BALLOON ALTITUDE CONTROL EXPERIMENT (ALICE) PROJECT

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Abstract

JPL has recently discovered and demonstrated a balloon buoyancy control concept which is applicable to several planets. This concept employs the control of phase change fluids such that a planet's atmosphere is used as a giant heat engine to provide the mobility energy to ascend and descend at will. Buoyancy control by means of reversible fluids was initially conceived for Venus where the high surface temperatures (460°C) and pressures (92 bars) are a severe challenge to space systems and science instruments. This harsh Venus environment has prevented any long-duration, direct intensive exploration of the surface and deep atmosphere. These conditions also present an opportunity to exploit the energy available from the large temperature difference between the surface and the cooler upper atmosphere. In 1993, engineers at the Jet Propulsion Laboratory in Pasadena, California, began developing and testing a concept for a long-life, automated, variable altitude balloon system for Venus using reversible fluid buoyancy control techniques. Such a system would descend to the surface for short excursions from the cool, high-altitude clouds. Passive, free-flight terrestrial experiments are underway using prototype vehicles in a program of Earth demonstrations called the Altitude Control Experiment or ALICE. The ALICE effort has included: the development of a new reversible fluid altitude control thermodynamic and aerodynamic balloon performance model, gas and envelope material thermodynamic parameter measurements (α, ε, and τ), material compatibility studies, flight qualification of commercial radiosonde for long-duration and low temperature operation, and the design, fabrication and testing of R114 heat exchangers. The results and the current status of the ALICE project and its demonstrations are summarized. Fig. 1 illustrates the concept of reversible fluid balloon altitude control for Venus. (Ref. 1,2)

Reversible Fluid Balloon Altitude Control Technology

The key technology to enable long term, periodic surface exploration of Venus and other planets by balloons is altitude control without ballasting or buoyancy gas release. The use of reversible fluids is one very promising candidate for altitude control of balloons. A reversible fluid is either a gas or a liquid, depending on pressure and temperature. It is this phase change which can be used to control the buoyancy of a balloon system. The choice of reversible fluid determines the equilibrium altitude about which the balloon system will oscillate

ALTITUDE STABILIZATION USING REVERSIBLE FLUID

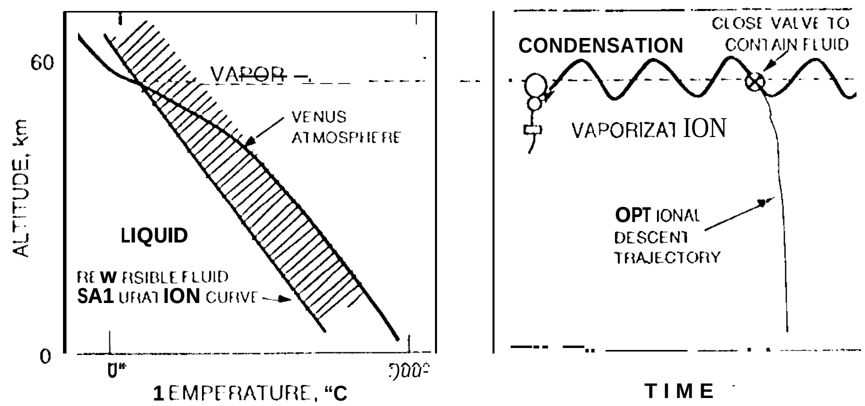

Fig. 1: Venus Balloon Equilibrium Altitude and Cyclic Motion

indefinitely. If the liquid is scaled in a pressure vessel before the balloon drops below this equilibrium altitude, the balloon will descend all the way to the surface. In order to control altitude range and equilibrium level, a primary balloon filled with helium or hydrogen can bc combined with a secondary buoyancy-control balloon filled with a reversible fluid that allows us to go to a high, cool equilibrium altitude. Reversible fluid altitude control systems arc feasible in any atmosphere where both pressure and temperature decrease with increasing altitude such as Mow the tropopause at Earth.

The Application Of Balloon Buoyancy Control for enus and Other Planets

By controlling vertical mobility, automated balloons can select altitudes where wind speeds and directions provide them wide range horizontal mobility and landing site accessibility. Wc term balloons with this robotic capability "aerobots". Aerobots may bc especially useful at Venus where rich altitude-variable wind gradients enable near global planetary access. onc feature of the thick Venus atmosphere is its opacity in visible wavelengths which may preclude visible surface imaging except very close (<5 km) to the surface. A Venus aerobot spends most of its life in the upper, cooler atmosphere with frequent, short excursions near or to the Venus surface for scientific investigations and observations. Venus aerobot concepts include systems which can repeatably bob up and down between lower, hotter altitudes where surface science measurements arc possible to higher, cooler altitudes where phase change materials can refreeze and where data can bc transmitted to Earth.

Such vehicles must transverse a wide range of environmental conditions from the harsh surface to the sulfuric acid containing clouds in the cooler upper atmosphere. Soft landing of the science payloads on planet surfaces can bc achieved by means of a flexible and possibly robotic landing "snake" tethered below the vehicle. Robotic snake concepts have been proposed for Venus which usc ambient atmosphere in a pneumatic control system to achieve desired articulation. As the snake. contacts the surface, it relieves the vehicle of some of its gravity load. Ibis enables the gondola to "hover" at a fixed distance away from the surface without impacting it. The kcy to long duration, cyclic deep atmosphere operation at Venus is altitude control. A variety of reversible fluids arc available for altitude control at Venus including met hylene chloride, wale.r and ammonia and many mixtures just now being studied

A Titan aerobot cqu ipped with reversible fluid buoyancy control systems would bc able to safe.ly and repeatedly explore the. postulated icc continents and methane oceans Mow the perpetual haze layers, recently revealed by the Hubble Space T'c.tc..scopc IR observations. Titan's atmosphere provides an excellent opportunity for a reversible fluid system similar in concept to Venus although using much different fluids. One fluid under consideration for Titan is Argon. Similar aerobot technologies apply to other bodies with deep atmospheres, such as Jupiter, Saturn, Neptune, and Uranus. (Ref. 3)

Altitude Control.Experiment (ALICE) Demonstrations

Because the Venus high-altitude atmosphere is similar to the Earth's in temperature and pressure, wc can demonstrate reversible-fluid altitude control technology in our own atmosphere. Fig. 2 is a Van't Hoff plot showing the Venus high-altitude atmosphere model along with a typical profile for Earth's lower atmosphere.

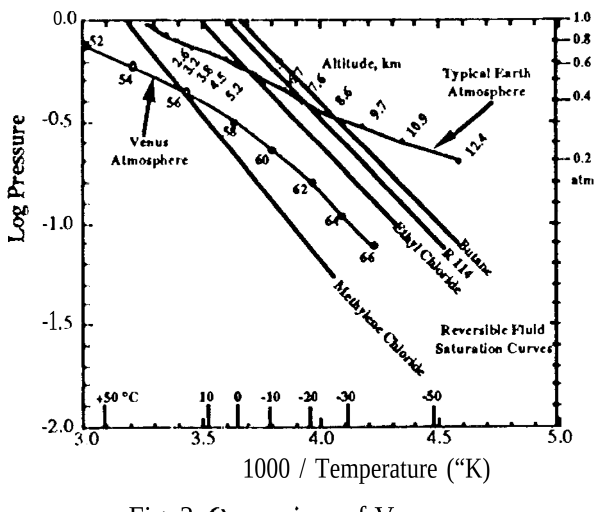

Fig. 2. Comparison of Venus lligh-altitude and Earth Atmospheres

Technology demonstrations arc underway at JPL under the Altitude Control Experiment (or Al .ICE) project In this project, a very small (total system mass < 3 kg) two-balloon system is being tested. The primary balloon is filled with helium and the buoyancy-control balloon is filled with a commercial refrigerant called R1 14, which is about 7-times heavier than air. At Earth atmospheric conditions, R1 14 becomes a liquid above about 4000 to 7000 meters depending on weather conditions. A typical

ALICE balloon system include.s a helium balloon, radiosonde and J?114 buoyancy -control balloon. Both rubber latex and clear polyethylene helium balloons have been flown. The radiosonde is a slightly modified commercial unit which provides an 8 channel capability for balloon telemetry in addition to the normal pressure, ambient temperature and humidity measurements. The R 114 balloon or bag (since it hangs from the system) is constructed from clear, 2-roil thick, seamless, 3 feet-wide lay-flat polyethylene film which is heal scaled to achieve the proper bag configuration. The balloon system in the most resent flights is fully instrumented to continuously monitor the temperatures of the helium gas and the RI 14 as it changed from a gas to a liquid. These temperatures arc measured by very small (14x20 roil) thermistors some of which arc in protective gold-plated cages to reduce the effect of solar radiation on the temperat urc measurements.

The first two tests employed standard 200-300 g rubber latex helium balloons which were launched during the day. In both flights the balloon ascent rates were seen to slow at a higher than expected condensation altitude, however, the balloons did not exhibit oscillatory behavior. Noted the sharp discontinuity in vertical ascent rate duc to the fluid condensation and collapse of the R114 bag in Fig. 3. Extensive balloon thermodynamic and aerodynamic modeling and balloon envelope thermodynamic parameter testing suggested several problems including higher than expected solar hc.sing of the helium balloon (causing greater lift).

The third flight of this concept began after sunset in order to better decouple model parameters relating to effects of forced convection and drag. This third flight was identical to the first two flights except that the balloon system was fully instrumented to continuously monitor helium temperature and R 114 temperature as it change phase from gas to liquid. After reaching about 6500 m altitude the balloon descended as predicted by performance model estimates. Telemetry was lost at about 2600 m as the balloon system descended below a mountain range (see Fig. 4). Rc-ascent before impact was predicted to be unlikely for this flight because the equilibrium altitude during February was only about 4000 m and the R114 bag did not incorporate a heat exchanger to facilitate liquid boiling.

The fourth flight, Al .ICE O/J), had two ncw features, namely, a 0.8 mil clear polyethylene helium balloon and an integrated heat exchanger, which facilitates fluid boiling at low altitudes, built into theR114 bag. Fig. S and 6 illustrate the balloon system configuration and the details of the heat exhanger construction. The total balloon system mass was about 3 kg (scc Table 1 for a detailed mass breakdown of this system). At 9 p.m. the night of July 24, 1994, the balloon system was filled with buoyant gases, assembled to its telemetry system, and released into the clear night sky from the foothills above J}' I.. The balloon system was tracked throughout the night as it ftcw over San Gabriel Mountains, Mojave Desert. It was sighted at daybreak the next day al Daylight Pass on the north-east rim of Death Valley. Ground vehicle chase terminated at about 8:00 am as the balloon ftcw over Nellis Air Fore.c Range and Nevada Nuclear Test Site. Data acquisition continued until loss of signal occurred at 11:20 am July 25 as the balloon passed over the horizon. The 14 hours of tracking data contains valuable information on balloon dynamic and thermodynamic conditions. Four complete oscillations between 5 and 9 kilometers in altitude were recorded. Fig. 7 shows mission profile from this ALICE O/D flight conducted in the CA/NV desert; the thin line is actual data with the post-flight model fit shown as a hold line. The bottom altitude profile is the topogr aphy under the ground track and the middle line shows estimated updrafts and down drafts during the flight. onc complete oscillation occurred after sunrise which should provide important insights into the performance of this ncw design during the day.

Table 1. ALICE 0/D Mass Breakdown

Equipment			Mass, g
Helium Balloon System			919
Helium Balloon	815		
Helium Balloon Fill Plug	75		
Helium Gas Temp. J'robe	29		
Radiosonde Assembly			472
Radiosonde	1	7	3
Batteries	**140**		
Miscellaneous	86		
S trobe	73		
R 114 Bag Assembly			206
Polyethylene Bag	157		
Temperature Probes	36		
Miscellaneous	13		
Buoyancy Gases			1409
Helium	409		
R 114 Freon	1000		
Total Balloon System Mass			3006

Actual flight data compared favorably with pre-launch model estimates of balloon behavior (Ref.4). The model estimate. of the. first peak altitude was

9700 m compared to the 9833 m actually seen. The frequency of oscillation was somewhat higher than predicted due possibly to the use of a spherical helium balloon aerodynamic model. The helium balloon actually was teardrop shaped which has less drag than a sphere. The pre-launch model also assumed a somewhat lower helium balloon leak rate than measured right before launch (-8 g of equivalent free lift vs the measured value of -12 g). The pre-launch model showed the balloon rising to burst altitude after sunrise. This did not occur probably due to the actual higher helium balloon leak rate. Fig. 8 illustrates the model estimate of the change of phase of R 114 all through the flight. Fig. 9 shows the actual temperatures recorded during the flight for the ambient air, helium, RI 14 gas and R1 14 liquid. Finall y fig. 10 compares the model estimate of helium temperatures with actual flight values. The general higher actual values are probably due to the fact that the thermistors for this flight were black, having not been coated because this was planned as a night flight.

Table 2 describes the issues and problems which have. been considered in the design of the ALICE hardware and incorporated into the flight dynamics models.

Table 2. ALICE Balloon System Design Issues

1. Thermodynamics Modeling
   - Thermodynamic parameters and characteristics of balloon envelope and gases (absorptivity, emissivity and transmissibility, IR emittance)
   - Balloon gas convection
   - Condensation and evaporative cooling
   - Ambient atmosphere convection
   - Thermal capacitance time tags
   - Radiation to dark space
   - Earth IR
   - Solar radiation heating of helium, RI 14 gas/liquid and balloon envelopes

2. Solar Radiation Effects
   - Temperature measurement corruption due to thermistor heating
   - Gas/envelope heating (see above)

3. Atmospheric Opacity
   - Clouds (above or below balloon)
   - Hazes

4. Balloon Envelope Permeability
   - Helium through polyethylene and rubber latex balloons
   - RI 14 through polyethylene
   - Ambient atmosphere (including water vapor) through polyethylene
   - Temperature, pressure, and material thickness effects
   - Buoyancy loss and gas leakage

5. Modifications to Commercial Radiosondes
   - Extended lifetime with additional batteries
   - Thermal control qualification for extended flight duration
   - Thermal sensor data acquisition circuitry
   - RF interference mitigation

6. Aerodynamic Drag Modeling
   - Helium balloon shape/size
   - Overall balloon system configurations (tether lengths)
   - Turbulent vs. laminar flow regimes

7. Up-draft/down-draft Effects

8. Amount of Balloon System Free-lift

9. Designed Buoyancy change capability vs. total Buoyancy (delta-buoyancy)

10. Winds Aloft and Vertical Model Predictions
    - Effect on ground tracking
    - Local topography effects

11. Material compatibility (R114 with polyethylene)

12. Evaporative heat transfer enhancement by integrated heat exchanger design.

Future passive, free,-flight tests will demonstrate reversible fluid altitude control during daylight tests. In addition, an optical navigation sensor prototype with GPS measure.mc.rrt capability will be included so that navigation simulations can begin of a Venus prototype. Follow-on larger, (-15-30 kg) controlled, balloon demonstrations will test manual and automatic altitude controllability, global circum-navigation and landing techniques. The.$c flights will include low permeability balloon envelopes and GEO satellite track ing.

Conclusions and Implications

Reversible fluid, dual balloon systems have been designed and tested in the Earth atmosphere. Altitude oscillations have been observed and arc beginning 10 bc characterized. A reversible fluid, dual balloon system performance model has been developed and is being modified bawd upon test results. These results give us some confidence that reversible fluid altitude control techniques can be successfull y employed at Venus and other planets to enable intensive in situ exploration of [heir surface-s and atmospheres.

Acknowledgment

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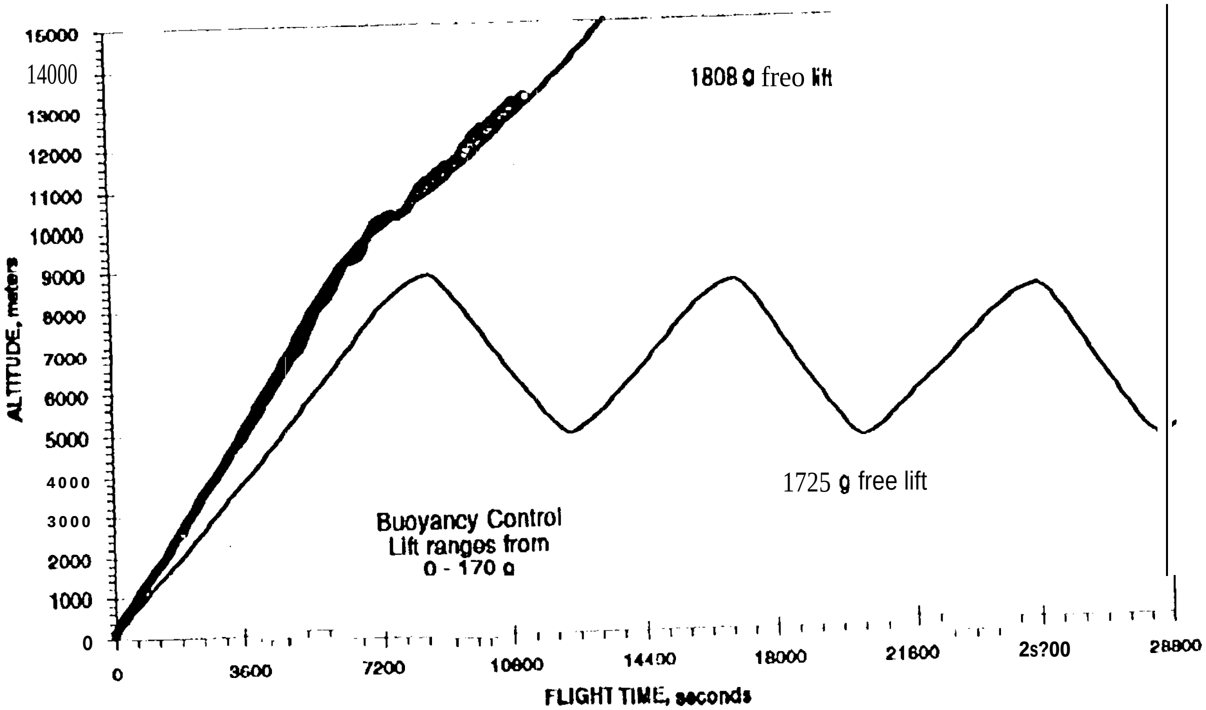


Fig. 3. Profile for Second Flight (Alice. 0/B)

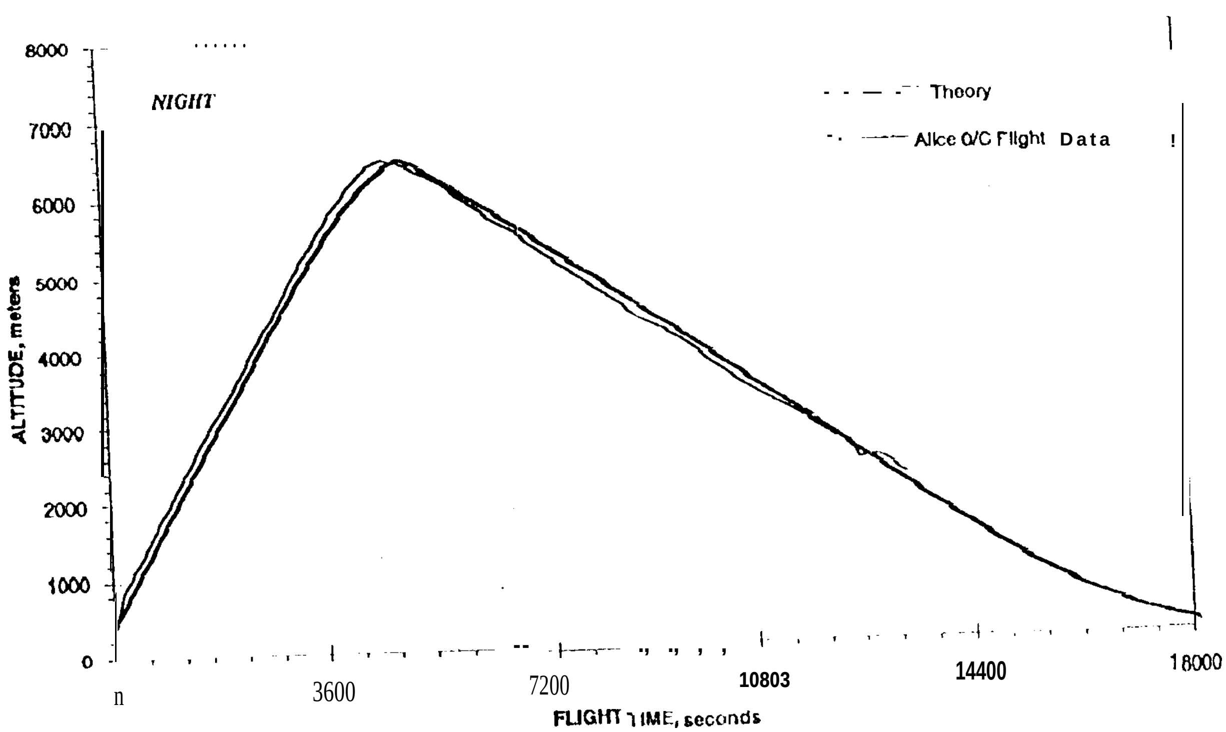


Fig. 4. Profile for Third Flight (Alice O/C)

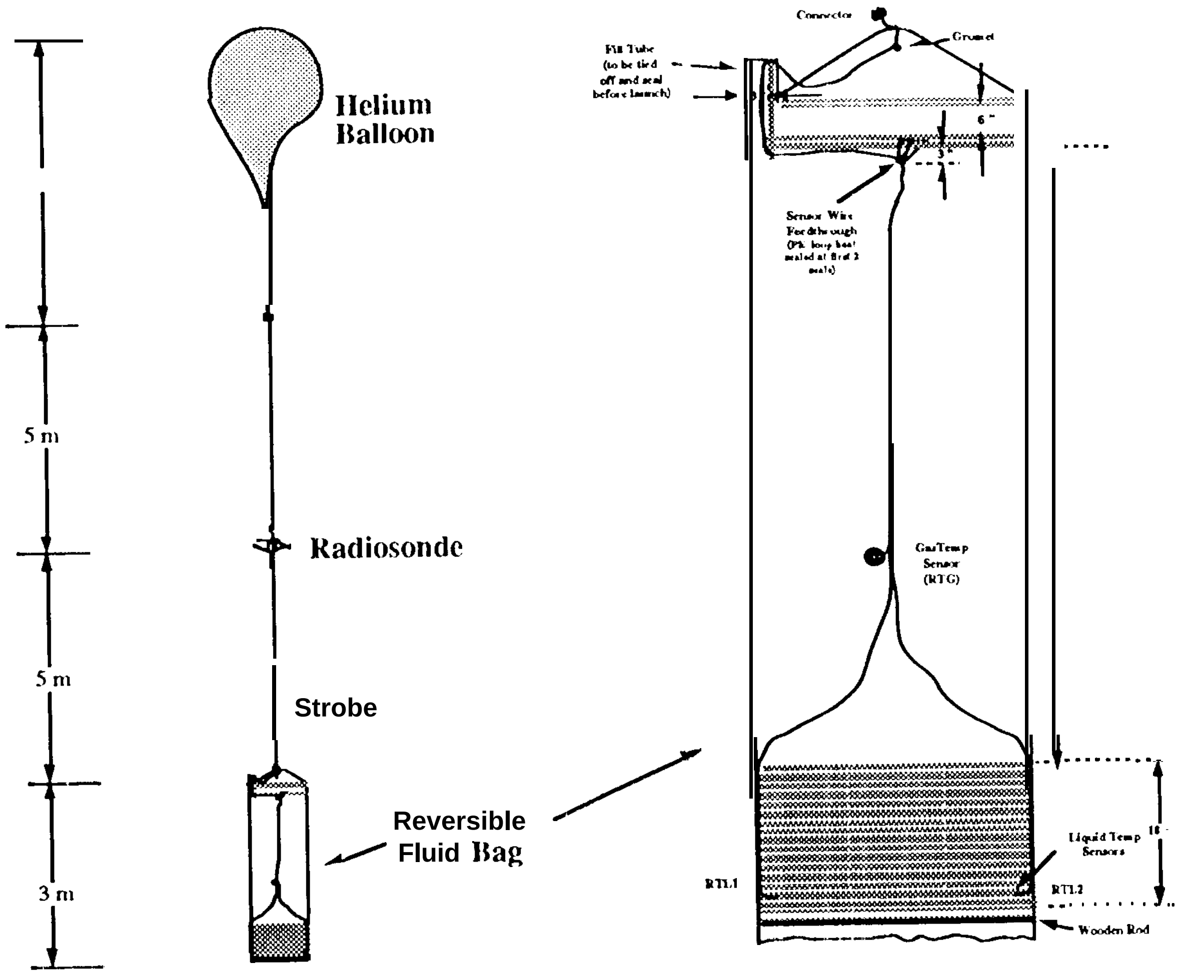


Fig. 5. Alice O/D Flight Configuration

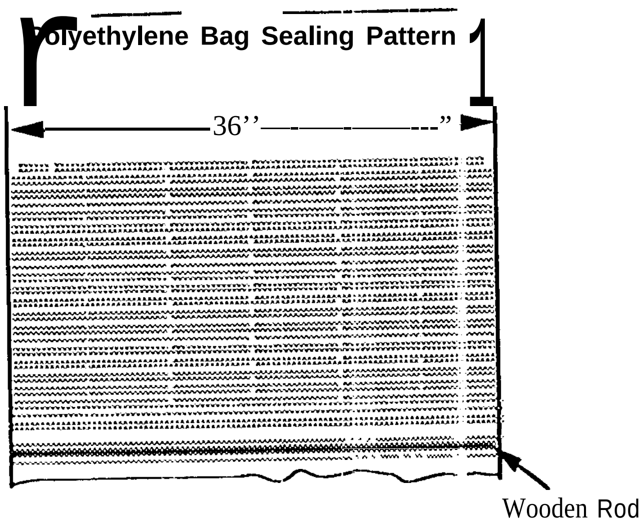


Fig. 6. Details of Heat Exchanger Design

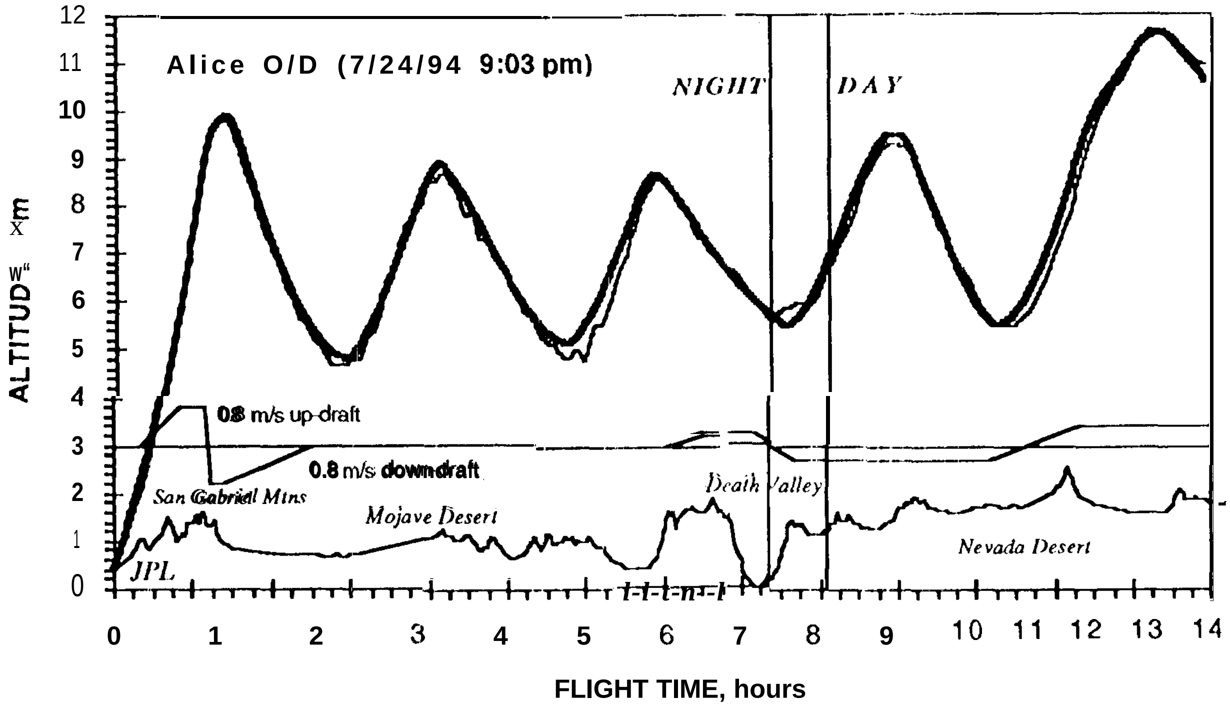


Fig. 7. Alice O/D Flight Profile

Fig. 8. Model Prediction of the Change of Gas to Liquid

Fig. 9. ALICE O/D Ambient, Helium, RI 14 Gas and RI 14 Liquid Temperatures

Fig. 10. ALICE O/D Actual vs Model Helium Temperatures

Figure 8

LIQUID FREON

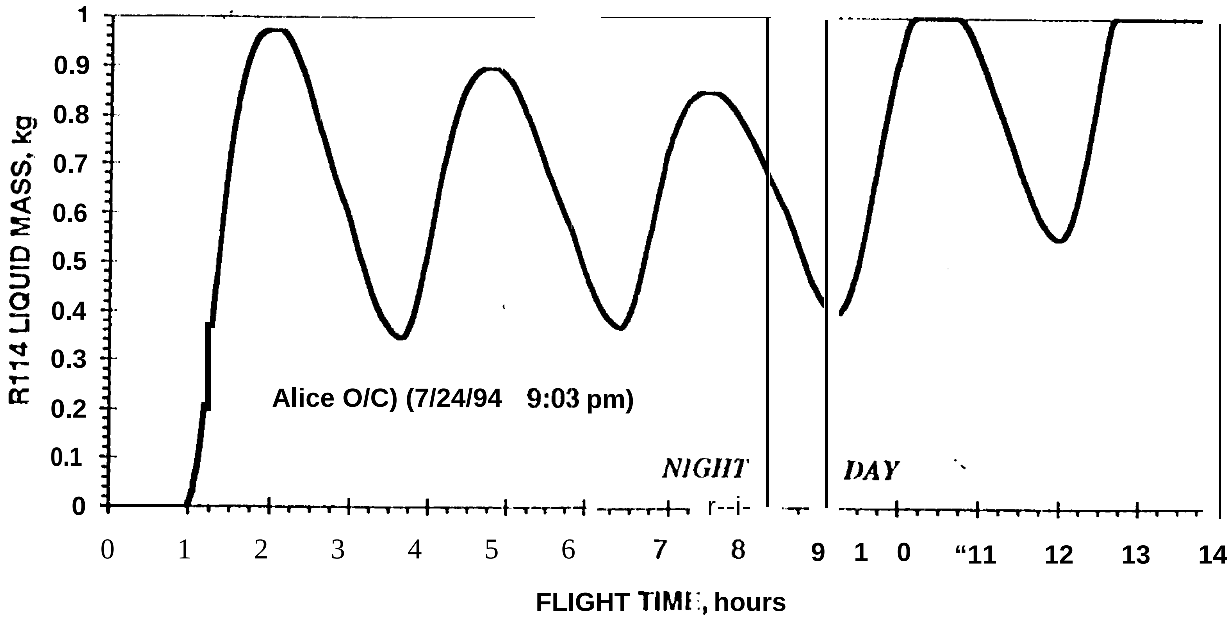
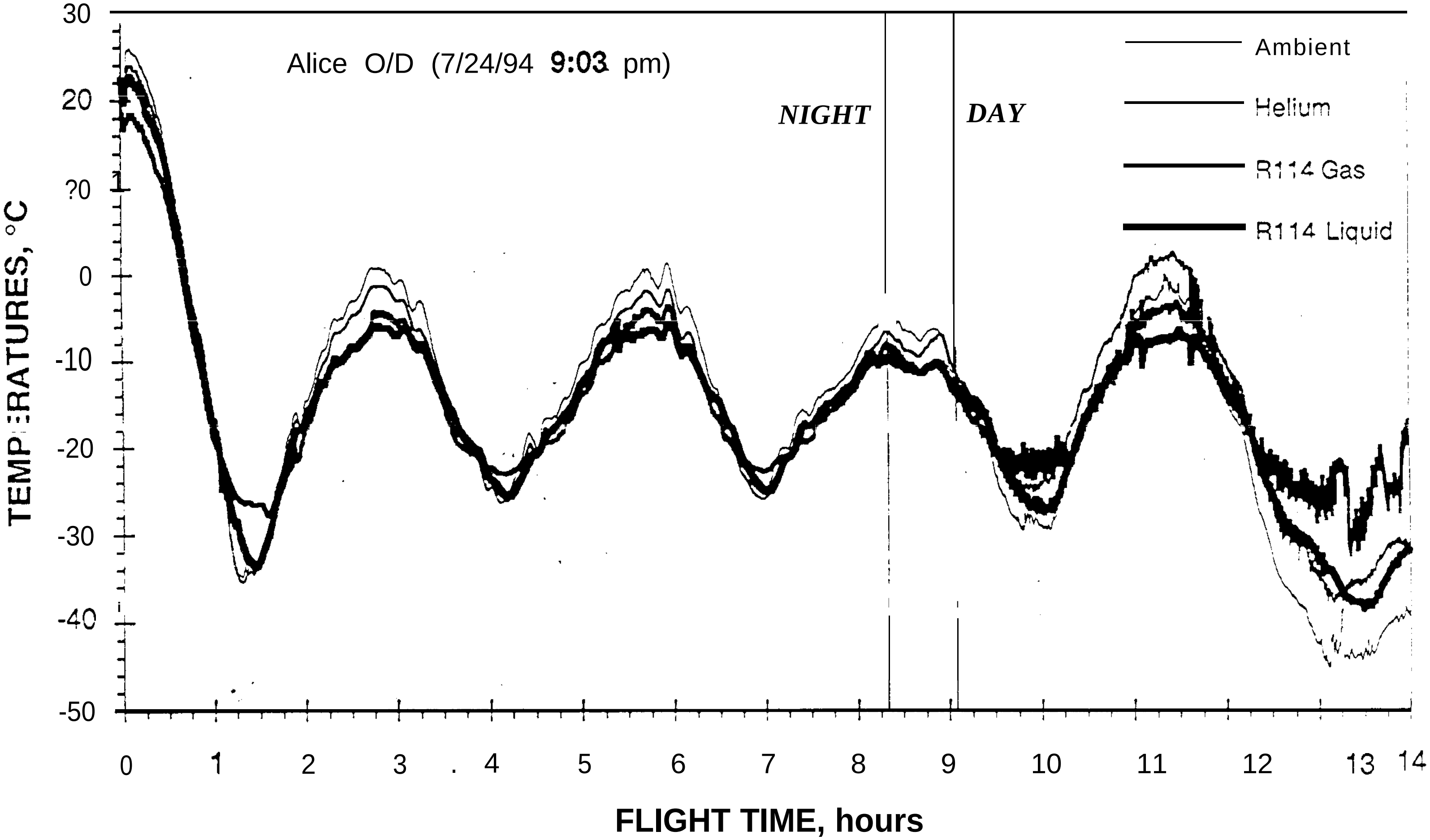


Figure 9

FLIGHT TEMPERATURES



TALL3.XLC (Alice 0/D)

3/21/95

Fill

Figure 10

HELIUM TEMPERATURE: