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A STRATOSPHERIC UNMANNED POWERED LIGHTER-THAN-AIR PLATFORM

— for the Antarctic Ozone Hole Observation and Long Endurance Communication Relay —

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Abstract

A feasibility study has been carried out on a high altitude (15-22km) super-pressured, and helium-filled PLTA (powered lighter-than-air) platform as an ideal platform for environmental observation. It has a long service life and larger payload than that of a large artificial satellite. This PLTA platform named HALROP (High Altitude Long Range Observational Platform), has an solar-powered electric propulsion system to maintain its position in space against wind currents. Solar power is acquired through photo-voltaic cells. Solar energy is to be stored for nighttime use in regenerative fuel cells. The altitude where the platform resides is the least windy area in the lower stratosphere, at a height from which one can have a direct line of sight on the ground within an 1,000km diameter range. To tackle global environmental problems, the acquisition of plentiful and precise data is necessary, and a means of conducting long-lasting high-resolution measurements over broad areas is required. A long-term scheduled point aerial observation of the Antarctic continent as well as of the hole in the ozone layer is not possible through use of free balloon platforms. HALROP may serve as an unmanned observational platform for a continuous Antarctic observation (Fig. 1). HALROP is capable of moving among the arbitrary predetermined observation points. Especially in the polar area during the summer, as well as late spring and early autumn, sunlight hours are much longer than the middle latitudinal regions; therefore, HALROP would not need nighttime propulsion batteries for polar area use. In this sense, HALROP is much simpler for Antarctic use and is to be developed before the materialization of HALROP for use in the middle latitudinal regions. The platform can also be useful to chase typhoons and to observe them from their births in the tropical regions(Fig. 2). This platform can replace a number of ground-based telecommunication relay facilities and can guarantee reasonable radio frequency intensity to secure good telecommunication quality. This unmanned PLTA does not need to use a rocket to reach its operating altitude, which is again environmentally friendly. This study is focused on energy balance and hull structure analysis of the platform.

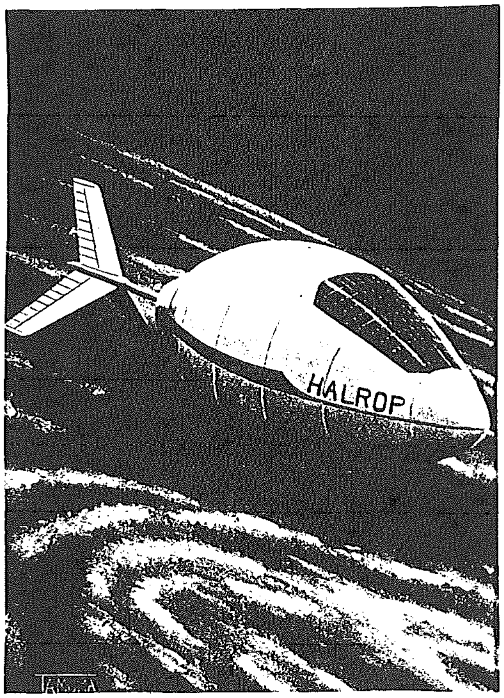

Fig. 1 HALROP during observational mission in the Antarctic zone (an artist's view)1)

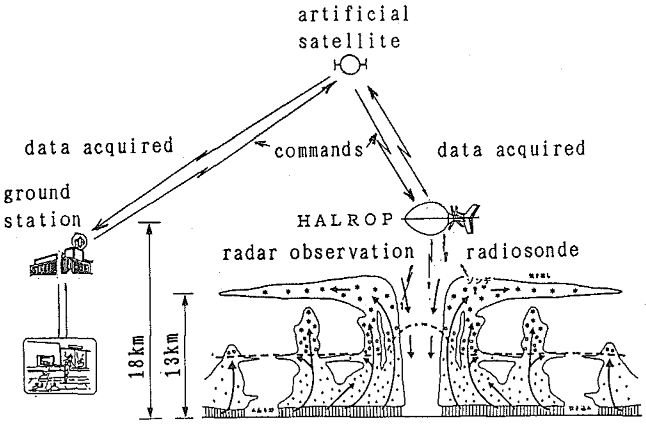

Fig. 2 HALROP flying over a typhoon for its observational mission

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I. Introduction

A proposal to develop an unmanned, stratospheric powered LTA platform was made in April 1990. A study group consisting of 20 engineers from some of Japan's foremost companies participated in one year of survey research. The group was formed in an association affiliated with the Ministry of International Trade and Industry (MITI). This high altitude PLTA platform 'HALROP' was the first to be numerically examined with an active boundary layer control propulsion system. The group is continuing its study to ascertain the platform's technical and economical feasibility. The study is also being conducted under collaborative research between the association group and our laboratory, and funding from the government is expected to continue in order to bring this concept to reality. Fig.3 shows a seven-meter-scale model of HALROP in an exibition flight in November 1990 in Tokyo Dome.

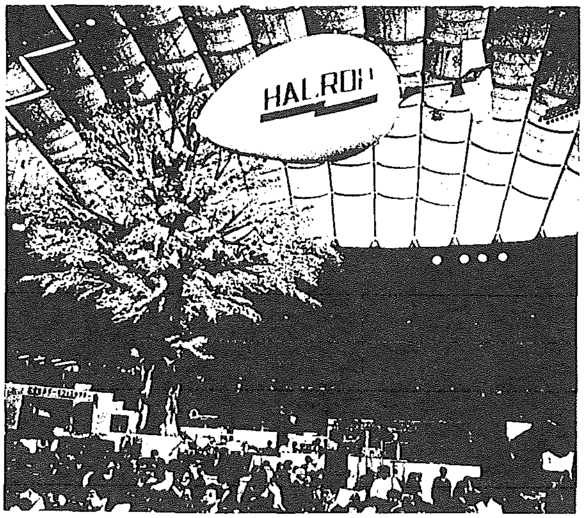


Fig.3 HALROP flying Tokyo Dome in November 1990

Another group under the Ministry of Post and Telecommunications is conducting a study to determine the optimal concept for a high altitude flying platform by the end of fiscal 1991. Their interest is primarily focused on its use as a telecommunication relay.

This paper introduces in Chapter II advantages of PLTA vehicles as long endurance high altitude aircrafts. In Chapter III, feasibility study is presented on using HALROP for Antarctic observation such as that of the ozone hole. The fundamental idea may be applied to intercontinental cargo transportation using the jet stream, and a concept of which is also introduced in Chapter IV. The stationary satellite type HALROP with nighttime batteries is presented in Chapter V.

II. HALROP - An Unmanned Stratospheric Solar Power Driven Airship

Before introducing HALROP for Antarctic use in detail, the authors wish to report briefly the results of a feasibility study on our early concept of an unmanned airship, HALROP (High-Altitude Long Range Observational Platform -- Fig.4). This is conceived to stay in the stratosphere for a period of a few years at about 20km from sea level over the middle latitudinal region. It serves as a stationary platform or a mobile vehicle for extra high-resolution environmental observations or high-performance telecommunication relay for which artificial satellites are not suitable.[2] More detailed analysis is given in Chapter V.

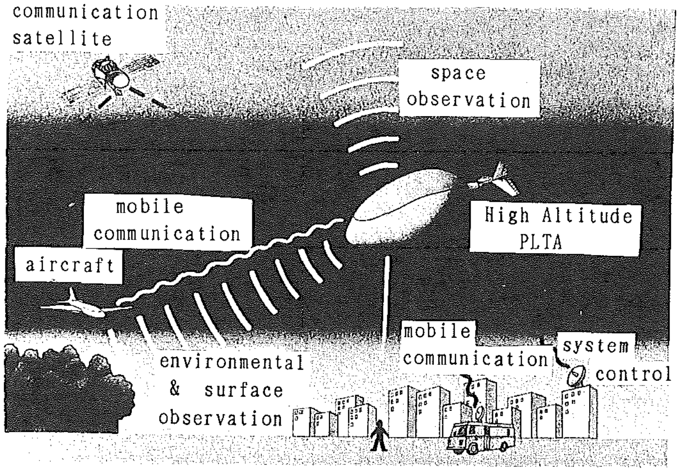


Fig.4 High altitude super-pressured PLTA platform for remote sensing and communication relay

During the daytime, HALROP obtains propulsion power and electricity for its payload equipment through solar cells placed on its hull surface, and stores a part of the electricity in regenerative fuel cells for the nighttime use. HALROP can be any type of airship but has to have a high propulsion efficiency hull, an example of which is shown in Figure 5.[3] At the time of the winter solstice in the middle latitudinal region, the sunlight hours are shortest and the wind is very strong. A study described in Chapter V shows that the airship must have a hull longer than 200m. It must be designed to achieve 31m/s against wind currents in order to stay at a fixed point above Tokyo on the day of the winter solstice; if it has to keep position with more than 99% certainty at an altitude of 40mb (22km altitude) isobar plane where wind is relatively weak.

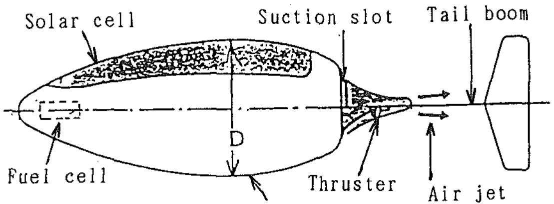


Fig.5 Layout of a type of HALROP hull

The total buoyancy of the non-rigid super-pressured HALROP is about 20 tons, and of this total buoyancy, 5 tons are fuel cells for nighttime propulsion. As shown in Table 1, various types of observational platforms have been made available, but there is no platform other than HALROP which can realize a continuous and economical high altitude observation of predetermined aerial points. However, the aforementioned study shows that development of 100kW regenerative fuel cells for nighttime propulsion will cost quite a large amount of money and will take a considerable length of time. In order to expedite the development of HALROP, the authors explored observation missions and other application fields which do not require secondary batteries for nighttime propulsion.

Table 1 Various aerospacial platform characteristics

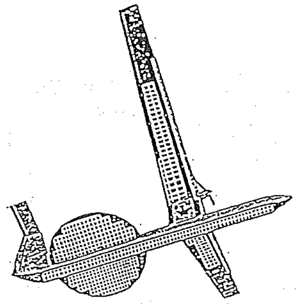
Item / Platform	Satellite (LANDSAT)	High alti. aircraft	Low alti. aircraft	Free balloon	Tethered balloon	High alti. PLTA
Altitude	900km	12km	3km	50km	5km	20km
Measuring width	100-200km	10-30km	-10km	100km	-20km	-200km
Coverage area	Large (185km sq.)	Medium	Small	Large	Small	Large
Observation cycle	Every 18 days	As necessary	As necessary	As necessary	Constant	Constant
Time-series data acquire	Easy	Difficult	Difficult	Difficult	Easy	Easy
Emergence	Not	Possible	Possible	Not	Possible	Possible

High-Altitude Fixed Wing Aircraft versus a Solar Powered LTA

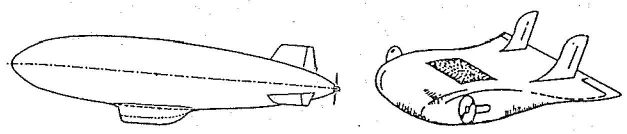
Let us consider why a solar powered LTA is being proposed. In general, there are two basic types of structures for powered stratospheric platforms that are considered feasible: airplanes and powered LTA vehicles. Airplanes have some drawbacks, one of which is referred to as the "square and cubic principle". As the size of an airplane becomes larger, its weight increases to the third order of the vehicle's length; whereas the lift increase produced by the wing is governed by the square of the vehicle's size (wing area increases by the second order). Accordingly, the payload capacity of an airplane is limited in very low density atmosphere as the wing lift is proportionally dependent on air density and thus requires a large vehicle. In the case of the PLTA, the vehicle is supported by buoyant gases held in the hull. The buoyancy, created by the Archimedean principle increases with the hull volume or to the third order of the hull length. Therefore, realization of a PLTA vehicle of huge size carrying a large payload is much easier even in a low density air environment.

The second major drawback of the airplane is its structural configuration. Payload is placed in the fuselage which is connected to the main wing, thus creating the aerodynamic lift. The structure must endure the stress concentrations that take place at the wing-fuselage junction. Meanwhile, the PLTA hull is supported in the air by an entirely distributed buoyancy, and the hull directly bears the payload. The load stress concentrations are easily distributed by balancing the buoyancy and by dispersing the payload weight in such a manner as using catenary curtains and catenary cables.

The third possible type of a high altitude long-endurance platform is the semi-buoyant or lifting-body airship. However, the structure of this kind of flying body would become too complexed, and very few detailed studies have been made. Currently, this type of semi-buoyant airship is considered to be too far-fetched for justifying further examination. Fig.6 shows these types of high altitude platforms.



Airplane



Airship Lifting-body airship4)

Fig.6 Three types of high altitude platforms

Long-endurance stationary platforms in the stratosphere must have sufficient continuous power supplies in order to maintain their positions in space. There are two approaches to this problem: one is solar power and another is high-powered microwave energy emitted from a ground-based station.5) Problems associated with high-powered microwaves include:

1) radio frequency pollution along the wave path and in the vicinity of the power station
2) limited operating range where the ground-based power station could be reached
3) low energy efficiency
4) the expenses and constraints of constructing large power stations in urban areas

In contrast, solar power generated from solar cells has none of the above drawbacks, although there is no energy supply at night. Therefore, a power storage device is neccessary. The quantitative validity of utilizing solar power generated from solar cells is presented in Chapter V.

III. HALROP for the Antarctic Observation

HALROP will not need any nighttime fuel cells if it engages in observation of the air and the surface of the Antarctic zone in summer when sunlight hours are quite long. As Fig.7 shows, in the southern hemisphere in the summer the altitude of the lowest stratospheric boundary becomes lower as it nears the South Pole.6) In the low stratosphere weak prevailing westerlies are blowing at the altitude of 15km-20km, and at this height the velocity of the wind blowing in the north-south directions is quite slow. These factors indicate that HALROP is suitable for an observation mission in the Antarctic zone where sunlight hours are long and the wind is weak. *However, it is not easy to bring HALROP to* the Antarctic continent to launch it there. It is more practical to build a base in New Zealand or Australia or in the southernmost spot of the South American continent to launch and to recover the airship. A remodeled old tanker could also make a good base. As Fig.8 shows HALROP can be launched from a raft after being pulled out of a floating hanger. HALROP for Antarctic observation will fly or stay in the stratosphere at about an 18km altitude. The atmospheric pressure at this altitude is 70mb, and the temperature is about -60 degree centigrade. The envelope of HALROP which contains helium as buoyant gas is made of light-weight composite material. The airship is designed to keep the necessary hull strength by having a pressure difference of 5mb's between the inside and outside of the envelope; this pressure difference has to be maintained all the time because the *envelope will rupture if the pressure difference* becomes too large. Since helium gas at sea level atmospheric pressure inflates its volume about 15 times at the 70mb altitude level, only 10% of the envelope volume is filled with helium gas at the time of launching and the rest is air.

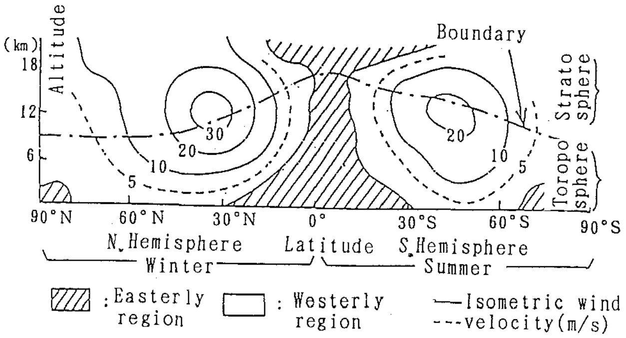


Fig.7 Wind distribution along a Longditude line in Northern and Southern hemispheres

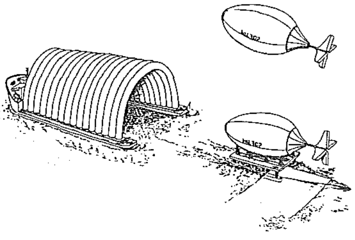


Fig.8 HALROP launching from a floating base

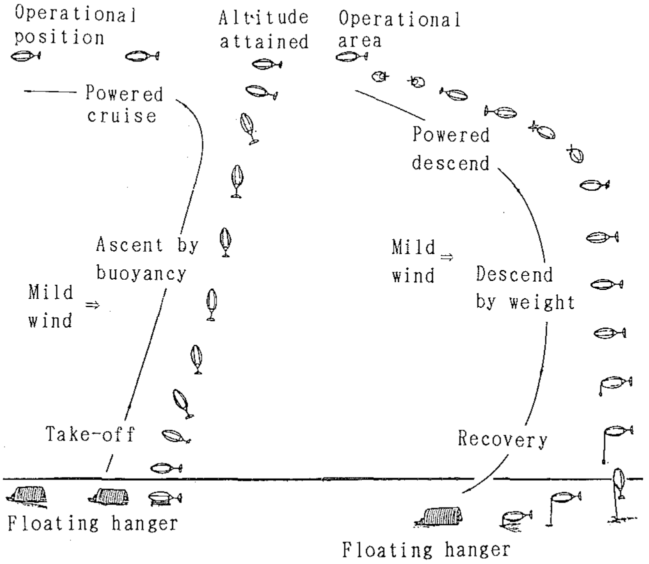


Fig.9 Launching and recovery of HALROP in the sea

As shown in Fig.9, as soon as it begins ascending, HALROP starts lifting its nose by receiving a wind drag at its tail wings. At the same time, the helium gas inside the envelope moves toward the nose and the vehicle's gravity center moves to the rear part of the hull until the airship begins to ascend in an upright position. When all the air inside the airship's hull is ejected while keeping only the helium gas inside, the vehicle's center of gravity and the buoyancy center almost coincide, and an attitude control of the vehicle by the tail wings becomes possible. The airship, then, *regains a horizontal attitude and begins a* horizontal flight. In order for HALROP to return to the base on its own power and to be recovered, it has to arrive there during the daytime. The wind conditions in its route have to be calculated in figuring the time the airship has to begin its return flight to reach the base during the daytime; or, the airship has to descend on the water and wait to be picked up by its mother-ship (Fig.10).

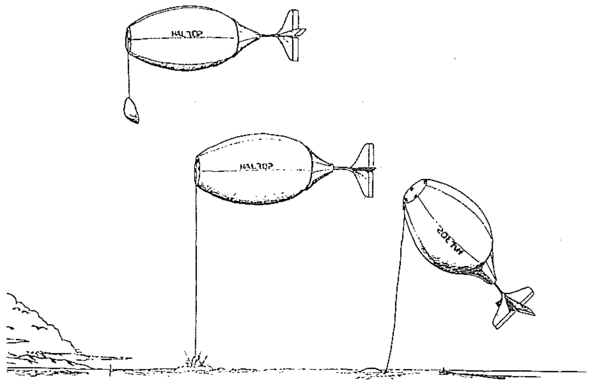


Fig.10 HALROP touching down to the water surface

In the case of HALROP for the middle latitudinal region, its hull is designed to be more than 200m long. However, it needs to cover only 15% of the hull surface with solar cells to obtain a 31m/s speed against the wind at the 40mb isobar plane altitude. A smaller size hull is preferable for the Antarctic HALROP also from the view point of handling. Therefore, the proposed Antarctic airship is designed to have an envelope 95m long and fly at the altitude of 70mb isobar plane(Table 2). As shown in Table 3, the total buoyancy, which HALROP with a 108m long hull may have at the 70mb isobar altitude plane, is about 7.6 tons: and the weight of the structural materials of the hull, motors and thrusters amounts to about 6 tons. As shown in Fig.11, the total electricity the airship requires as a propulsion power and for its payload equipment is about 80kW. Considering the hull geometry and the angle of the sunlight, it is expected that about 0.1 tons of solar cells (50 micron meters in thickness, and 15% energy conversion rate) have to be layed in order to generate the necessary amount of electricity. The cells would be on the airship's hull covering about 450 square meters of its surface. The total weight of the payload equipment to be accomodated to the airship will be about 1.6 tons.

Table 2 Antarctic HALROP's basic specifications

envelope volume (length 95m)	81,255m^3
vehicle hull length	108m
maximum diameter	40m
envelope surface area	10,140m^2
fineness ratio	2.72
total buoyancy	7.56ton
flight altitude	isobar plane 70mb
designed max. speed	31m/s
required propulsion power	54kW
solar cell required average output	81kW
solar cell area	401m^2

Table 3 Antarctic HALROP weight distribution

Total bouyancy	7.56ton
envelop + duct	3.44ton
tail boom	0.03ton
tail wing	0.72ton
solar cell	0.12ton
propulsion system	1.25ton
reinforcements	0.41ton
subtotal	5.97ton
payload	1.59ton

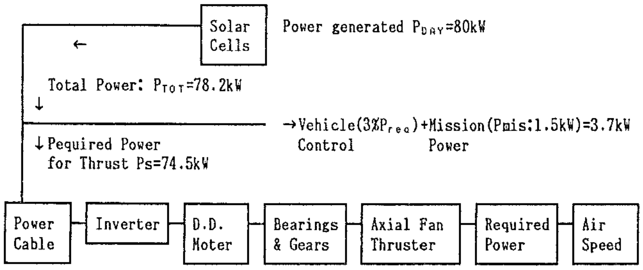


Fig.11 Power transmission system of Antarctic observational HALROP

In the case that the airship is set to fly toward the Antarctic zone in the spring in the southern hemisphere (September-November), it will not arrive in the zone before the sunset of the day it is launched provided it leaves for its mission cruise from a base somewhere in the middle latitudinal region. If the base is located in the high latitudinal region, the airship has a better chance of arriving in the zone during the daytime of the same day. Whether or not the airship comes across the sunset depends upon the sun's trajectory, the airship's flight speed, its cruising altitude, the latitudinal location of the base, wind conditions in the flight route and other factors. In the nighttime, the airship's motor stops due to the lack of a power supply. In November, the airship will be blown to the east by the prevailing westerlies of about 15m/s average velocity. On the second day of the flight, however, the airship begins its flight from a spot much closer to the Antarctic zone and will be able to arrive in the "nights with midnight sun" zone before the sunset.

Table 4 Starting day of and latitude of the "nights with the midnight sun" in the Southern hemisphere

September 24	S90 degree
September 30	S87 degree
October 10	S84 degree
October 20	S80 degree
October 30	S77 degree
November 10	S73 degree
November 20	S71 degree
November 30	S69 degree

Three case studies concerning the observation mission are shown in the following section.

Antarctic Observation Mission Case Studies

Case 1 Fig.12 shows the wind directions and the velocity at the 70mb isobar plane in the area which extends from the South Pole to near the equator. This figure shows the average data collected every September of the past nine years. In the middle latitudinal region, the wind also blows westward around the Antarctic point in October and November. In this case study, an assumption is made that the base is located at the 45 degree S.lat. and 170 degree E.lon. point, the southernmost tip in New Zealand (Fig.13). In this case study, the airship is set to be launched on the 15th day of November (37 days before the summer solstice in the southern hemisphere), and the sun rises at 17:08 and sets at 07:44 Greenwich time (see Table 5) on that day. If HALROP flies, from a point at 15 degree S.lat., to the south at an average ground speed of 31m/s, it is supposed to come across the sunset at 60 degree S.lat. later than the time the sun sets at 45 degree S.lat. However, during the flight HALROP will be blown to the east a little by the prevailing westerlies and will come across the sunset a little earlier than the sunset at 60 degree S.lat. In other words, there will not be much difference in

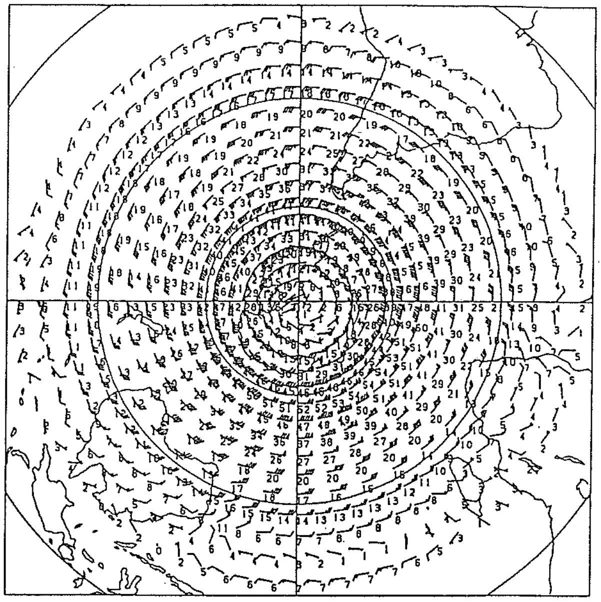


Fig. 12 Winds in September in the Southern Hemisphere

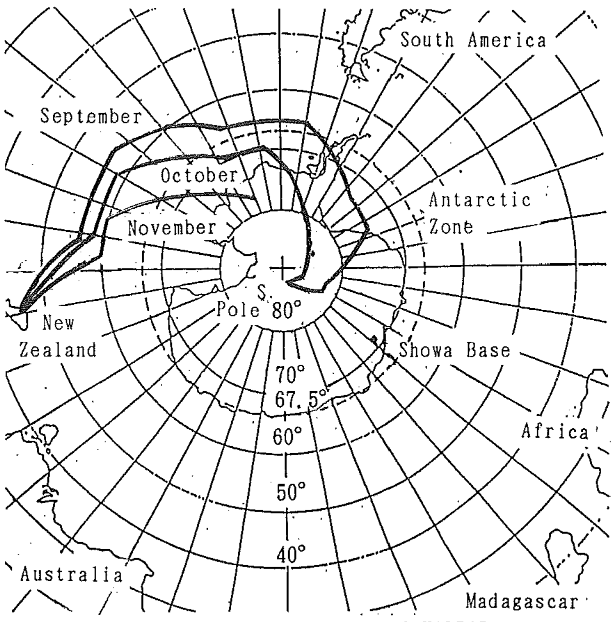


Fig. 13 Flight routes of HALROP

the time HALROP comes across the sunset whether it is launched at 45 degree S. lat. or at 15 degree S. lat. During the nighttime, as the buoyant gas inside HALROP cools and shrinks, the altitude of the airship will decrease, and the hull rigidity will decrease a little. However, HALROP will be freed from the aerodynamic loading and stress that are sustained from powered flight and fly as a free balloon. HALROP will arrive, later in the day of November 16, at a point at 75 degree S. lat. South of this point is already the "nights with midnight sun" zone, and it is possible to fly continuously every day executing observational works for 24 hours. If the launching base is in a spot or on a mother-ship located south of the 60 degree S. lat. and 170 degree E. long. point, where the sun sets at 14:24 and rises at 7:11, HALROP will be able to arrive south of 75 degree S. lat. in one day.

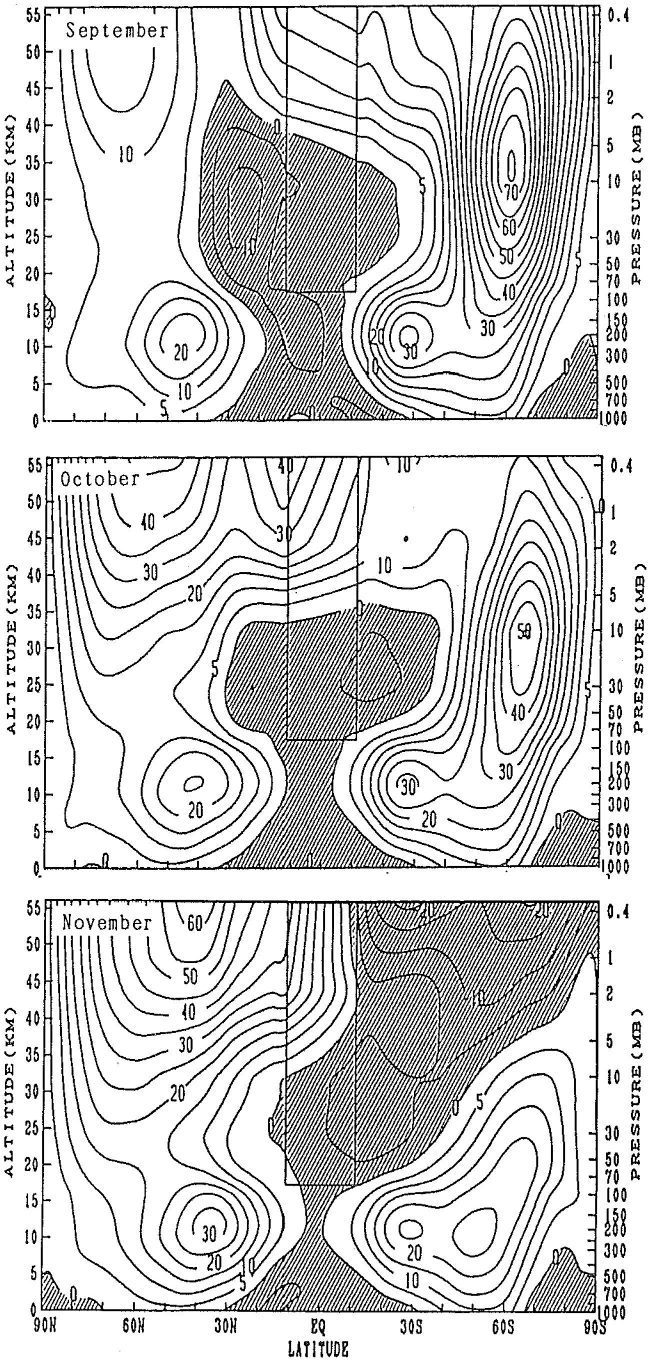


Fig. 14 Monthly avaraged data of East-West wind in September, October and November (m/s)

Case 2 In the case that HALROP is to be launched from New Zealand on October 15 when the sun rises at 17:54 and sets at 7:02 Greenwich time, HALROP will arrive in the "midnight sun" zone on the 3rd day of the flight after being carried 2 nights by the wind which is blowing in this area at the average speed of 35m/s.

Case 3 If HALROP is to be launched from the aforementioned base on September 15, it will arrive south of 85 degree S. lat. in the Antarctic zone on the 4th day of this mission cruise. However, "midnight sun nights" do not begin at the Antarctic point until September 24. Therefore HALROP will have to wait in this area until that date. During this season, the hole in the ozone layer begins to show from around this altitude, and so HALROP is ideally positioned for its mission.

Table 5 Sunrise and sunset times, wind velocities in September, October and November in conjunction with HALROP's flight dates

No.	Date	Longitude (deg.)	Latitude (deg.)	Sunrise	Sunset	Sunlight &(flight hours)	Wind speed (m/s)
(September)							
1.	9/15	S45	E170	18:50	06:24	11h35m	30
2.	9/15	S56	E189	18:40	06:03	-	43
3.	9/16	S56	E214	15:58	03:25	11h27m (10hr)	43
4.	9/16	S66	E248	14:51	02:01	-	35
5.	9/17	S66	E276	11:55	23:13	11h18m (9hr)	35
6.	9/17	S75	E315	09:34	20:24	-	15
7.	9/18	S75	E339	08:52	19:54	11h02m (8hr)	15
8.	9/18	S83	E011	07:17	17:08	-	5
9.	9/19	S83	E028	05:56	16:13	10h17m (5hr)	5
10.	9/19	S87	E040	06:24	14:14	-	3
(October)							
1.	10/15	S45	E170	17:54	07:02	13h08m	25
2.	10/15	S58	E190	17:13	07:03	-	35
3.	10/16	S58	E209	15:55	05:49	13h55m (12hr)	35
4.	10/16	S70	E249	12:33	03:54	-	20
5.	10/17	S70	E262	10:36	02:06	15h30m	20
6.	10/18	S86	E046	(South of S80, nights with midnight sun)			3
(November)							
1.	11/15	S45	E170	17:08	07:44	14h36m	15
2.	11/15	S60	E185	15:06	07:48	-	22
3.	11/16	S60	E195	14:24	07:11	16h47m	22
4.	11/17	S77	E248	(South of S71, nights with midnight sun)			7

IV. Jet-Stream-Riding Solar Airship Transportation: JS-RISAT

Toward the realizaton of a stationary satellite type HALROP, which stays at an altitude of 20km above Tokyo, a concept of an unmanned airship for the Antarctic ozone hole observation has been introduced; it does not need a large quantity of heavy batteries to store energy for nighttime flights. This unmanned polar-area-use airship is a stratospheric airship. However, it is would be easily understood that this sort of airship will not be needed in number of more than a few tens as long as their missions are the polar area observation. For the development of stratospheric airships to create a full-fledged industry, a market and a demand for a certain amount of such airships is indispensable. Therefore, the authors propose, to produce such a demand and a market, the concept of JS-RISAT --- an environment-friendly mass transportation system by solar airships which ride on the jet stream.

A Solar Airship Which Rides on the Jet Stream

The "jet stream" defines the strong prevailing westerlies which circulate in the north hemisphere around the north pole at the altitude of about 13km and of the speed of 120-150 knots. The jet stream weakens in the summer and goes up near the Arctic zone, becoming strong in the winter and moving down to the south.

The altitude limit for the regular airlines is set at 41,000 feet(13.5km), and no commercial airplanes fly above this height. It leaves the jet stream above a 45,000 feet height(15km) open. The idea of flying eastward in the north hemisphere by riding the jet stream has long been known. Up until now, a few manned free balloons have travelled across the Pacific and the Atlantic Oceans for several days. During World War II, free balloon bomb carriers were fabricated and actually used. The air density at an altitude of 15km is only about 16% of that at sea level, but three times greater than the air density at an altitude of 22km (5% of the air density of the sea level), where HALROP flies for stationary use in the middle latitudinal regions. Consequently a jet-stream-riding airship of the stationary type HALROP size will gain three times greater total buoyancy than HALROP.

As for the energy, JS-RISAT will need only a small battery to store the nighttime energy. It requires energy storage only to stay within the jet stream, to ascend into the jet stream after the take-off, and to descend from it to the destination. JS-RISAT needs to store energy only to correct the airship's position within the jet stream during the night; it climbs and descends during the day. The airship will be unmanned and operated via communication satellites.

Performance characteristics of a 200 meter class HALROP (400,000m^3) for JS-RISAT Plan can be roughly outlined as below:

From Japan to North America including the flight to the destination: 1.5 days,

From North America to Japan including the flight to the destination: 3 days,

Average speed: 400km/h = 240km/h(jet stream contribution) + 160km/h(solar power contribution),

Payload: 50 tons.

Jet Stream Riding Solar Airship Transportation (JS-RISAT) is completely polution free and carries as much air cargo as a Jumbo jet without consuming any type of carbon hydrate fuel. One of the serious obstacles will be the loading and unloading of the cargo. Floating off-shore terminals may be necessary for island countries like Japan. The cost to develop JS-RISAT will be about the same as those to develop Antarctic Ozone Hole Observation solar airships.

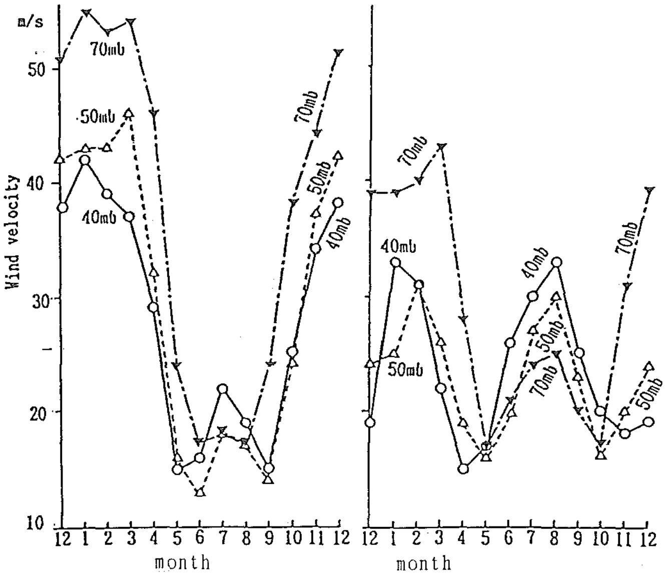
V. HALROP for Stationary Use in the Middle Latitudinal Regions

HALROP is expected to contribute solutions for global environmental problems such as the destruction of the ozone layer and climatic changes due to an atmospheric temperature increase. It has *the potential of conducting high resolution* remote sensing. HALROP could also to serve as a telecommunication relay, replacing a number of ground-based facilities and guaranteeing sufficient radio frequency intensity to secure quality telecommunication transmittal. For this purpose, HALROP is required to stay still in the air, especially in the middle latitudinal regions where this kind of markets resides. In this chapter, fundamental design data of HALROP for stationary use in the middle latitudinal regions are presented.

Flying Environment of 'HALROP' and the Maximum Design Speed

The airspace at an altitude of approximately 20 km above sea level has the lowest wind flows above the jet stream. The air density is 1/14 of that at sea level and the pressure is about 50mb.[7] The *average atmospheric temperature above Tokyo* at this altitude is -56.5 degrees Celsius and is almost constant over the length of an entire day as well as throughout the year. Average wind speed is 15 meters per second and the maximum wind speed sometimes exceeds 40 meters per second in the winter above the Japanese archipelago and its vicinities. The wind direction there is always westerly. Fig.15 shows a wind velocity histogram in terms of *altitudes by atmospheric pressure*. Due to the fact that the PLTA sustains large drag, and that the vehicle's required thrust power increases according to the third order of the design velocity, a reasonable level of vehicle speed should be determined from the data in Fig.15. An altitude of 40mb was chosen, and a 99 percent ceiling versus all wind velocity cases was selected as the design maximum speed which gives 31 meters per second of wind velocity.

Tateno:36o03'N,140o08'E			S.Daito:25o20'N,131o14'E		
pressure	Jan.	July	pressure	Jan.	July
70mb	18,591m	18,838m	70mb	18,339m	18,892m
50mb	20,604m	20,886m	50mb	20,462m	20,989m
40mb	21,984m	22,286m	40mb	21,866m	22,407m



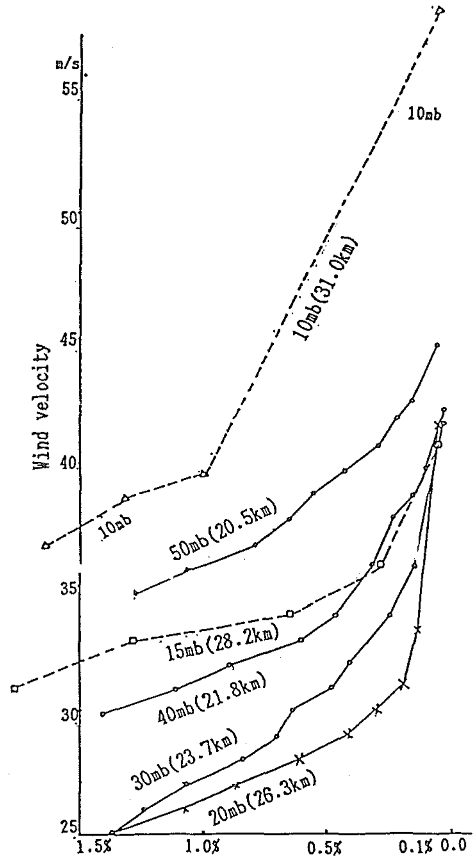
(a) *Wind velocity by seasons and altitudes*

Required Power for Maintaining Spacial Position

The stratospheric powered LTA should have a low drag coefficient to economize propulsion power. Required propulsion power is provided by the following equation;

$$\mathrm{Preq} = \frac{1}{2} \times \frac{\rho \cdot C_D \cdot v^3 \cdot Q^{2/3}}{E} \times \frac{1}{102} \qquad (1)$$

where, Preq: required power(kW), $\rho=6.65\times10^{-3}$: air density at 40mb altitude($\mathrm{kgf \cdot s^2/m^4}$), 1kw=102kgf·m/s, C_D:drag coefficient(-), Q: hull volume($\mathrm{m^3}$), E=1.0: efficiency of the propulsion system(-), v=31: top air speed(m/s).



(b) Histogram of stratospheric wind velocity in December, January and Feburary in the past 20 years at Tateno, Tsukuba

Fig.15 High altitude maximum wind velocity histogram

The calculation of required propulsion power at 40mb altitude is based on a maximum design speed of 31 m/s. Assuming a drag coefficient of 0.0174 and a hull volume of about 400,000m^3, this yields a required propulsion power of 90kW. In order to obtain this minimum drag coefficient, a "boundary layer control" hull is used for the platform. A schematic diagram of this platform is shown in Fig.5 in Chapter II. The smaller the length/diameter ratio of the hull, the better the volume/weight performance of the hull. In this model, a Goldschmied body of a length/diameter ratio of 2.72:1 is applied to retain a drag coefficient of 0.0174 from Goldschmied's experimental results.[8]

The propulsion power should be generated through an axial fan thruster driven by electric motors. These motors are controlled by inverters. Power transmission loss will take place in power cables, reduction gears and bearings. Total power transformation efficiency is estimated as about 60%.

The platform requires a power source for the mission payload, and this is assumed to be 5kW for observatory devices. The platform also requires maneuvering power, estimated to be approximately 3% of maximum propulsion power. Altogether, the peak power consumption on board would become 150kW. Fig.16 shows HALROP's power flow diagram.

Solar Power Acquisition and Storage

Solar Cells Since the sky is always clear in the stratosphere, solar cells can continually produce electricity during daytime hours. We have examined several candidates for solar cells using power/weight ratio criteria. The results are tabulated in Table 6. A value of 629W/kg for crystal silicon with 15% conversion efficiency was chosen as the most practical value. Solar power generation for daytime use and nighttime storage (total 570kW) requires approximately 15% envelope surface coverage by solar cell which is equivalent to 1.15 tons of weight. The amount of the solar cells is determined on the condition of most windy winter day and with a sun-seeking attitude control.

Table 6 Various Solar Cell Characteristics

Solar cell types	Conversion efficiency	Power/weight	Cost
Amorphous Silicon	5-10%	421W/kg	low
Monocrystal Silicon	14-22%	629W/kg	
Policrystal Silicon	14-18%	144W/kg	low
Ga-As	18-29%		high
In-P	20%	130w/kg	high

Regenerative Fuel Cells Generated electricity has to be stored in batteries for nighttime use. For this purpose, the implementation of regenerative alkaline fuel cell batteries is a promising candidate given the batteries' operational life which is long enough to last for the duration of the platform's mission. Ni-Cd batteries, widely used for today's space missions, are quite heavy. Fig. 17 shows power and energy density characteristics of various regenerative batteries and internal combustion engines.[9] The regenerative fuel cell system of a constant-output power has a portion whose weight does not depend on power supply duration as is shown in Table 7: these are the electrolysis subsystem, radiators, etc. Power/weight ratio of this portion is about 12kg/kW. The other variable weight portions are tanks and reactants (hydrogen and oxygen). Power/weight ratios of these

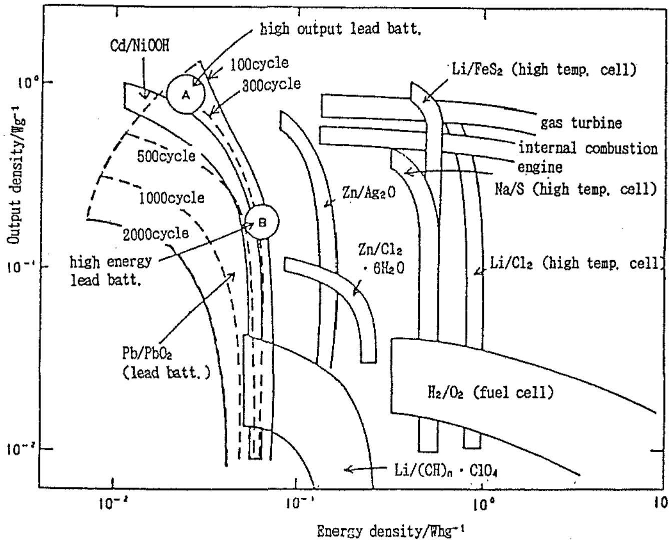


Fig.17 Energy characteristics of batteries and engines

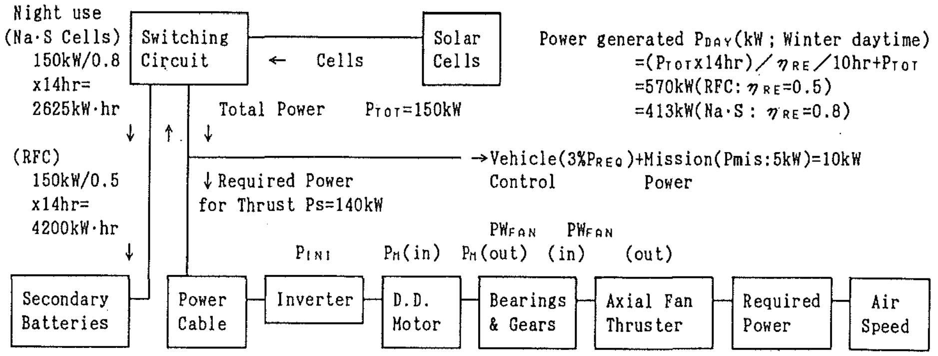


Fig.16 HALROP power flow diagram of HALROP with nighttime propulsion batteries

portions are altogether 27kg/kW for 14 hours duration of the longest winter night. Specifically, 12kg/kW plus 27kg/kW times 150kW becomes 5.85 tons.

Other state-of-the-art energy storage methods like fly wheels and thermal solar systems were surveyed. So far none of these technologies have been comparable with fuel cells in terms of energy storage and output densities.[10]

Table 7 Alkaline regenerative fuel cell weight distribution

Output power 100kW system	kg
Fuel cell	250
Electrolysis cell	350
Power conditioner	287
Isolation heat exchanger	19
Space radiator	293
Subtotal	1,199
Tank & reactants (H_2 & O_2 gases, and water) for 14hr duration	2,730
Total	3,929/100kW

Structural Design and Vehicle Weight Distribution In this section critical hull deformation conditions and hull strength are reviewed. Table 8 shows the total static load configuration of the proposed super-pressured PLTA platform with nighttime propulsion batteries.

Table 8 Weight & buoyancy balance of HALROP with nighttime propulsion batteries

Total buoyant gas volume	400,000 m^3
Total buoyancy	20.55 ton
Envelope & duct weight	5.85 ton
Fuel cell(420kW10h;day, 150kW14h;night)	5.85 ton
Solar cell(570kW output)	1.15 ton
Power cables & wiring	0.25 ton
Main motors(total 100 kW)	0.5 ton
Propellers & gears	1.0 ton
Mission payload	2.0 ton
Control equipment	0.6 ton
Empennage	2.2 ton
Reinforcement	*0.7 ton*
Boom	0.45 ton
Total weight	20.55 ton

Horizontal Equilibrium Analysis of Bending Moment and Shear Stress The vehicle portion weight can be properly distributed along the hull in order to maintain horizontal equilibrium. Fig.18 shows the bending moment and the shearing stress diagram under the loads of buoyancy and the vehicle's distributed weight.

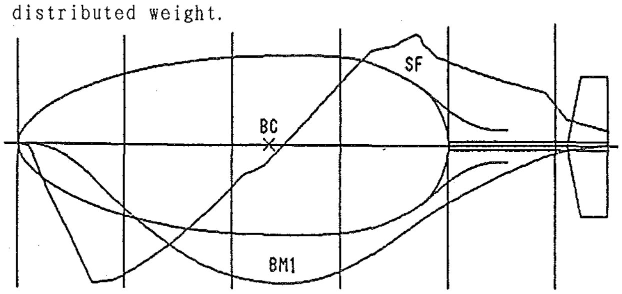


Fig.18 Bending moment and shearing force diagram

Buckling of the Envelope The static bending moment due to the mass distribution and buoyancy can be reduced to a minimum so as not to cause buckling of the thin-skinned hull. The rigidity of the hull is controlled by the internal buoyant gas pressure. The critical pressure, which resists the bending moment caused by buoyancy and weight, is called Pbw and is described as the following;

$$Pbw = (2 \cdot Mbw - \pi \cdot k \cdot R^4)/(\pi \cdot R^3) \qquad (2)$$

where Mbw: maximum bending moment to the hull(kgf.m), k: unit buoyancy of gas(kgf/m^3), and R: radius of hull(m). The maximum value of Mbw can be reduced up to 3.57x105kgf·m and Pbw can be kept as low as several millimeters of water column pressure.

Deformation of Envelope Nose by Wind Pressure Aerodynamic pressure Pn imposed on the platform nose is calculated as;

$$Pn = 1/2 \cdot \rho \cdot v^2 \qquad (3)$$

where ρ: air density($kgf \cdot s^2/m^4$), v: wind velocity(m/s). The calculated value Pn also becomes several millimeters of water column pressure due to low air density.

Bending Moment by Gust *The empirical gust load* formula for a conventional airship hull flying in the turbulant troposphere is given below;

$$Mg = 0.01 \cdot q \cdot Q^{2/3} \cdot L \qquad (4)$$

where Mg: bending moment to the hull(kgf·m), q:wind pressure(kgf/m^2), Q: hull volume(m^3), L:hull length(m). Even utilizing such severe load criteria, the required internal gas pressure to bear this bending moment is only several millimeters of water column pressure.

Loads by Maneuver The final and probably largest load on the hull is the bending moment due to *maneuver, which can be estimated by the results of* wind tunnel tests of a reduced model of this hull shape. Assuming appropriate maneuvering responses, necessary internal gas pressure can be held to a few tens of millimeters of water column pressure.

Instantaneous Buckling of the Vehicle Structure and Safety Factor By considering all of the conditions, the internal gas pressure in the hull Pi can be determined as at highest 50mmaq. Safety factors can be more or less than 1.5. Even if larger loads than those values analyzed above cause buckling of the envelope, it does not mean the destruction of the envelope. For instance, even if buckling takes place due to a gust or instantaneous *excessive loads, the envelope shape is recovered as* soon as the loads are removed. As well as the envelope, the tail fins and the boom are to be made as pressurized fablic structures. Therefore, under heavier load condtions than the designed conditions, buckling may take place, but this does not lead to destruction.

Hoop Tension The maximum hoop tension of the hull created by this internal gas pressure Th can be described by the following equation;

$$Th = Pi \cdot R = 16.75 \ (kgf/cm) \qquad (5)$$

where Pi is the internal hull pressure (50mmaq=50kgf/m^2), R is the maximum radius of the hull(33.5m). The maximum hull hoop tension including a reasonable safety factor is on the order of tens of kgf/cm. Textiles of this strength with a specific weight of 200g/m^2 can be manufactured with using modern, high tension fabrics such as Kevlar or Vectran.

Structural Analysis of the Tail Fin under Normal Maneuvour As is described above, the tail fins are made as a pressurized fablic structure and the internal pressure is chosen as a 20-times-larger pressure of the aerodynamic stagnant point. Structural analysis is made by the finite element method under a normal maneuvour condition. Fig.19 shows the input model to the FEM program. Fig.20 presents a superimposed figures of the input model and a deformed shape of a tail wing. Deformation is enhanced by 1,000 times and actual value is quite small compared to the size of the wing.

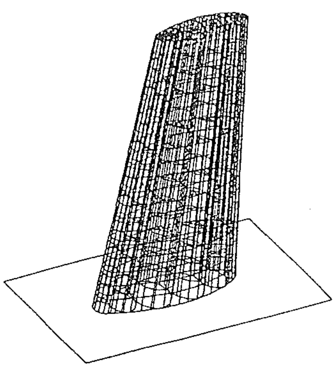


Fig.19 Input model of a fablic-made HALROP's tail wing for FEM method structural anaysis

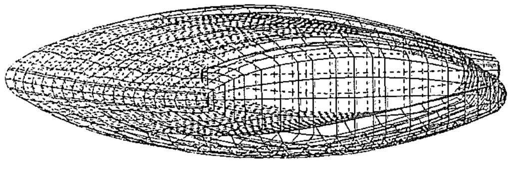


Fig.20 Deformation of a tail wing of HALROP (top view) made under normal maneuvour

Conclusion

The above studies indicate that HALROP, an unmanned stratospheric airship without propulsive ability during the nighttime, will make an excellent observational platform for a long-term Antarctic observation of the ozone layer. HALROP will also make a highly accurate observational platform for the analysis and observation of a broad range of atmospherically scarce substances, such as the long-term observation of the Antarctic ice sheets. The observational mission by HALROP for polar area use can be carried out by utilizing technologies available at present, and we need not wait for the development of high-powered, regenerative fuel cells or other advanced technologies which may require a considerable investment.

Research results on the feasibility of a stratospheric super-pressured powered LTA platform with nighttime propulsive capability indicate great potential. The dimensions of this platform are approximately 200 meters in length, 400,000 cubic meters in volume with a total buoyancy of 20.5 tons and a 2 ton payload. Further study is required to determine the validity of the boundary layer control effects, durability of the on-board solar power system, etc.

Reference

1) Tamura, T. "Nihon no Koukuugigyutsu ha Kokomade kita: Japanese Aerospace Technology now" by K. Kato, Yomiuri Science Books No.33, Oct. 1990
2) Japan Industrial Technology Association, "Neo Powered LTA Study Group's Annual Report 1991"
3) Goldschmied, F. R., "Integrated Hull Design, Boundary-Layer Control and Propulsion of Submerged Bodies: Wind-tunnel Verification", AIAA 5th LTA Systems Conference, Anaheim, California, July 25-27, 1983
4) Kimura, J., Takeda, R., Fujimatsu, Y.& Kato, T., "Hikousen no Kanousei ni tsuite - Sono 2: Potentials of Airships - Part 2", Bouei Gijutsu: Defence Technology, October 1985
5) Matsumoto, H., "Microwave Energy Transmission System for Solar Power Station", Energy and Resources, Vol.9, No.3, 1988
6) Fukuchi A., "High Altitude Weather and a Way of Reading Fax Diagram", Seizan-do Press
7) Tokyo Astronomical Observatory, "Scientific Chronological Tables in 1988"
8) Parsons, J. S., Goodson, R. E. & Goldschmied, F. R., "Shaping of Axisymmetric Bodies for Minimum Drug in Incompressible Flow", AIAA J. Hydronautics, Vol.8, No.3, July, 1974
9) Takehara, Z., "Developement and Trend of New Batteries", Energy and Resources, Vol. 8, No.4 1987
10) Kodama, T., "Present Status of Fuel Cell Development", Energy and Resouces, Vol.8, No. 4, 1987