A CONCEPT FOR GENERATING COMMERCIAL ELECTRICAL POWER FROM SUNLIGHT

William R. Cherry

NASA/Goddard Space Flight Center
Greenbelt, Maryland

ABSTRACT

This paper proposes a method for reducing the critical electrical peak power shortage in the U.S. without adding further to the atmospheric and surface water pollution. Also, very small amounts of surface area are required and it will reduce the consumption of our earth's rapidly diminishing mineral resources.

Our most abundant and limitless natural resource, solar energy, can provide over 250,000 kw of electrical power per square mile, (equivalent to the NYC Indian Point Nuclear Plant) using todays solar cell technology. It is proposed to float a "Solar Rug" on a helium mattress, between 50,000 and 70,000 feet, above the major cities in the U.S., well out of the weather and its disturbances, to supplement the peak power demands during the daylight hours.

Calculations show that a square mile mattress 100 feet thick can support 10,000 tons at 53,000 feet elevation, sufficient to provide for a manned power station.

While several aspects of the idea will require some major engineering development, a large proportion of this has already been done on a smaller scale in the space program and could be directly applied to solving some of our most critical terrestrial problems.

INTRODUCTION

The U.S. and other populated parts of the world are faced with a critical shortage of electrical power beginning in the 1970's. Present methods of power generation are not keeping up with the demands, which are doubling every ten years. In addition to this general power shortage, the conventional power generating systems are major contributors to planet pollution.

L. P. Gaucher of Texaco, Inc. made a comprehensive study of energy consumption in the U.S. from 1800 to projections as far ahead as 2200 AD (1). His study, summarized in Figure 1, shows that means other than fossil fuel, nuclear or hydroelectric must be developed to provide energy to our economy within the next 50 years. It is possible that due to the great concern for our ecology a new pollution free power generation process will be encouraged immediately.

During the 1970's, fossil fuel power plants will account for the major source of electrical power (2) while the nuclear power plants will be increasing their percentage portion steadily through the turn of the century, as shown in Table 1. Fossil fuel plants account for about 1/2 of our present SO_2 and 1/4 of the particulate air pollution in the U.S. In addition to heat, fossil fuel plants dump millions of tons of water vapor, CO_2, CO, N_2O_x, into the air. The introduction of the nuclear plants has created serious thermal problems in the adjacent streams as well as introduced nuclear pollutants which are having yet undetermined effects on the ecology. The disposal of nuclear wastes from the atomic power plants is another problem which will become severe in the not too distant future. Present power plants require, in addition, thousands of acres of ground for plant and transmission lines, which have recently caused great concern and protest by the citizens of our land.

Most of the choice sites for hydroelectric installations have been dammed and the nation is actually running out of rivers which can be used for power production. Actually, the electrical energy is needed in the high population density areas where land is at a premium and where it is wasteful to tie it up for that purpose. In any event, as shown on Table 1, the hydroelectric installations would provide only a very small percentage of the electrical energy needed in the U.S. through the turn of the century.

During the periods of extremely hot weather, when air conditioning, factory and business electric power demands are at a maximum, considerable difficulty is being

(1) L. P. Goucher "Energy Sources of the Future for the U.S." Solar Energy 9, 119 (1965)

(2) F. Stewart Brown "Trends and Growth Projections of the Electric Power Industry" Oct., 1969, and accompanying statement of Chairman [illegible] Power Comm. to the Joint Committee on Atomic Energy

experienced in providing sufficient electrical service in the densely populated regions of the U.S., especially along the Eastern sea-board. Figure 2, clearly shows the troubled areas (3). Even in regions where the power availability is considered good, the large cities within these regions, such as Minneapolis, St. Paul, St. Louis and Chicago, are rated potential candidates for brown or blackouts.

Peak demands on electrical power usually occur on extremely hot days between the hours of noon and 7 PM. During the summer of 1969 it was estimated that between 25 and 35% of the peak load on these hot days was due to space conditioning (2).

The reserve capacity to take care of the peak demands along the Eastern seaboard has decreased from about 16% in 1965 to nearly 9% in 1970. New power stations are not being built quickly enough to keep up with the ever increasing demand of the consumer.

A means of generating large quantities of electrical power during the peak demands, which are close to the high population centers, is urgently needed. Further, the generators should not pollute the atmosphere or water bodies, and preferably not use up much valuable real estate. The cost of such a system should be competitive with conventional electric power generating methods as well.

GENERAL CONCEPT

An examination of the many methods of generating electricity shows that the only way to do this without planet pollution of some kind, is the direct conversion of solar energy. No gaseous effluents, no thermal unbalance, nor any other type of disagreeable pollutant is generated when using solar energy. Furthermore, solar energy is inexhaustable and costs exactly nothing as a "fuel".

While solar energy on the ground is influenced by seasonal, day/night cycles, and by weather, it is possible to get above the weather and to take advantage of full sunlight. Ascending to a height of 50,000 to 70,000 feet, it is possible to get out of most of the weather problems. By moving farther and farther north until one reaches the North Pole, the sunlight period increases, reaching 100% sunshine hours from March 21 through September 21. This, however, requires the transmission of power over many hundreds of miles to reach the populated regions of North America. If the power station is located over a city it would be analogous to a power dam some 10 to 15 miles from the urban area.

While the problem of 24 hour service has not been solved, there would be abundant power available to cover the peak periods, e.g., the hours between noon and 7 PM during the summer, when the threat of blackout is greatest.

To help relieve the critical electric power shortage, it is proposed that a solar power source be used to supplement the power network during peak power periods. Fewer fossil fuel and atomic reactors would thus be needed, and a considerable step could be made to reduce planet pollution. Eventually, a large segment of the electrical power needs of the populated world could be derived from such solar powered systems, improving our atmosphere, eliminating thermal and nuclear waste pollution, and conserving our rapidly diminishing fossil fuels for other purposes.

THE CONCEPT

Several methods of converting solar energy directly into electricity have been extensively studied for our space program: solar cells, thermoelectrics, and thermionics. The method proposed here is to use solar cells made of silicon or some other thin film material such as CdS.

A "Solar rug", illustrated in Figure 3, supported by a helium inflated "mattress" could be floated at an elevation between 50,000 to 70,000 feet which is above the weather disturbances found near the ground. This is also well above the 40,000 foot ceiling of present day commercial jet aircraft.

Solar Array

The solar cell array would be made up of mass produced cells about 4 mils in thickness mounted on a plastic substrate and connected so as to generate an appropriate dc high voltage. Using today's conversion efficiencies of 7 percent at 50°C, over 250,000 kw of raw dc power would be generated from a 1 square mile area. Perhaps passive or even active cooling techniques could be incorporated into the design which would enhance the power output even more. If the array could be maintained at a temperature of 0°C, for example, a 25 percent increase in power output could be extracted from the solar arrays. The proper interconnecting conductors and insulation would be required to avoid the corona discharge phenomena associated with these altitudes.

At the elevations mentioned, energetic particle radiation would not be a problem, but the strong UV light would have to be taken into consideration to avoid material degradation.

The array would be oriented to some degree with the rising and setting of the sun so as to take advantage of maximum power output. Appropriate catwalks or ladders would be provided so that the array could be serviced as needed. A properly designed array, however, should be serviceable for many years because it would be away

(3) "Warning: Low Voltage" Newsweek Magazine May 18, 1970 p. 123

from weather, animal life, and harmful energetic particle radiation.

Mattress

The supporting mattress would be made up of balloon sections of appropriate size, shape, and material, approximately 100 ft × 100 ft × 100 ft, as shown in Figure 4, capable of being interconnected or assembled either on the ground or at high elevations. The cavities of the mattress, made of polyethylene or other suitable materials about 5 mils thick, would be filled with a lighter-than-air gas, such as helium or hydrogen. Calculations for a mattress one mile square and 100 ft thick show that about 4000 ft^3 of helium per day would be diffused through its exposed surface; an amount easily supplemented at the power station. A purification system connected to the various balloon sections by a manifold would permit refinement of the lifting gas as well as replace loss. Provisions would also be made for repair on the spot of any leaks or punctures which might occur on the mattress.

A mattress 1 mile square and 100 feet thick could support 10,000 tons at a 50,000 foot elevation, which is in approximately 0.1 atmosphere.

The mattress would require 2.76×10^8 ft^3 of 1 atm pressure Helium. Approximately 1 billion ft^3 of Helium is recovered each year by the Bureau of Mines (4) and over 15 billion ft^3 is presently stored in the Cliffside field underground reservoir near Amarillo, Texas. Perhaps even more helium could be recovered per year if needed or possibly a mixture of helium-hydrogen could be used under the conditions stated herein.

Frame Work

Above, below, and between each of the mattress segments, see Figure 5, an I-beam frame or structure would be assembled, either on the ground or at the higher elevations, to secure the mattress segments and make a reasonably rigid structure for supporting the solar array. Lightweight materials would be used in all frame construction such as aluminum, magnalium, or magnesium. The frame could be secured together with rivets, nuts and bolts, or by welding techniques commonly used today. Certain sections or cubes of the mattress would be left vacant, and within the void a power substation would be built to gather the electrical power from the array and to put it into the proper form for transmission to the ground.

(4) Philip F. Myers, Tethered Balloon Handbook, Goodyear Aerospace Corp., Dept of Commerce publication AD 685183 p. 162 done under USAF Contract F19628-67-C-0145

Power Transmission to the Ground

Two methods are considered for transmitting power to the ground. One involves tethering the mattress by special high tensile strength cables and conducting the dc power to the ground as illustrated in Figure 6. This method, while possibly feasible, is unattractive because of the hazard of long tethers suspended from the mattress which must sustain severe near ground weather conditions. They would also be a hazard should they break.

Another technique is to convert the dc power to microwave frequencies, and beam the power to a receiving station on the ground. The solar rug power station would then be a free floating body. Recent research (5) in the microwave transmission of power has shown that conversion, transmission, and reconversion may be better than 80 percent efficient in the near future. Should this technique be used, then some power conversion machinery would be required on the solar rug to convert the dc to high frequency power. Reference (6) further discusses this concept.

Microwave antennas, designed for most efficient transmission of power on orientable mounts would be suspended beneath the mattress in the proper numbers and sizes. See Figure 3. The intensity of the microwave beam(s) would be up to 50 times that of solar energy so that aircraft and animal life should not venture into the beam. Appropriate safety precautions would have to be taken to prevent such accidents.

Stabilization and Control

The solar rug would be provided with a stabilization and control system for station keeping and to provide orientation to the sun for the solar array. During the daylight hours, plenty of electrical power would be available for this system. At night an auxiliary powered unit would be needed, either run on batteries or fossil fuel.

Since the solar rug is still in partial atmosphere, perhaps propellers or jet engines could be used for stabilization and orientation.

Life Support

The solar rug could be a manned power station as if it were on the ground. Compressors to provide air at near 1 atmosphere would be provided. The "stationauts" would wear protective clothing capable of providing the

(5) Ernest C. Okress, ed "Generation, Transmission, Rectification" Microwave Power Engineering Vol. I Academic Press, 1968

(6) Peter Glaser, "Satellite Solar Power Station" The Journal of Solar Energy Science and Technology Vol. 12, No. 3, p. 353

necessary shielding against the UV and for supporting breathing. The "Stationaut" would necessarily have to wear a parachute as a safety measure in case of a fall. All of these devices have already been developed in the space program. Actually, the "stationaut" would be safer than a man working on a tall building because of the large amount of time he would have to activate his safety equipment in the case of a fall.

Servicing Solar Rug

The solar power station would be manned to insure proper operation and allow for maintenance and repair. The solar rug would be ascended to by a balloon gondola with a propulsion system. At 50,000 feet this should require about 40 minutes from the ground.

Weight Estimates

Insufficient engineering has been done on this concept to establish absolute weight requirements. However, some estimated values are given in Table 2.

Designs of solar arrays on 1 to 2 mil thick Kapton substrates weighing 0.1 lb/ft^2 have already been developed. Solar array for this concept must be produced in enormous quantities under highly automated processes as illustrated in Figure 7. A square mile, 27.6 million square feet, would weigh about 1,400 tons.

The weight of the helium "mattress" is based on 5 mil thick heavy density polyethylene. Most balloons attaining 80,000 to 120,000 feet are made of 1 to 1-1/2 mil thick polyethylene. The 100 ft $\times$ 100 ft $\times$ 100 ft gas containing bags were made extra thick to reduce the Helium gas leakage to an acceptable level. Thus 2,200 tons is allowed for the weight of the 2,800 cubes which make up the mattress.

The mattress framework, wiring and insulation for the solar array is estimated at 3,000 tons. This allows about 2 lbs per running foot of frame work spaced about 50 feet apart and allowing for vertical members at the corners of each gas containing cube. Materials like magnalium would reduce this weight by at least 700 tons. Actually the shape of the station might be considerably different than depicted in this paper especially when aerodynamic pressures are considered. Figure 8 depicts the variation of dynamic pressure as a function of altitude.

About 1,000 tons is allowed for several power station structures which would collect the dc power and either conduct it to the ground or convert the dc to microwave frequencies. The power conditioning is estimated at 1 lb/kw or 125 tons, which is considered conservative. Units today weigh nearer to 0.3 or 0.5 lb/kw.

1,000 tons is allowed for either tethers or microwave antennas. A trade-off of voltage and current must be made to reduce the weight of tethers so they can withstand their weight as well as the buffeting associated with storms. If microwaves are used to transmit the power to the surface, then all the antennas projecting beneath each of the power collection stations must not exceed the 1000 tons allowed for this purpose.

To maintain the power station over the proper receiver on earth will require a stabilization and control system. 100 tons has been allowed for this. It is desirable during different seasons of the year to raise or lower the station in order to seek the optimum altitude for the lowest wind profile.

The life support for the stationauts could be done for about 100 tons of equipment including air compressors, water supply, heat and sewage. Each man would be provided with a "space suit" adapted for the station environment and equipped with an air compressor, heater, and parachute in the event of a fall.

This leaves about 1,075 tons to be distributed around where needed to make up the 10,000 ton lifting ability of the helium mattress. Some flexibility is possible by making the "mattress" thicker or thinner to adjust its lifting capability.

MAJOR PROBLEM AREAS

While the general state of technology now exists to construct the described solar rug power station, considerable development is required to adopt the technology to this specific use.

Low Cost Solar Arrays

Silicon solar arrays, in hundred square feet quantities, cost several hundred dollars per watt. Considerable reduction in price per watt is anticipated when millions of square feet are to be made. In all probability solar cell construction methods would be highly automated and might resemble the conceptual process shown in Figure 7, rather than the jewelry industry approach presently used to fabricate solar cells. To be competitive with current commercial processes for generating electrical power, the solar array will have to come down more than 2 orders of magnitude in cost.

A study should be made to ascertain the facilities and processes needed to manufacture solar arrays for less than $1.00 per watt.

Mattress Structural Design

The structure to hold together the helium mattress is illustrated conveniently in Figure 3 as either a square or circular area. In all probability this would not be dynamically suitable since the solar rug would be subjected to certain wind loads and stresses even though the atmospheric density is quite low. Perhaps a dirigible shape is better suited for the proposed station. A study to optimize the design is therefore needed.

Transmission of Power to the Ground

This is probably one of the most difficult problems to be solved. While designs exist for tethers greater than 100,000 ft in length, its quite another matter to design one which can conduct large amounts of electrical power and survive surface storms as well. A trade-off of conductor size and voltage will have to be made.

Further exploration into the possibility of wireless microwave transmission of power to the ground over a distance of approximately 10 to 15 miles is very intriguing. Efficiencies over such distances are presently less than 20% but with the proper emphasis perhaps considerable improvement is possible.

A study program is required to identify and trade off the aforementioned methods of power transfer and others which might appear feasible.

Attitude Control and Station Keeping

Due to the enormous volume associated with the solar rug power station and the requirement it be located over a specific spot on the earth's surface, a study of attitude control is needed. The tethers or microwave antennas must be properly located or focused at all times. Further the station must be permitted to ascend or descend as the need arises to stay out of unfavorable winds or turbulances.

Helium Gas Pruification

Helium gas will tend to out diffuse from the mattress and air will tend to enter. Some means of recovering the diluted helium from the bags must be developed so that the gas is purified for future use. A recycling manifold system operated by personnel on the power station could possibly do the job.

Life Support

This solar power station is envisioned to be manned with crews which would stay on board for a week or more at a time. Due to the extreme cold (-40 to -70°F) and rare (0.1) atmosphere along with strong ultraviolet radiation, the stationauts would have to be protected from these elements. Life support would include some adaptation of the space suits used by our astronauts utilizing an air compressor in place of an oxygen back pack. Also, as a safety measure, each suit would have a built in parachute in the event of a fall. The chute could be automatically actuated by barometric pressure in the event the stationaut should loose consciousness during the fall.

Other life support systems would have to be designed to contain water and food provisions, work areas, housing and sewage disposal. Much of the present space technology could be used almost directly in the solar power station application.

Table 1

Electric Utility Requirements and Supply
For U.S.*

	1970	1980	1990
Hydroelectric	51 (15%)	68 (10%)	83 (7%)
Pumped Storage	4 (1%)	24 (4%)	65 (5%)
Internal Combustion and Gas Turbine	16 (5%)	27 (4%)	42 (3%)
Fossil Steam	261 (76%)	399 (60%)	562 (45%)
Nuclear	12 (3%)	150 (22%)	509 (40%)
TOTAL (million kw)	344	668	1261

*From: "Trends and Growth Projections of the Electric Power Industry"; F. Stewart Brown, F. P. C., October 1969.

Table 2

Solar Rug Weight Estimates

	tons
Solar array at 0.1 lb/ft^2	1,400
Helium "mattress" 53 × 53 5 mil polyethylene 100' × 100' × 100'	2,200
Aluminum frame, wiring, insulation	3,000
Power stations	1,000
Power conditioning at 1 lb/kw	125
Tethers or μ wave antennas	1,000
Stabilization and Control system	100
Life support - air compressors, water, heat, sewage	100
Miscellaneous	1,075
Total	10,000 tons

ENERGY CONSUMPTION IN THE UNITED STATES

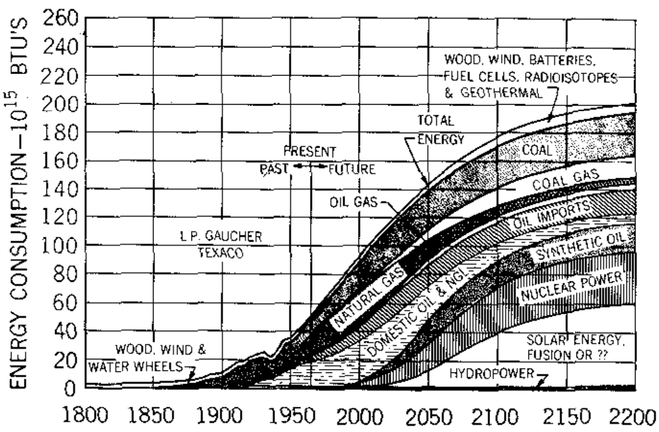

FIG. 1. ENERGY CONSUMPTION IN THE UNITED STATES 1800 - 2200

SOLAR RUG

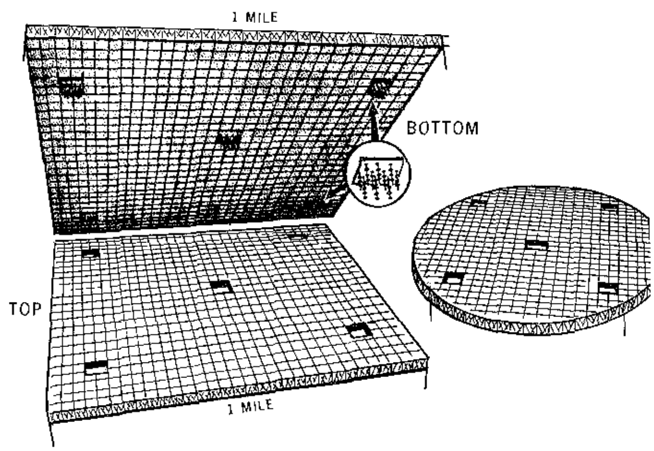

FIG. 3. SOLAR RUG CONCEPT

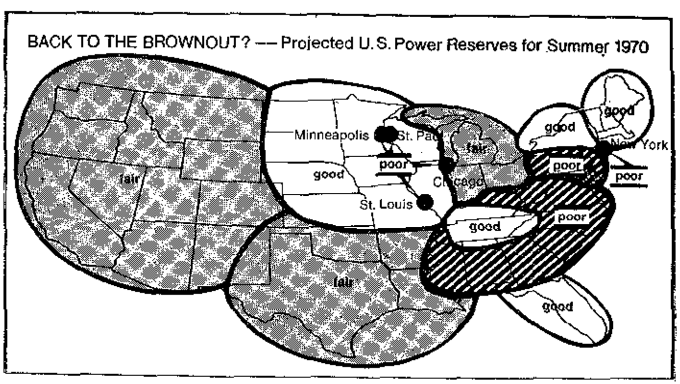

FIG. 2. PROJECTED POWER SHORTAGE AREAS IN U.S. - SUMMER 1970

SEGMENT OF HELIUM MATTRESS

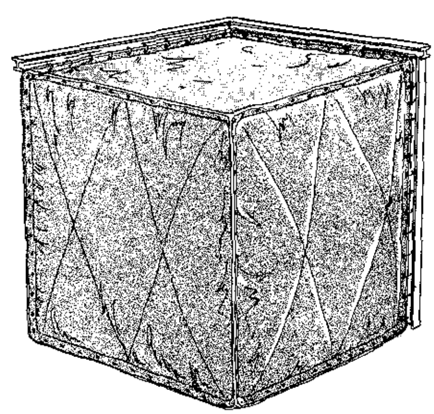

FIG. 4. HELIUM MATTRESS SEGMENT

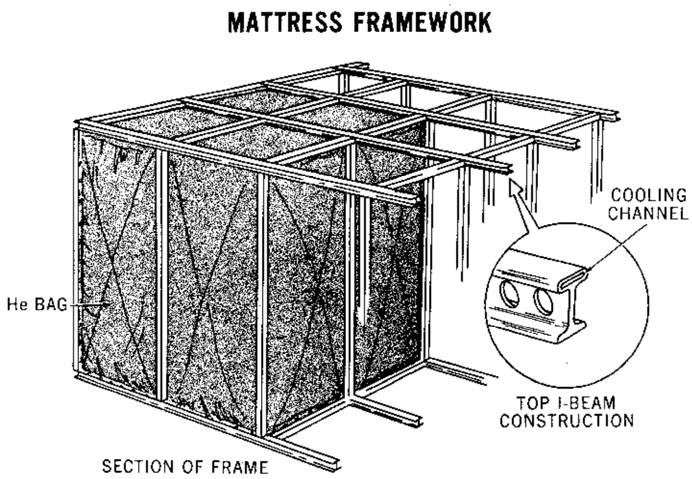

FIG. 5. HELIUM MATTRESS FRAMEWORK

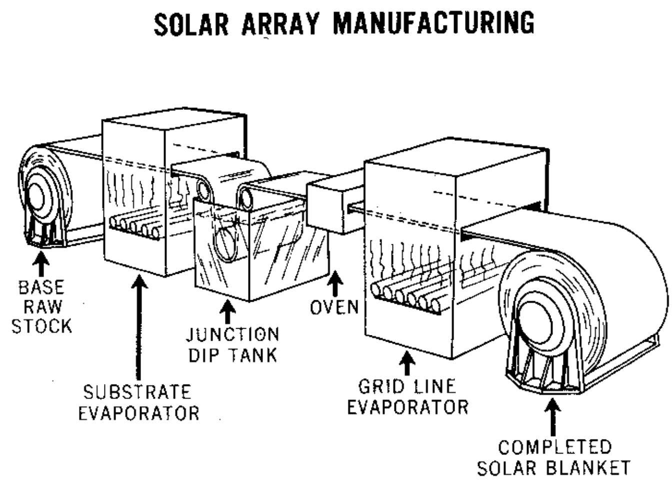

FIG. 7. SOLAR RUG MANUFACTURING

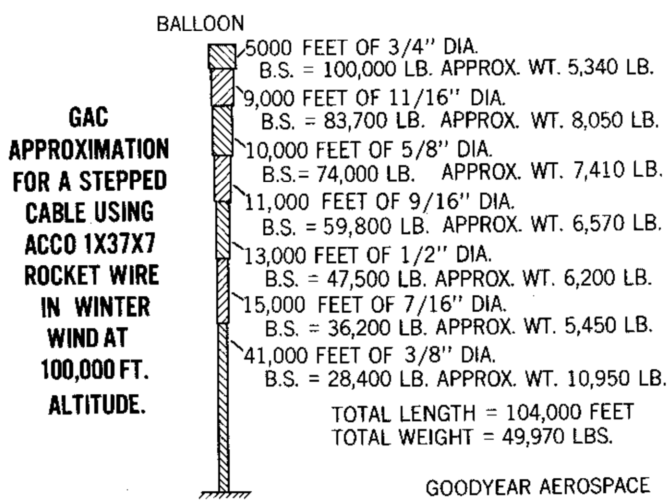

FIG. 6. TETHERED BALLOON CABLE DESIGN

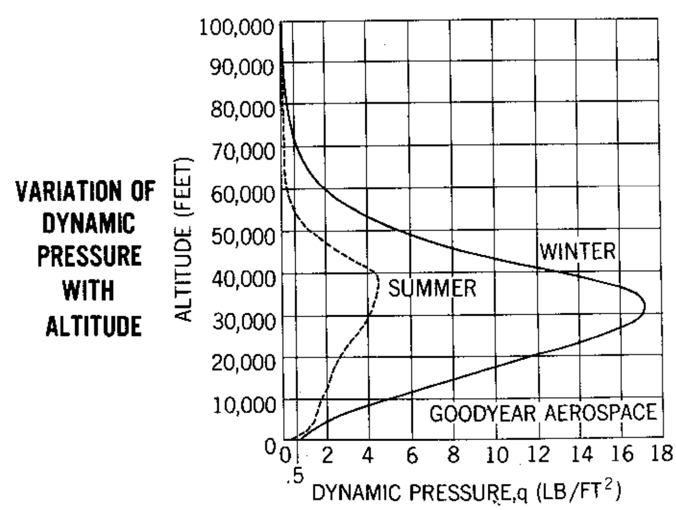

FIG. 8. DYNAMIC PRESSURE VS. ALTITUDE