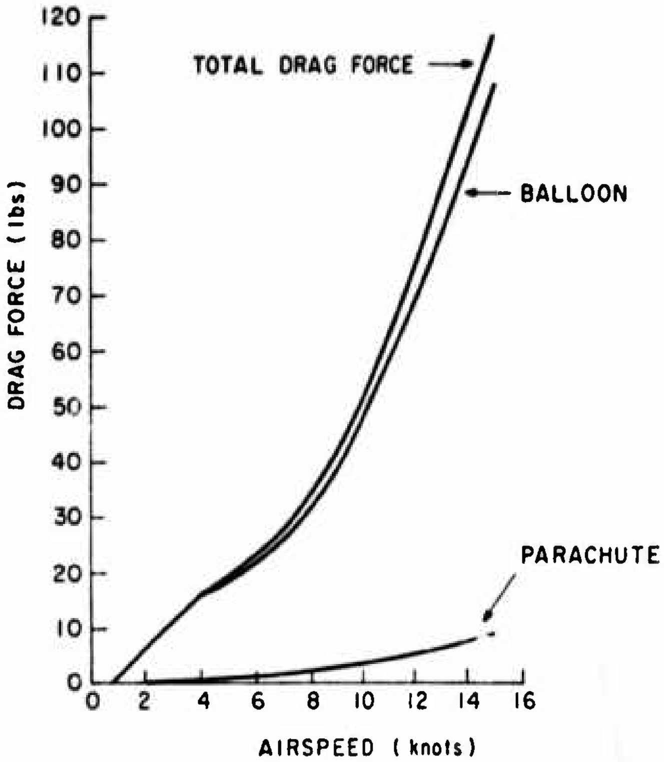
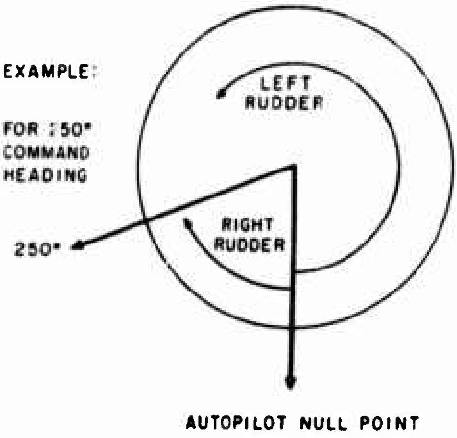


Figure 5. Drag Force Versus Airspeed



NOTE: If the gondola magnetic heading is leftward from the desired command heading, as far as South, the right rudder is commanded. To correct a heading to the right of the command heading as far as South, the left rudder is activated.

Figure 6. Autopilot-Rudder Action

There was a difference in magnitude of error that would produce the full rudder deflection. Consistently, a 36° deviation from course produced full right rudder, whereas a 72° error in the opposite sense was required before full left rudder was achieved.

When the rudder turned just off course, there was no lag in rudder response. At the null point in the magnetic compass (see Figure 6) the changeover from full left to full right rudder, or vice versa, took place in less than 4 sec. The resolution of the stripchart records was 3° deflection and 0.3 sec.

Rudder control was not always adequate to prevent the gondola from making large transient deviations off course. There are other portions of the trajectory when the pointing error was small and the corrective action of the rudder was effective in rotating the gondola back onto the desired magnetic heading.

The gondola was unstable in yaw. Part of this yawing motion was due to coupled torque from the balloon which had not yet stopped its ascent rotation when the power was first turned on.

The data indicate that right rudder was more effective than left rudder, but this can be interpreted as further evidence that the unwanted yawing motion was predominantly clockwise. (See "Effect of Power Startup", Section 4.8).

4.7 Gondola Heading With Power Off

When power was turned off after a powered run, the rotation damped out rapidly and the gondola assumed a heading that it maintained for 6 min or more, changing only gradually as the free balloon trajectory changed. Figure 7 is a typical record when power was turned off.

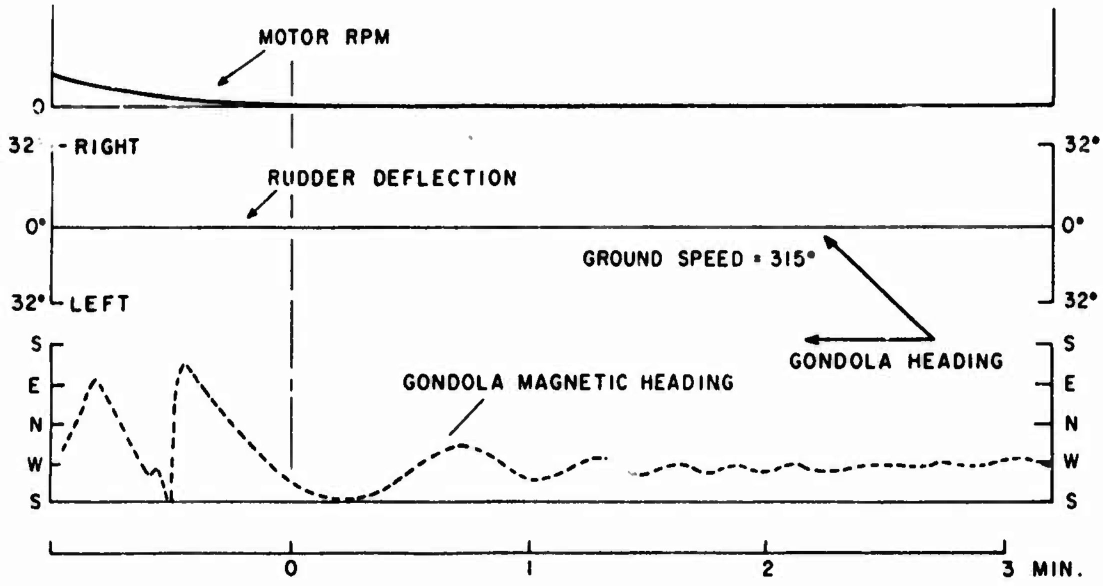


Figure 7. Typical Gondola Heading Record, Power Off

4.8 Effect of Power Startup

When the motor was turned on, while the rudder was still in neutral position (manual operation) the gondola began to turn clockwise (North toward East). The turning rate differed on each run. Some of this yawing motion was gyroscopic, a transient precession while the propeller accelerated to its full speed. Other sources for yawing instability are considered in Section 4.9.

4.9 Effectiveness of the Rudder

From the flight data using manual control, the evidence (from examining the changes in trajectory direction and gondola heading with rudder deflection) is that at less than full rudder deflection, the rudder torque was too low for dependable steering. When the system had developed some airspeed, full rudder deflection for at least 2 min was required to change the flight path. The trajectories, with rudder-deflection directions and gondola headings are discussed in Appendix A (see Figures A1 through A5).

In considering POBAL steering one must remember that while the balloon was supporting the weight of the gondola, the gondola was towing the balloon through a long, flexible suspension line. The initial effect of rudder deflection is to rotate the gondola about the suspension line; an immediate response of this system as a rigid unit is not possible, neither is it mandatory for the POBAL hovering mission. Aside from the steering complications introduced by a flexible tow line, the POBAL system, like all lighter-than-air powered craft, can be expected to require almost continual manipulation of the rudder. During curvilinear flight, the lift is always vertical; the vehicle cannot execute a banked turn to provide an inward component of lift for centripetal force.

4.10 Results of Flight H72-57

4.10.1 SUMMARY

Under power, when winds were 6 knots or less the POBAL gondola was unstable in yaw. With power off, and also during one interval when power was on, with slight or neutral rudder, and winds above 6 knots, the gondola tended to hold a steady heading for 4 to 6 min.

Computations using radar ground velocity, gondola heading and estimated wind direction show airspeeds in the range, 6 to 12 knots. Accuracy of these low airspeeds is limited by the natural variations in the winds. For this flight the computations are also affected by the low precision of the "skin-track" radar data and the yawing instability of the gondola. Estimated random error is 15 percent.

POBAL thrust corresponding to 12-knot airspeed is about 75 lb. There is limited evidence of accelerations that required up to 85-lb thrust.

With less than full rudder deflection, the rudder torque was inadequate. Steering in a curved trajectory was accomplished by holding full rudder deflection for longer than 2 min.

4.10.2 DISCUSSION

4.10.2.1 Motor-Propeller Performance

The "housekeeping" or monitoring records show that the motor rpm and current were steady, and the motor was operating within the proper limits. These parameters directly measure performance of the motor, not the propeller; however, it is reasoned that if the propeller were not absorbing normal output power from the motor, this fact would be evidenced by changes in the values of motor rpm and current.

In assessing the performance of the motor-propeller system, on the basis that the propeller was absorbing essentially full design power from the motor, there is a choice of two premises:

(1) the propeller was operating near design efficiencies, and the useful axial thrust was, in fact, close to the 108-lb design value; or

(2) the propeller performance was degraded and the axial thrust was less than expected.

Even allowing for 15 percent random error in the airspeed computations, it appears that the 15-knot airspeed goal was not achieved. If the full useful thrust was being produced at reduced airspeed, then the drag forces on the system probably were larger than assumed. One possibility is that the drag force on the gondola is, in fact, not negligible compared to the balloon drag force. (Drag force on the extended parachute in the gondola suspension line was included in the estimates of thrust stated earlier in this report.) A further source of discrepancy between computed and actual thrust values is the fact that the data are not sufficiently precise to show accelerations in airspeed (Section 4.4). If the system was still accelerating at the times for which airspeed was computed, then the estimated thrust is too low by about 6 lb for each knot/min unit of acceleration.

If, on the other hand, the propeller forward thrust was below design value, then the power was not being utilized at design efficiency in the direction of airspeed. Presumably, then, the effective propeller blade angle was not optimum for the actual operating conditions.

Pitching motion, theoretically, could alter the effective blade angle, but the maximum pitch angle during flight was only 4.8°, and for most of the flight the pitch angle was less than 1.5°.

The tendency of the gondola to rotate about the balloon load line—that is, to yaw during this flight—would also result in reduced thrust in the direction of airspeed. When the thrust axis is not aligned in the direction of airspeed, the thrust available to balance the drag forces is only a fractional component of the axial thrust. Simultaneously, the characteristic propeller "side force" due to yaw appears (Ribner, 1945).[9]

4.10.2.2 Yaw Instability

Prior to the first powered run, as the POBAL system ascended to float altitude, the heading record shows that the gondola, ostensibly driven by the rotating balloon, was winding and unwinding on the load line. This is typical of a free-balloon system as it approaches float altitude. Generally, by 10 to 20 min after float altitude has been attained, the balloon rotation has been reduced to an occasional turn of period 4 min or more.[10] Undoubtedly, part of the yawing torque that appeared during the Autopilot test, Run No. 1, was due to balloon rotation. This did not continue to be a major effect, however, because the gondola heading tended to be steady during subsequent periods of unpowered flight.

Some gondola yaw was gyroscopic reaction associated with propeller spin. Gyroscopic yaw will be produced by any unbalanced torque about a horizontal axis perpendicular to the propeller axis of spin. Angular acceleration of the propeller is equivalent to such a torque and would cause transient yawing during power startup and stopping, as evidenced by the clockwise rotation under neutral rudder when power was turned on to start the powered runs. Also, since the propeller thrust axis and the point of application of the POBAL drag force at the gondola are not colinear, there is a couple in the proper direction to produce yaw in the clockwise direction. Finally, in addition to propeller side force (which was considered in the gondola design) another possible source of yaw is aerodynamic instability associated with interaction between the propeller slip stream and the contours of the gondola.[11]

No effort was made to streamline the gondola for this first flight test because its largest dimension in the vertical plane was so much smaller than the propeller radius. Nevertheless, streamlining the gondola might lessen instability due to the above-mentioned slipstream lateral force. The addition of a nose cone ahead and a cowling directly behind the propeller also should improve the propeller

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[9] Ribner, H.S. (1945) Propellers in Yaw, NACA Report 820.

[10] Toolin, R.B. and Poirier, N.C. (1970) Sun oriented atmosphere optics measurements using the high altitude balloon, Proceedings, Sixth AFCRL Scientific Balloon Symposium, AFCRL-70-0543.

[11] Munk, M. (1936) Aerodynamics of airships, Aerodynamic Theory, W. Durand (editor), Dover Publications, Inc.

output thrust in flight (when the system has positive forward speed)[12] even though under the static, airdock tests (zero forward speed) the forward thrust was satisfactory.

5. CONCLUSIONS

Results of the POBAL flight test indicate that it is possible to power a natural shaped balloon against the wind. Airspeeds of 10 to 14 knots[6] were achieved even though directional control of the gondola was marginal. The rudder must be increased in size so that a given gondola heading can be maintained for a longer period of time.

Post-flight analysis indicated that rudder separation was caused by failure in the aluminum support tube due to improper heat treatment after welding.

Propeller efficiency was less than that obtained by calculation. Ground equipment and onboard instrumentation systems functioned as designed and are adequate.

The POBAL system can be recovered without major damage.

The flight was successful enough to justify reflying the system with a larger, stronger rudder and increased propeller pitch.

6. RECOMMENDATIONS

6.1 POBAL System

Several immediate low-cost improvements which can be made for another flight of the demonstration system (propeller-driven gondola suspended on the parachute beneath the balloon) are:

(1) Use of the radar transponder or another source of accurate ground-velocity data.

(2) Substitution of a more sensitive and dependable balloon-borne airspeed sensor.

(3) Addition of a nose piece to shield the boss of the propeller, and cowling at least behind the propeller; if possible, streamlining the entire gondola

(4) Omission of the 200-ft extension to the load line. (This extension was used to facilitate the first launch of the heavy gondola with the huge propeller.

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[12] Durand, W. (1936) <u>Aerodynamic Theory</u>, Vol. VI, Dover Publications, Inc.

Shortening the suspension line will lessen the possibility that the balloon and gondola are being subjected to winds of different speed and direction, and also will reduce the system weight.)

5. Addition of a sensor that will indicate torsion in the suspension line.

6.2 Flight Plan

Gondola headings should be monitored throughout ascent, and the first powered run should be postponed until the gondola heading record shows that the rotation due to balloon ascent has damped out. This usually will be 10 to 30 min after the system has attained float altitude.

The flight plan should include at least one interval during most powered runs with neutral rudder held for at least 3 min, and more frequent runs with power off to indicate the current wind vectors. One run with a 5-min interval of neutral rudder would be useful. Powered runs of less than 10 min probably would be too short to yield useful propulsion data, and in light winds, off periods under 6 min might show large errors in wind direction due to the slowly decelerating balloon system. Consequently, 10-min on and 10-min off sequences are recommended, subject to change as the flight progresses.

During a time when winds are fairly steady, a course opposing the wind should be attempted throughout a powered run. The pilot also should demonstrate the effect of full left and full right rudder sustained for 2 min or longer, or until the prolonged rudder deflection would cause the gondola to wind up on the load line. A course perpendicular to the wind should also be followed.

7. LONG DURATION POBAL SYSTEM FEASIBILITY STUDIES

7.1 AFCRL Computer Study

The fundamental premise for the POBAL design is that the balloon volume required to support the system increases with the fuel supply load, while the fuel consumption rate depends upon the wind-drag force and therefore upon the cross-sectional area of the balloon. Even in the minimum wind fields, if a powered balloon of practical size is to achieve a hovering mission of several days duration, the propulsion system must have an unusually low specific fuel consumption rate and light weight. It also, of course, must function dependably in the near-vacuum at 60,000- to 80,000-ft altitude. In 1971, an in-house survey showed that the proven power sources which best met these qualifications were a hydrogen-oxygen fuel cell, or an array of cadmium-sulfide solar cells with rechargeable silver-zinc batteries. A Fortran program was written[13] to "design" the smallest natural-shaped superpressure balloon for a mission of specified duration and wind speed, using state-of-the-art gas barrier materials having sufficient strength to support the required load, and powered either by fuel cell or an undirected CdS solar-cell array. Subsequently, production of CdS cells was halted, and the more expensive, but more efficient silicon cells were considered. Next, the program was modified for an aerodynamically shaped balloon.

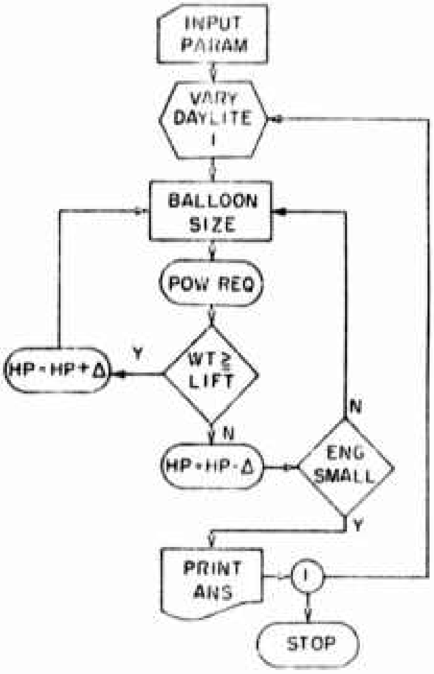

Figure 8. Flow Diagram, POBAL Design Study

Figure 8 shows a generalized flow diagram for this computer program. For a fuel-cell study, the daylight cycle is omitted. The studies were based upon the following parameters:

Useful Payload	200 lb
Balloon Drag Coefficient:	
Natural	0.19
Aerodynamic	0.07*
Fuel Cell:	
Weight of reactants	0.8 lb/kW-hr
Cryogenic tankage	0.5 (weight of reactants)*
Cell hardware	30 lb/kW
Solar Cell Array:	
CdS	4.6 W/ft^2
Si	10 W/ft^2

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* Up-dated values are: drag coefficient aerodynamic balloon: 0.055; cryogenic tankage weight; 0.31 weight of reactants.

[13] Leclaire, R. and Korn, A.O. (1972) The powered balloon system, Proceedings, Seventh AFCRL Scientific Balloon Symposium, AFCRL-TR-73-0071.

A comparison of several systems with 15-knot and 20-knot true airspeed capability for 7 days is shown in Figures 9 and 10. A natural-shaped balloon appears feasible at 15-knot capability, but in 20-knot wind fields an aerodynamically shaped balloon must be used. For durations up to 20 days, fuel cells are superior to solar cells; for durations of 30 days or more, solar cells are the only possible power source.

7.2 Survey of Alternative Power Sources

In view of the high cost and various operational complications involved in using fuel cells or solar cells on a balloon, it was desirable to know how far short of desired performance and cost the other available power sources might be. There remained also a faint hope that in the interim following the Goodyear Aerospace Corp. POBAL study, some less expensive small power device might have been developed which could meet the POBAL requirement. In 1972 the literature was reporting very favorable advances in lightweight, high-energy chemical batteries and small gas-turbine technology, and rumors of breakthroughs in low-cost solar cell development (proprietary) were rampant. Therefore, a search was made for any type of existing power source[14] with the following characteristics as guidelines:

(1) Operable above 60,000-ft altitude at speeds under 15 knots.

(2) Capable of delivering either 3.5 kW to an electric motor, or 2 to 20 shaft horsepower to a propeller, or 50 to 100 lb thrust.

(3) Overall weight including fuel supply for 6 days at 50 percent duty cycle, 1000 lb or less.

(4) Capable of many start-stop cycles at altitude, and throttle-controlled.

7.2.1 GAS TURBINES

Air-breathing gas turbines have very attractive weight characteristics. Figure 11 shows the range for allowable specific fuel consumption versus dry weight for engines delivering 10 to 20 shaft horsepower, to meet criterion (3) above. There are a few small turboshaft engines having specific fuel consumption (lb/hr per hp) and dry weight in the required range, but they produce considerably more than 10 shaft horsepower at ceiling altitude, and their ceiling altitudes are below 60,000 ft. On the other hand, there is no difficulty in finding turbojet engines that operate well above 60,000 ft. Some of them propel unmanned aircraft. They are not designed for multi-start-stop operation, however, and would require an auxiliary starter. Turbojets weigh upward from a few hundred pounds and produce 1000 lb or more thrust (sea level rating). Figure 12 shows allowable

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[14] Rice, C.B. (1972) Power sources for a powered balloon, Proceedings, Seventh AFCRL Scientific Balloon Symposium, AFCRL-TR-73-0071.

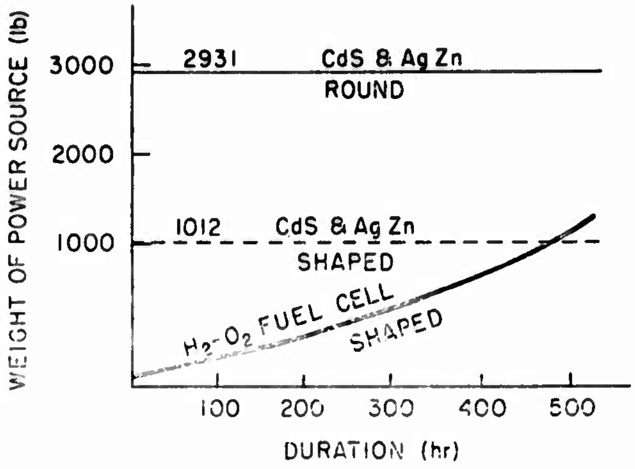

Figure 9. Comparison of Power Supplies at 15-knot Airspeed

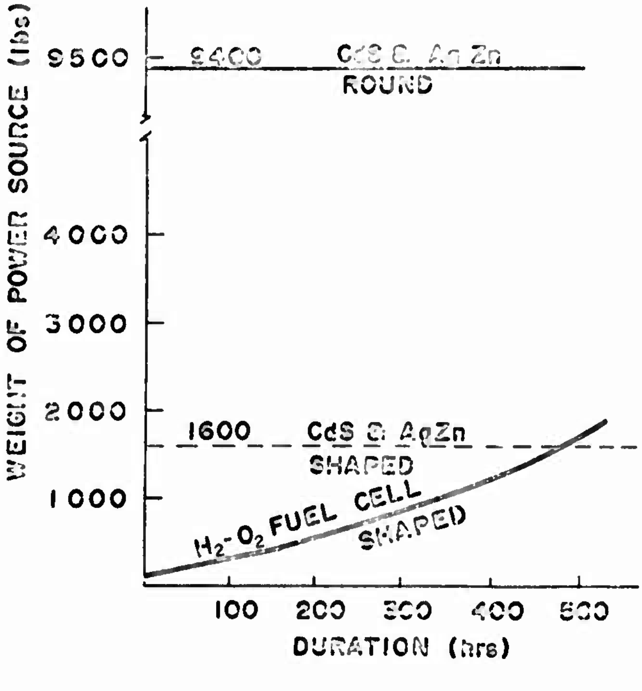

Figure 10. Comparison of Power Supplies at 20-knot Airspeed

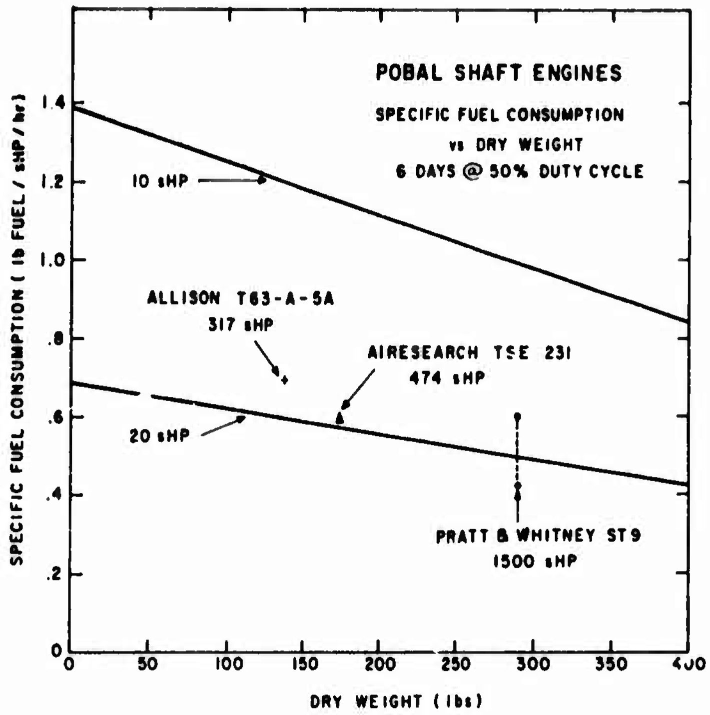

Figure 11. Specific Fuel Consumption Versus Dry Weight, Turboshaft Engine

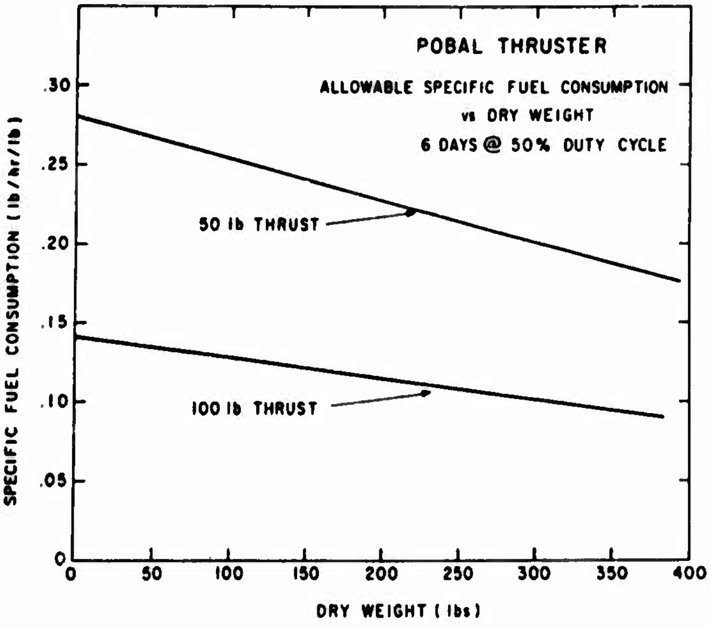

Figure 12. Specific Fuel Consumption Versus Dry Weight, Thruster

weight versus specific fuel consumption for a thrust-producing device. It is clear that the fuel consumption rate must be better than 0.28 lb of fuel per hour per pound of thrust delivered. The best rates for existing lightweight turbojets are greater than 1 lb/hr/lb, and these usually are attained only by the very large capacity engines. Even if we could find a turbojet with auxiliary starter that weighed, for example, 100 lb, and its thrust, scaled to altitude, was 50 lb, at 1 lb/hr/lb consumption rate it could provide only a 36-hr duration at 50 percent duty cycle.

These results were generally confirmed by the USAF Aeropropulsion Laboratory at Wright-Patterson AFB, which subsequently informed AFCRL that there are no suitable turboshaft or turbojet engines that can meet the POBAL requirements.[15]

7.2.2 ELECTRIC THRUSTERS

The many small thrusters that have been developed for space applications develop thrust only in micro- or, at most, millipounds—and their cost is measured in 10^5 dollars.

7.2.3 CHEMICAL THRUSTERS

There are families of simple, chemically-fueled thrusters (small rockets) that do produce thrust in the 50- to 100-lb range. Dry weight is only 10 to 20 lb, but they burn fuel at rates exorbitant for POBAL, 4 to 5 lb/hr/lb of thrust. Durations are a matter of seconds, and, in general, chemical thrusters are not throttle controlled.

7.2.4 SOLAR HEAT ENERGY

Several schemes to convert solar heat into useful mechanical or electrical power in the 3- to 30-kW range were underway in the early 1960's. Solar heat rays concentrated at the focus of a parabolic mirror or Frenel reflector drove a turbogenerator, a thermopile, a thermionic generator or a closed cycle, Stirling heat engine. Sunflower, for example, with a 32-ft diameter folding petal reflector, used vaporized mercury to drive a 30-lb turbogenerator to produce a nominal 3 kW electrical power. In field tests, however, the sun-tracker focussing was not sufficiently accurate to achieve the predicted power output. By that time, several nuclear-powered SNAP (Systems for Nuclear Auxiliary Power) devices were progressing rapidly. Perhaps a cumbersome superstructure to supply 3 kW was no longer desirable; at any rate, the funds to complete the solar-powered engines were not forthcoming.

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15. Simpson, E. (1972) Private communication from E. Simpson, Director Turbine Engine Div., AF Aeropropulsion Labs., Wright-Patterson AFB, to A.O. Korn, 30 May 1972.

7.2.5 NUCLEAR POWER

Nuclear powered devices for space applications are of two basic types: radiosotope-fuelled thermoelectric generators (RTG's), and reactors. Table 3 lists weight and power output of some of the sources developed in the SNAP program.

Table 3. Typical Nuclear-Powered Devices for Space

Radioisotope Thermoelectric Generators	Weight (lb)	Power (W)
SNAP 3	4	2.5
SNAP 9A	32	25
SNAP 19	30	25
SNAP 27	65	65
Nuclear Reactors (Fission)		
SNAP 2 (Particle Collector)	-	3×10^3
SNAP 10A (Thermoelectric)	960	500
SNAP 8 (Turbo Generator)	10,000 (est.)	35×10^3

Categorically, we can eliminate the reactors for POBAL because they are too heavy. On a power to weight basis, in the low kilowatt range, an RTG, if available, would be roughly competitive with solar cell arrays, but probably heavier than the new, lightweight arrays.

7.2.6 POWER SURVEY CONCLUSIONS

Among currently available power sources, turboshaft engines cannot operate at POBAL altitudes. Turbojets are altitude-qualified, but there are none with low enough thrust, and if there were, their fuel consumption would be at least 5 times too high. Electric thrusters fall short of the POBAL requirement by a factor of 10^4. Much higher power output is in the offing, but those systems will be reactor powered and much too heavy for POBAL. Chemically-fuelled thrusters consume fuel at 50 times too high a rate and generally are not throttle-controlled. Several solar-heat converters had excellent weight and power characteristics for POBAL, but they developed unexpected problems and development was abandoned. At the time of this writing, the predicted breakthroughs in low-cost fuel cell development and in high-energy chemical batteries suitable for POBAL have not yet been realized.

Radioisotope thermoelectric generators are a possibility for the future, but they involve operational (safety) restrictions and would be considerably more expensive than fuel cells or solar cells.

In preparation for the Space Shuttle, however, the weight and performance of the H_2-O_2 fuel cell have been significantly improved and lighter weight fuel tanks are available. This is without question, the best available choice for the POBAL mission.

References

1. Nolan, G.F. (1964) High Altitude Minimum Wind Fields and Balloon Applications, AFCRL 64-843.
2. Nolan, G.F. (1967) A Study of Mesoscale Features of Summertime Minimum Wind Fields in the Lower Stratosphere, AFCRL 67-0601.
3. Nolan, G.F. (1969) Meteorological considerations for tethered and hovering free balloons, Symposium Proceedings, Earth Observations from Balloons, Am. Soc. for Photogrammetry.
4. Vorachek, J.J. (1968) Investigation of Powered Lighter-Than-Air Vehicles, AFCRL 68-0626.
5. Goodyear Aerospace Corp. (1972) R&D Design Evaluation Report, Free Balloon Propulsion Payload, GER 14076, Contract F19628-72-C-0072.
6. Vorachek, J.J., McGraw, E.W. and Bo batchenko, J.W. (1973) Development of a Free Balloon System, Final Report Contract F19628-72-C-0072, AFCRL-TR-73-0128.
7. Gildenberg, B. (1972) Private communication from B. Gildenberg, Chief, Flight Control Analysis, AFCRL Det. 1, Holloman AFB, to A.O. Korn, 13 October 1972 and 30 November 1972.
8. Sherburne, P.A. (1968) Wind Tunnel Tests of Natural Shape Balloon Model, Goodyear Aerospace Corp., AFCRL-68-0123.
9. Ribner, H.S. (1945) Propellers in Yaw, NACA Report 820.
10. Toolin, R.B. and Poirier, N.C. (1970) Sun oriented atmosphere optics measurements using the high altitude balloon, Proceedings, Sixth AFCRL Scientific Balloon Symposium, AFCRL-70-0543.
11. Munk, M. (1936) Aerodynamics of airships, Aerodynamic Theory, W. Durand (editor), Dover Publications, Inc.
12. Durand, W. (1936) Aerodynamic Theory, Vol. VI, Dover Publications, Inc.

13. Leclaire, R. and Korn, A.O. (1972) The powered balloon system, Proceedings, Seventh AFCRL Scientific Balloon Symposium, AFCRL-TR-73-0071.

14. Rice, C.B. (1972) Power sources for a powered balloon, Proceedings, Seventh AFCRL Scientific Balloon Symposium, AFCRL-TR-73-0071.

15. Simpson, E. (1972) Private communication from E. Simpson, Director Turbine Engine Div., AF Aerospopulsion Labs., Wright-Patterson AFB, to A.O. Korn, 30 May, 1972.

Appendix A

A1. COMPUTATION OF AIRSPEED

The trajectory was scanned for intervals when the gondola held a reasonably steady course and the estimated winds were also quite steady. For those intervals, it was assumed that the direction of POBAL airspeed is the same as the geographic heading of the gondola. The average groundspeed and the trajectory direction were derived from the radar data.

The magnitude of the airspeed was computed by vector subtraction, using the known groundspeed vector as diagonal and the directions of the wind and the airspeed as sides of a vector parallelogram. Figures A1 through A5 show the trajectories for powered Runs No. 1 through No. 4 under manual control. Gondola headings and average groundspeeds are indicated on the trajectories. One-minute groundspeed averages were used for Runs No. 1 and No. 2. As the balloon approached Holloman AFB, the radar data were more precise and half-minute averages were used.

A2. RUN NO. 1

Winds were 4 to 6 knots until 14:42 hr. At about 14:21 the groundspeed was 12.3 knots and computed airspeed, 8.9 knots. From 14:28 to 14:30 hr, Figure A1, the gondola headings, wind and trajectory were all in the same general direction. At 14:29 average groundspeed was 10.9 knots, and computed airspeed, 5 to 7 knots.

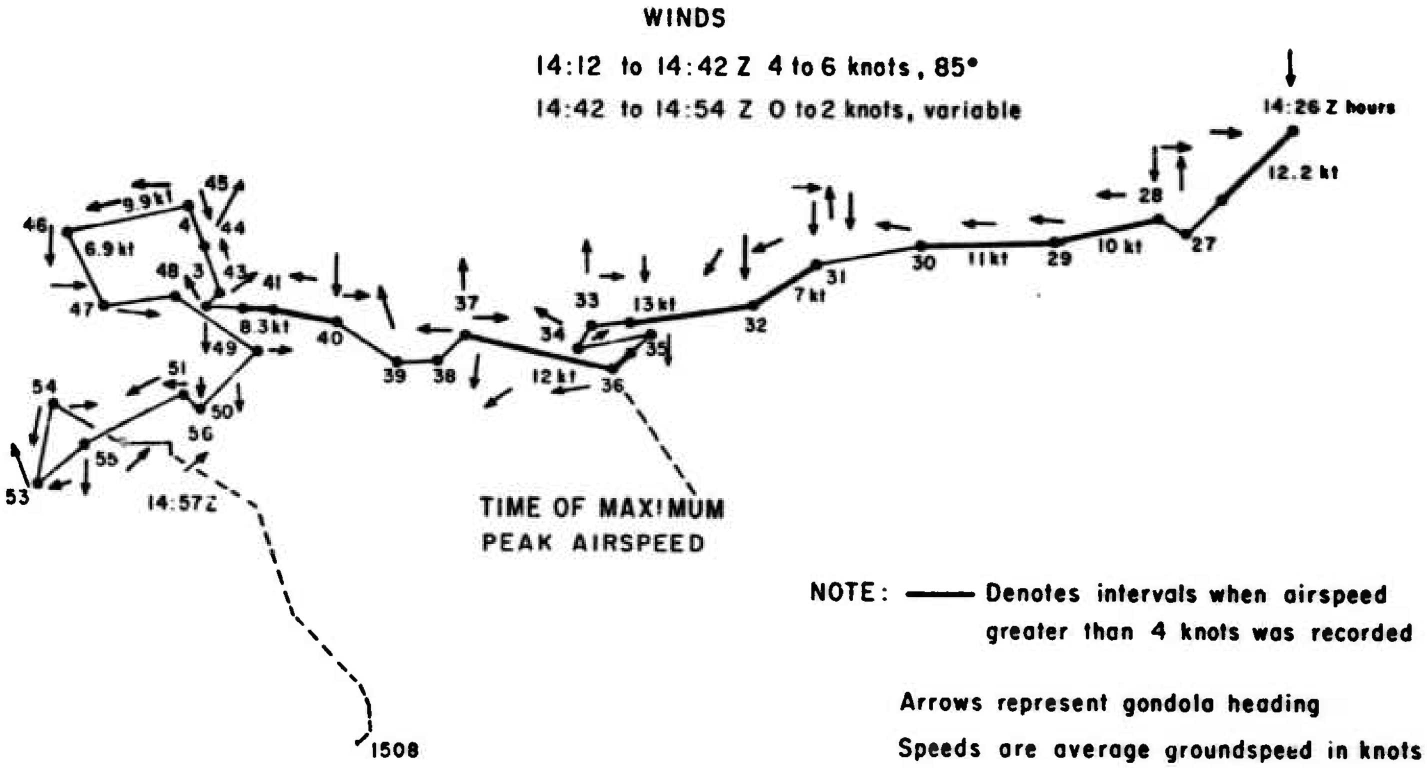

Figure A1. POBAL Trajectory, Gondola Headings and Average Groundspeeds - Manual Control Run No. 1

During this run the gondola made three complete reversals or turns. From 14:34 to 14:35 hr when POBAL was opposing the wind, the 5-knot average groundspeed was not very different from the average forward groundspeed immediately afterward when POBAL would have been aided by the wind. It follows that unless the wind direction suddenly changed, the wind speed was actually very light. This turn differs from the others in that the turn was started with full left rudder held on steadily. (Generally, during manual operation the controller was applying the rudder briefly and intermittently in attempts to discover the source of the difficulty in holding a gondola heading.)

A3. RUN NO. 2

The winds were more difficult to determine during this run because the balloon was travelling through a region of "mountain-valley variations".[7] There is a 9-min period from 15:23 to 15:31 hr, Figures A2 and A3, when the gondola heading relative to the trajectory and the estimated wind direction were steady. This period is of special interest because the gondola behaved as it did during unpowered flight, maintaining its heading without the yawing that was evident when the winds were lighter. Computed airspeed from 15:23 to 15:25 hr is 7.4 knots. Radar tracking was lost during the next 7 min, and only the average direction and groundspeed are known. Using those data, the computed airspeed was 5.8 knots.

A4. RUN NO. 3

From 16:05 to 16:07 hr, Figure A4, the computed airspeed is 11 knots.

A5. RUN NO. 4

The rudder was in continuous use and valuable steering information was obtained during this run (see Figure A5). No attempt was made to find effective values for the direction of thrust by integration of gondola headings because during gondola rotation the propeller thrust is degraded due to its angle of yaw.

A6. RUN NO. 5 - RUDDER FAILURE

During the unpowered flight after Run No. 4, observers reported seeing an object fall from the gondola. When power was turned on for Run No. 5, the motor

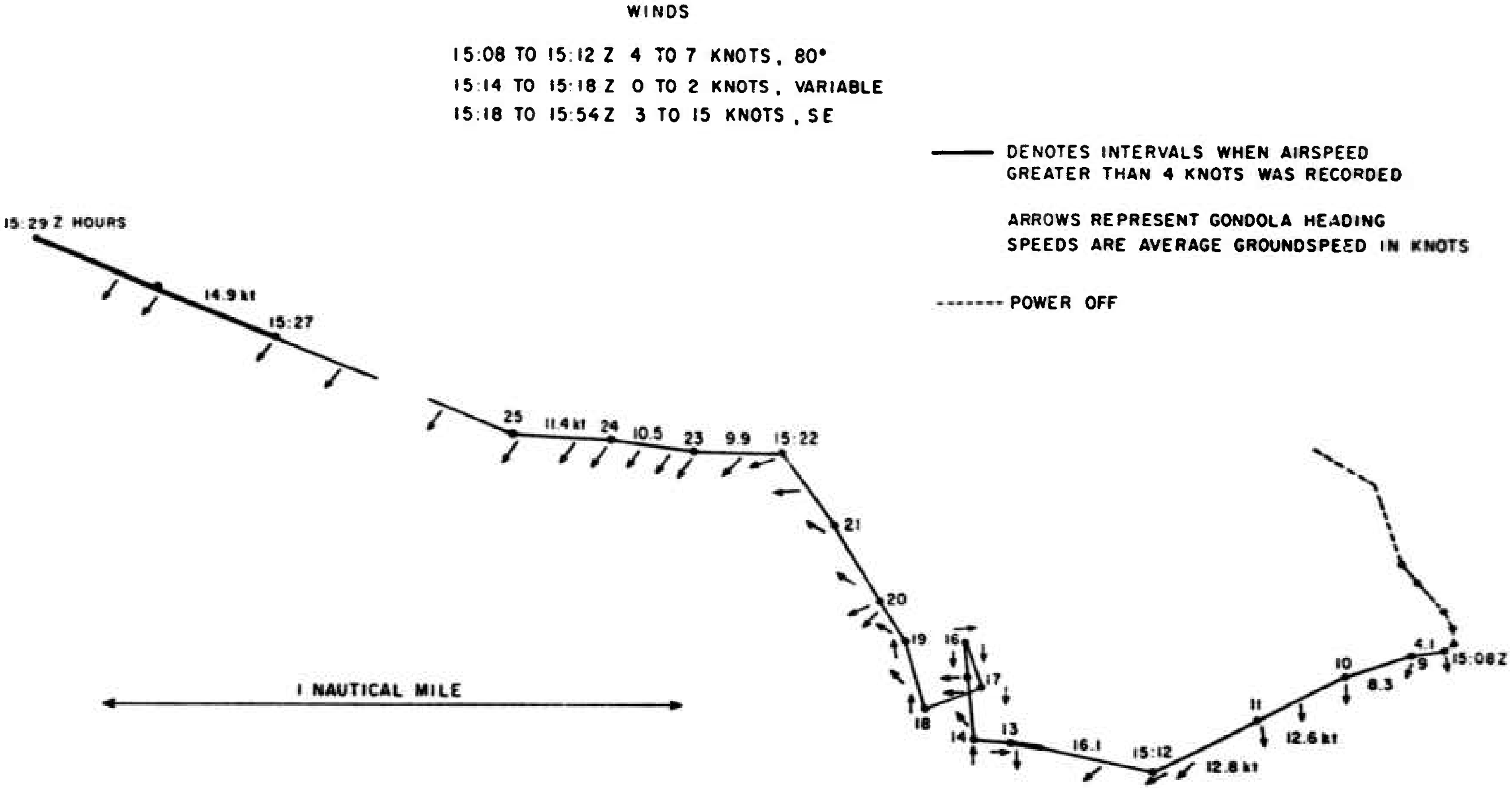

Figure A2. POBAL Power Run No. 2

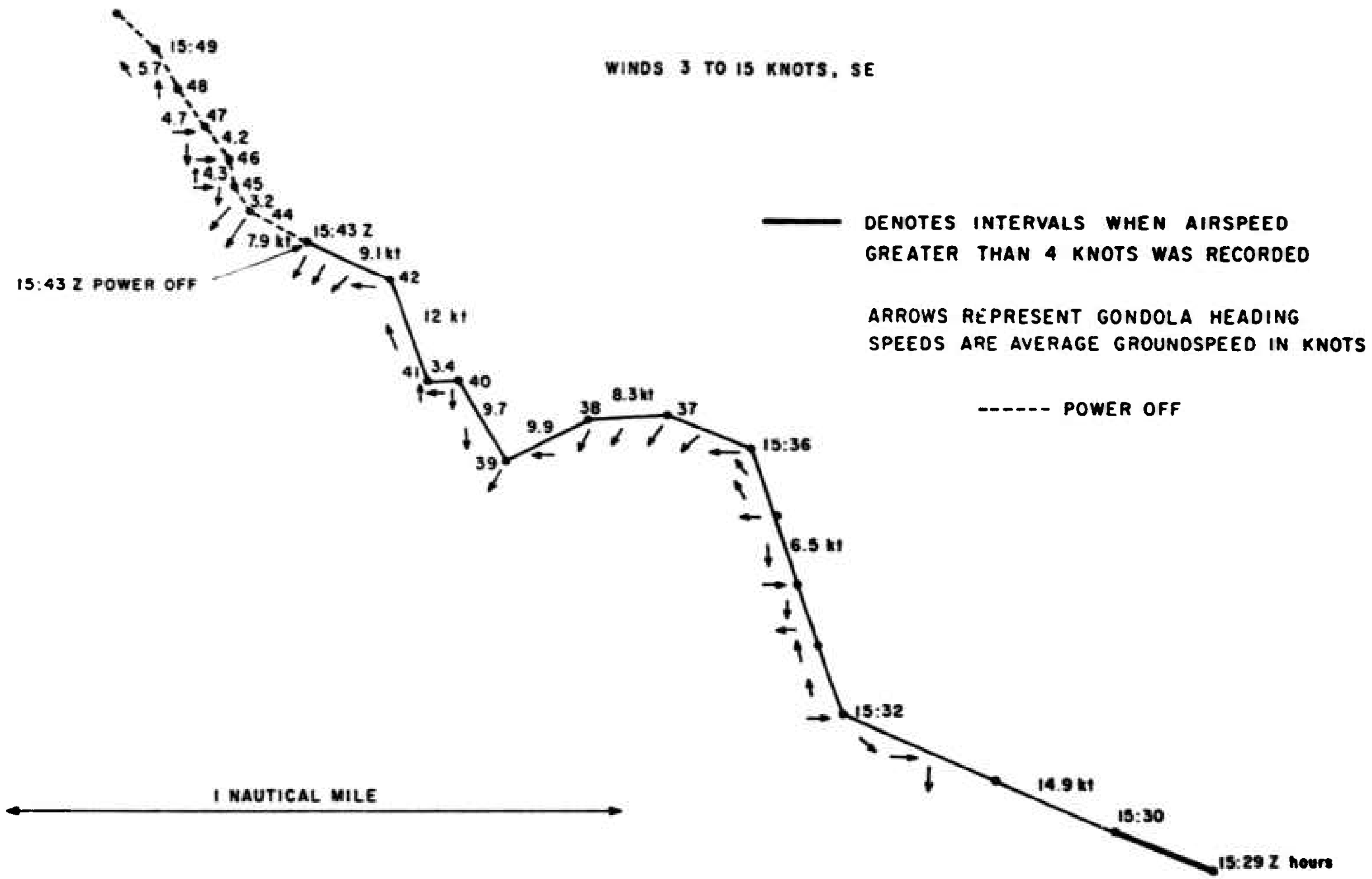

Figure A3. POBAL Power Run No. 2 (Contd.)

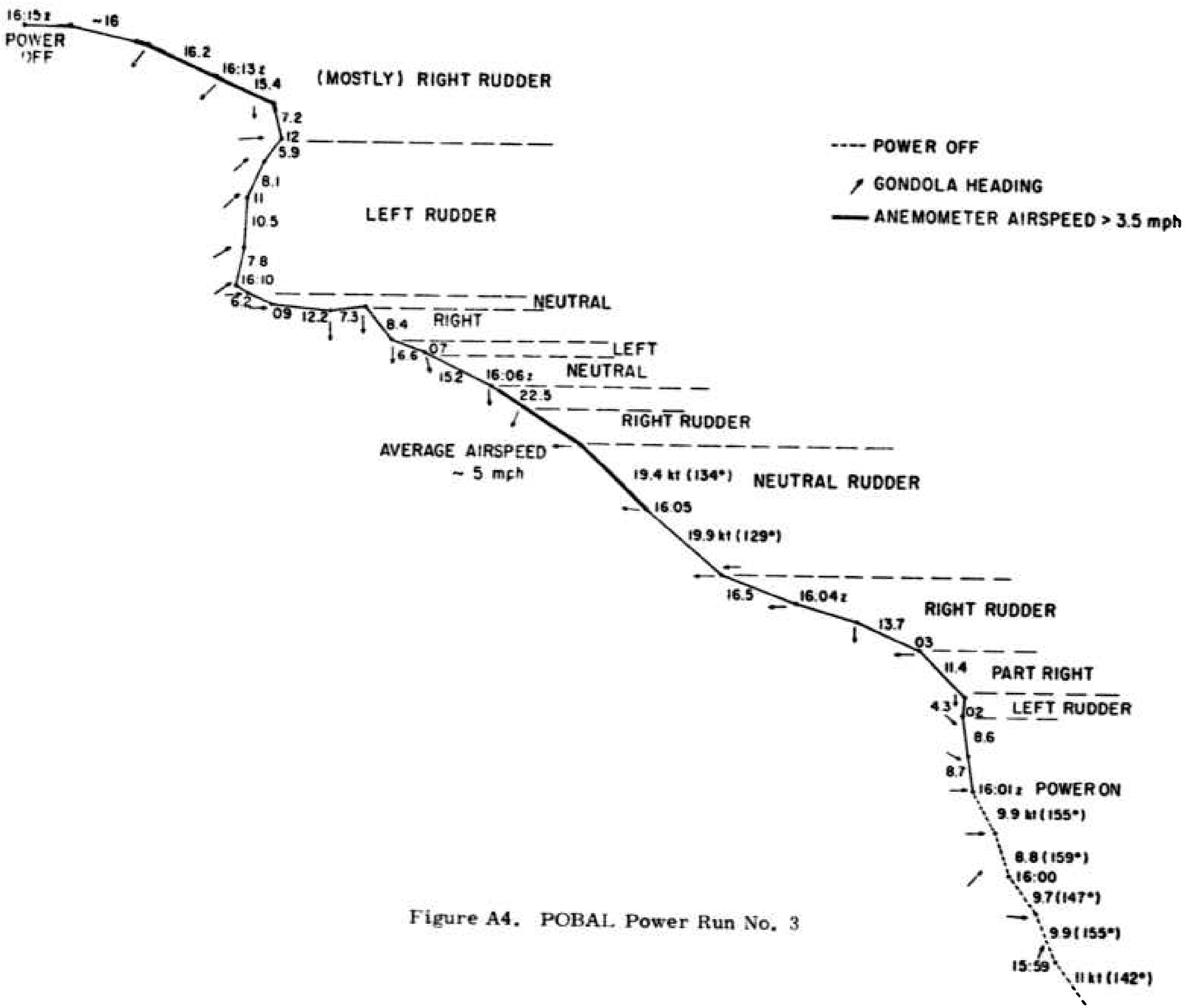

Figure A4. POBAL Power Run No. 3

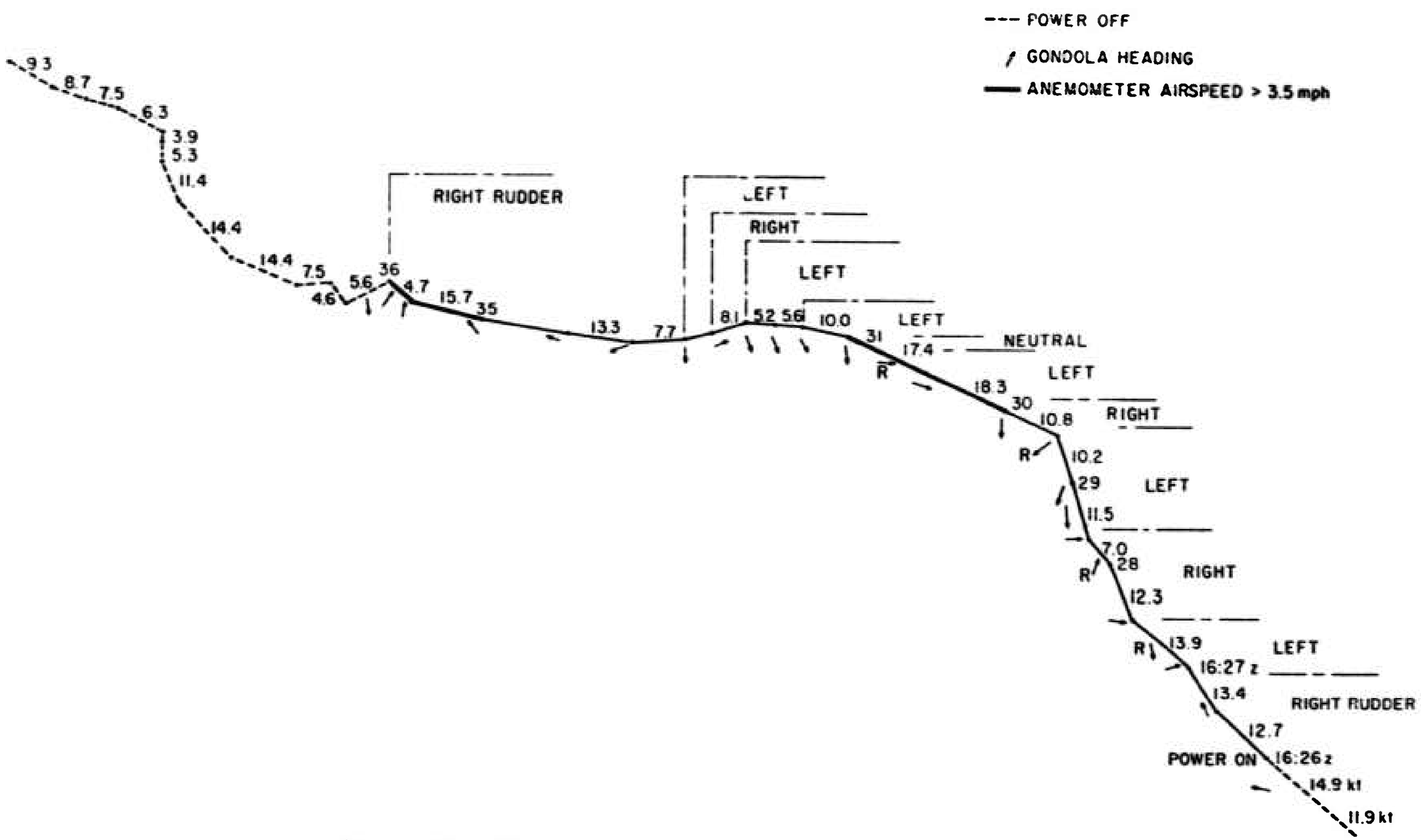

Figure A5. POBAL Trajectory Powered Run No. 4

current and rpm were normal but the gondola had a complex yawing motion compatible with static imbalance due to loss of weight aft, and it was readily determined that the fallen object was the rudder. Power was shut off at 17:13 hr. Thereafter, a rapid wind-unwind motion gradually damped out until the flight was terminated.

A7. RUDDER FAILURE ANALYSIS

The rudder has not been recovered. The fracture occurred on the shaft just above the rudder pivot assembly, which was recovered with the gondola. A metallographic examination of the failure was made by the Arnold Greene Testing Laboratories. The following summary is quoted from their letter report to AFCRL:

"....Our examination leads us to the following options:

(1) The welds and heat-affected zones, while larger than necessary as indicated by the amount of burn-through present, contain the expected microstructures.

(2) The tube starting material may have been in the T4 condition rather than T6.

(3) The welded assembly should have been reheat-treated and aged for good mechanical properties.

(4) The fracture does not appear to be brittle but is probably ductile.

(5) The slot would have naturally caused a stress increase in the tube, but with the material in the proper temper and a larger tube wall thickness the increase could have been handled. We suggest a design review at this juncture. In summation, we feel that the material used was not in the proper temper and should have been reheat-treated after welding even if it had been in the T6 temper. Since the evidence indicates that a ductile failure occurred, a basic design review should be conducted."