A Macro System for the Production of Storable, Transportable Energy from the Sun and the Sea

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Introduction

The purpose of this paper is to present a candidate technical concept for solar energy utilization in large scale. This concept, though offering nothing new in technical detail, does offer a singular departure from previous concepts on the overall systems engineering level. This is the idea of locating the solar energy conversion system on the open seas, as opposed to basing it on land.

The important technical benefits of sea-basing a solar energy conversion system are these 1) Proximity to an excellent thermal sink and source of working mass (viz. the ocean, particularly the depths), 2)Mobility of rotation and translation, 3) Space availability for large solar collector areas, and 4) Logistical ease in initial construction, servicing, and in the distribution of products from the macro system on a world-wide basis.

Proceeding from the fourth point, the energy form to be produced is required to be both storable and transportable over significant duration and distance by way of delivering this energy to the ultimate consumer. It is proposed that solar energy be used to convert water (purified sea water) into cryogenic liquid hydrogen and oxygen. In this form the stored energy of the sun can be readily shipped to points-of-use on a worldwide basis via "cryotankers". Once unloaded at port, the cryogenic liquids can be stored and eventually transported by rail, over-the-road trailers, or by pipelines. Alternatively, the hydrogen and oxygen can be gasified and piped in the manner of natural gas. The energy form can be finally consumed in the process of heat-release or it can be converted into an electrical form by fuel cells or their shaftpower-producing equivalents.

Also, though not really assessed in the paper, a number of collateral products in addition to the cryogenic energy form may be readily produced from a sea-based solar energy converter. Possibilities are these: seafood products, mineral and chemical products, and certain finished and semi-finished goods. If these prove economically feasible, such coproduction might very significantly reduce the cost of energy by spreading the capital investment and operating cost over a wider range of salable products. This surmise is, however, taken to be outside the scope of the present paper. Much more study will be required to quantify the potential of such collateral output; a multidisciplinary effort is clearly needed here.

Finally, the candidate scheme, as is characteristic of solar energy utilization systems in general, offers one extremely important advantage to our environmentally-conscious world: Its operation will not degrade the environment. No fossil-fuel is combusted and no radiation conditions are produced nor are long half-life radioactive wastes created.

This unique environmental aspect of the solar energy conversion approach, together with its intrinsic non-dependence on resources in increasingly short supply, may in fact be a decisive factor in favor of its eventual development. Unfortunately, it is not yet apparent what the economic ramifications of these characteristic benefits will be, hence these can not be assessed in the paper.

In summary, the paper introduces and discusses a new energy system concept based on the synthesis of known subsystem approaches to create a "macro system" (large scale system-of-systems). This macro system employs solar energy to convert water to the energy form: cryogenic hydrogen and oxygen. This is deemed a feasible storable and transportable commodity for a wide variety of end-consumption means. The macro system will not produce environmental degradation in its operation, nor at the point of consumption. Water is the sole "exhaust" product in reconversion as heat or electrical energy (thermal rejection will occur, however, dependent on the conversion efficiency). The approach offers distinct possibilities of cost-beneficial coproduction of other salable products, although this aspect is not further developed in the paper.

Description of the Technical Concept

A general overview of the problems addressed, the general technical approach to be taken, and the technologies which might contribute to feasibility, for the subject macro system approach has been published (1, 2)* and will not be repeated here. Rather, this paper concentrates on a specific formulation of the technical approach, sizing calculations, and a rough cost estimate applicable to the macro system. Necessary to this scope, a brief analysis of the solar energy input to be received is included, including cloud-cover considerations.

Production of cryogenic hydrogen and oxygen from sea water using solar energy takes place by integrating five of the six systems (blocks) in the manner shown in Figure 1. The sixth system, "Marine Farming System", is representative of a potential collateral production unit (seafood), which uses ocean resources and solar energy (via photosynthesis). Also, the "sea water concentrates" output of the Water Purifier System (top) is suggestive of chemical and mineral production. Figure 2 is a pictorial schematic of the macro system reflecting an overall geometric relationship of the constituent systems. Note that items are located both on the surface and in the ocean depth for reasons to be discussed.

The macro system is sized on the basis of an equivalent production of 1000 Mw of cryogenic energy form continuously. The energy-content reference is the higher heating value of hydrogen at 61,030 Btu/lb. This equates to a daily production of 670 tons of liquid hydrogen and 5360 tons of liquid oxygen (609 and 4890 metric tons, respectively).

Macro system operation is conducted in basically two modes: 1) During periods of solar energy collection for 8 hours of day (when there is no cloud cover), and 2) Around-the-clock during which product liquefaction takes place. The consideration governing the continuous liquefaction process lies in the problem of the characteristic extended start-up and shut-down time involved with industrial liquefier train operation. This need (and it should be more closely examined) assumes a supply of "service power" which is provided by reconversion of some of the hydrogen and oxygen electrolyzed from water to create an electrical supply at all times. The remainder of the macro system is operated only during periods of sunlight. This entails the Solar/Electric Conversion System, the Water Purifier System, and the Electrolytic Cells System as "off-on"-capable units. It is noted that the specific characterization of Figures 1 and 2 represent a "first look" with regard to macro system formulation. It is by no means optimized; a number of improvements are forseen.

* Numbers enclosed in parentheses denote references listed at the end of the paper.

Cryogenic Hydrogen and Oxygen

Central to the theme of the macro system is cryogenic hydrogen and oxygen, the "energy form" to be produced. Hydrogen, in combusting with oxygen in the air or with pure oxygen (the approach emphasized), provides greater heat-release per unit mass than any other chemical fuel. On a volumetric basis, however, hydrogen has about one-third the energy content of natural gas (principally methane), and less than one-fourth of that contained in the conventional liquid hydrocarbon fuels, gasoline, kerosene, and fuel oil. The characteristic problem of hydrogen's very low density is evident here.

Technology deriving from the aerospace sector over the past several decades, and particularly that from the Apollo effort, has made consideration of the cryogenic form of hydrogen (liquid oxygen development and mass-use came much earlier) eminently practicable for large-scale system applications. Liquid hydrogen, despite its extreme physical characteristics (viz. 0.07 specific gravity, $21^{\circ}K$ boiling point) has been demonstrated to be a tractable, desirable chemical fuel and working fluid (See Scott's volume on liquid hydrogen technology (3) for cases in point).

The potential of hydrogen as a fuel has been frequently discussed. Apollo represents a pinnacle of experience in actual usage in ground-testing of engines and stages, as well as in the actual mission flights. A recent review with emphasis on the cryogenic form is that of Jones in Science (4). The clean combustion characteristics of hydrogen (water only with oxygen, whereas a nitrogen oxide problem remains with combustion in air) has caused increased attention to be given this fuel in recent times. A number of prime move types have been operated on hydrogen-air and hydrogen-oxygen. Still others have been proposed (viz. 5) for a number of technical advantages gained over hydrocarbon fuels. Fuel cells operating on hydrogen-oxygen are well developed as demonstrated in the Gemini and Apollo programs.

A second, longer-term incentive for considering hydrogen as an "emerging" energy form is reflected in a study recently undertaken by the Institute of Gas Technology for the American Gas Association. This is the consideration of hydrogen as a distant-term replacement for natural, and synthetic "natural" gas (via coal gasification, for example). The consideration here is that of natural resource exhaustion of fossil-fuel reserves, and a conversion to a nuclear-electric energy base. A basic approach here is the use of nuclear power to extract hydrogen (and oxygen) from water; hydrogen is very significantly cheaper to transmit over long distances via pipelines than electrical power, particularly so if the electrical conduits must be placed underground. Since this study effort was only recently announced (6), no published results are yet available. Gregory's review of this area (7) provides a worthwhile overview.

The "arrival" of cryogenic hydrogen and oxygen as a viable energy form capable of long-term storage and long-distance transportation -- characteristics crucial to the concept of the paper -- is indicated in the equipment shown in Figures 3 - 5.* Figures 3 and 4 show the largest liquid oxygen and hydrogen tanks in existance as located at the Kennedy Space Center, Florida. These vacuum-jacketed spherical tanks approach one million gallons in capacity. Figure 5 shows liquid hydrogen (foreground) and liquid oxygen (background) barges used to transport the cryogenics from their point of production to the test facility of NASA near Gainesville, Mississippi. The liquid capacities are over 300,000 and 100,000 gallons, respectively. Hydrogen and oxygen are also shipped routinely across country in rail tankers and over-the-road trailers. Although hydrogen and oxygen "cryo-

* Photographs courtesy of Chicago Bridge & Iron Company, the equipment suppliers

tankers", as envisioned to supply the macro system's product to the mainland, do not presently exist, the commercial success of LNG (a "mild cryogenic" at -258°F) tankers presages success. A dozen LNG tankers are currently in service, and by 1980 there are projected to be one-hundred (8). Actually, hydrogen cryogenic vessels have been considered in some engineering detail in Air Products & Chemicals' comprehensive study of liquid hydrogen production for global hypersonic aircraft fueling (9).

Solar Energy Available in a Practical Large-scale Array

The rate of energy radiated by the sun is 3.805×10^{26} watts which corresponds to a continuous loss of solar mass of 4.234×10^{12} g/sec, or 4.67 million tons per second via nuclear fusion conversion. Of this amount of radiant energy, the Earth-atmosphere system receives each year 5.445×10^{12} joules (1.301×10^{24} cal). This corresponds to an energy density as expressed by the Solar Constant of 135.3 w/m^2 (1.353 kw/m^2). (The Solar Constant is the amount of total radiant energy received from the sun per unit time per unit area exposed normal to the sun's rays at the mean Earth-sun distance in the absence of the Earth's atmosphere.) (The data given in this paragraph were taken from (10).)

In principle, a solar collector located in near-Earth space and oriented continuously toward the sun would receive energy perpetually at the Solar Constant rate. This "ideal" condition has, in fact, been proposed by Glaser in several papers (e.g. 11) as one which we should seriously consider exploiting.

Unfortunately, but invariably, Earth-bound collectors will receive considerably less energy than such a space-borne system. Of that potentially available, large-scale collectors at sea level may receive 6 to 10 percent of the maximum value. This is because of the following essentially uncontrollable factors: 1) Rotation of the Earth occluding the sun for much of the time, 2) Seasonal variations in the mean sun-angle for a fixed latitude, 3) Clear-day atmospheric attenuation, and 4) Cloud-cover and adverse weather conditions (fog, humidity, etc.). Further, though perhaps easy enough for a space-borne collector, it is usually not practical to orient large Earth arrays normal to the sun as it moves across the sky. Instead, the array is layed out in the horizontal datum plane of the Earth's surface. This results in a loss in incident radiation over that potentially available proportional to the cosine of the total sun-angle.

A typical observed solar radiation pattern over a (clear) day's observation period is presented in Figure 6 (the upper right hand note calls out this curve), as adapted from Daniels (12). The integrated radiation intensity (Langleys*/min) for that day was reported as 678 Langleys*. Returning for the moment to the case of an ideal collector located in Earth-space, a maximum of 1.937 Langleys/min times the number of minutes in a 24-hour period would be received. This is approximately 2790 Langleys. The observational data of Figure 6 accordingly represents about 24 percent of that potentially available. As will now be shown, a practical large-scale collector will not achieve this effectiveness.

Returning to Figure 6, the dashed curve has been estimated as a "maximum solar radiation characteristic" for an Earth collector. At noon the peak intensity of this estimated reference curve is about 1.4 Langleys/min, or 72 percent of the potential 1.937 (Solar Constant). Over a 24 hour period, however, only the order of 25 percent can be realized. Also, the sunrise/sunset "tails" of the baseline data curve were clipped to accord to the "sudden" nature of the sun's appearance and disappearance in the tropics.

* See Figure 6 for a definition of the Langley unit and its equivalent in kw/m^2

Unless the collector's constituent areas are rotated normal to the sun's rays at all times during the collection-day (and do not shield one another from the sun) this 25 percent effectiveness cannot be achieved in practice. This results in the cosine loss factor mentioned previously as denoted in the third curve of Figure 6, that of least area. Also the length of the nominal day has been reduced to the 12 hours experienced near the equator (for it is the quasi-equatorial region which appears most desirable for locating the macro system). This time-scale forms the basis of the nominal sun-angle scale established below it. The quite-evident narrowing of the daily intensity characteristic due to applying the cosine loss factor (array non-normal to the sun, except nearly so around noon) significantly reduces the area under the curve, the integrated solar energy quantity received.

One more penalty is observed as the deletion of the shaded areas on each side of the curve. This corresponds to non-operation of the solar collector at sun-angles greater than 60 degrees (as can be noted on the lower scale). This somewhat arbitrary cut-off is for practical design considerations as will become evident when the collector geometry envisioned for the macro system is introduced in a later section.

The last two reductions in effectiveness (non-normal collector and cut-off beyond 60 degrees) account for a reduction of the 25 percent effectiveness to approximately 18 percent. Over 8.0 hours the net result is that the net energy collected is 5.86 kwh/m^2 for a horizontal, quasi-equatorial, concentrator type solar collector. The mean daily (clear skies) input of 0.732 kw/m^2 for 8.00 hours was entered into the macro system sizing calculations. This will be reduced by the "clear skies" factor next to be developed.

Cloud Cover Considerations

Since the solar energy collector type selected is of the concentrator (i.e. focused) configuration (the arguments for this are cost and available technology), operation can take place only in direct sunlight. Therefore cloud cover must be minimal commensurate with restraints applied to the macro system, e.g. sea-basing. It is for this reason that desert locations are typically suggested in solar energy conversion proposals. For example, Meinel cites 330 clear days per year for Yuma, Arizona (13) in connection with his recent proposals.

As it turns out, an ocean-borne solar converter such as the subject macro system will not fare nearly this well as becomes evident in examining a marine climatic atlas (14). Such an atlas can be used to develop a "clear skies factor" to be applied to the solar energy characteristics developed in the preceding discussion. Representative results are shown in Figure 7, where the selection of a favorable locale is indicated for the macro system in the mid-Pacific as determined by cloud-cover minimization tactics. The hatched area was found to be contained by the maximum monthly clear skies isopleth over the year as read from the "total cloud cover" charts of (14). (An exception was the month of June, for which the 60 percent isopleth was displaced to the east, as can be noted on the figure.)

The indicated area was then selected as the model for quantifying the clear skies factor whose value was estimated as 0.497, or approximately 50 percent. Geographically, this region is centered at 8°S, 138°W and is about 250 km northeast of the Marquesas Islands. A depth of over 14,000 ft is noted with a mean surface water temperature of about 82°F. The clear skies factor of 0.497 was entered into the sizing calculations.

Macro System Sizing Calculations

The energy and mass-flow characteristics of the macro system were determined on the basis of the foregoing findings (solar energy characteristic, clear skies factor) and the physical characteristics of the constituent systems. This required an estimate of individual system efficiencies, process variables, and associated physical and chemical data for the process fluids and their transformations. These assumptions derived from information made available to the writer in communication with a number of workers in the various fields involved, as well as that from the open literature. However, in the end-analysis the values listed represent only opinion -- hopefully, a reasonably informed one. Two estimates are made, a "current" and a "projected" technology basis.

The scope of the paper does not allow for the details of these assumptions or the calculations to be included here, unfortunately. However Table 1 provides a summary of results. These provide a basis for physically characterizing the macro system, which in turn will provide a baseline for a rough cost assessment.

Conceptualizing the Macro System

Physically, as would be expected for any solar energy converter, the overall macro system layout is dominated by considerations of collector area. The required active collector area for 1000 Mw continuous equivalent liquid hydrogen and oxygen production is 47.3 km^2 (6.88 km square) and 26.9 km^2 (5.19 km square) for the "current" and "projected" bases, respectively (Table 1). The latter is 57 percent of the former. However, the larger "current" technology version will be used as the baseline for conceptualization and costing in the paper in order to bias the results toward a more conservative estimate.

Rounding the 6.88 km on the sides to an even 7.0 km, an obvious geometric arrangement of 49 square modules, each 1.0 km on the side is arrived at. If the central one of these is removed to provide for a "central operations" zone for the macro system, as shown in Figure 8, the total active area is 48 km^2, slightly more than the indicated 47.3 km^2 requirement.

Figure 8 reflects a spacing-out of the modules by a separation of 414 m, enlarging the overall area required by a factor of 2. The reason for this is to provide complete rotational freedom for the individual square modules. Somewhat closer spacing is possible for other than square modules, the limit being reached with circular shaped units whereupon the expansion experienced (Figure 8) can be reduced by about 64 percent. The need for rotational freedom is associated with the characteristic of the solar collector geometry assumed, viz. a two-dimensional reflector.

An individual 1-km square module (designated L-3, for a third level of modular build-up) is conceptualized in Figure 10. This unit is equipped with twenty 100x500 m solar collector modules, referred to as L-1 units, the basic building block of the macro system solar array. Each symmetrical corner of the L-3 module consists of 5 solar collectors and is designated L-2. The overall macro system is thus composed of 48 L-3s, 192 L-2s and 960 L-1s (Figures 8-11).

A five-flotation-point suspension is shown supporting the frame of the basic L-3 1 km^2 module. This places the support points a maximum of 600 m apart which, in view of the much larger spans achieved by bridge builders, seems reasonable. With lightweight structural elements and the use of tension rigging, a minimal-mass structure should be achievable. Any concentrated loads such as machinery, tanks and personnel accomodations can be separately floated below the array or located within the flotation units. The solar collector surface is elevated considerably above the ocean surface to minimize adversities of the ocean-atmosphere interface, such as salt-spray.

On the other hand, the center of mass and wetted volume of the flotation units (spar buoy configuration) is sufficiently deep to be virtually uninfluenced by surface and near-surface wave action. A number of spar-buoy type vessels such as FLIP (15) and MOSES (16), have demonstrated the intrinsic stability afforded by this configuration. Each flotation unit, towed into its assembly point in a horizontal attitude, and erected by ballast control, is equipped with its own propulsion system. Electrical or hydrogen-oxygen (5) powered thrustors will be used to position and stabilize the flotation units, and also to provide azimuthal rotation of the L-3 modules as well as translatory capability (e.g. to counter currents).

An overall "macro-servomechanism" is envisioned to maintain the geometric integrity of the entire macro system without "hard" structural connections. This includes the rotation for sun-tracking (Figure 9), translation of the total array with respect to the ocean body, and maintaining proper inter-modular spacing.

The essential features of the 50,000 m^2 solar collector module (L-1), which is a two-dimensional "trough" paraboloid-of-translation, are represented in Figure 11. Instead of a point-focus, this configuration provides a line-focus of considerably lower intensity. In this application, the focal boiler being of linear design, the geometry is quite compatible with the working fluid flow path as energy is absorbed. It can be seen that, since the module is free only to rotate and translate on a horizontal datum, viz. the ocean, it must be oriented such that the vertical plane containing the sun must also contain the focal line. Hence, continuous rotation of the module to "track" the sun is required. (An exception to this would occur for an equatorial site on the equinoxes). Figure 11 reflects the need for overhanging the focal boiler for full-mirror utilization up to the cut-off angle of 60 degrees. The problem of tracking the sun effectively beyond this angle is apparent in that the amount of overhang becomes quickly impractical, and/or only partial utilization of the mirror can be made. Hence, the "cut-off ruling".

The focal boiler is viewed as basically a linear receiver of focused solar radiation for transferring this energy to the working fluid (provisionally, water). A transparent casing surrounding the metallic or refractory receiver/working-fluid passage may be applicable, in which case a vacuum or inert gas atmosphere can surround the receiver element. An objective is to minimize thermal losses due to reradiation and convection, and to protect the high temperature element from oxidation.

If water is used as the Rankine cycle working fluid, then conventional steam turbine and associated equipment can be employed. There will be an incentive to raise the steam temperature well over the conventional utility-plant levels of 1000-1100 °F, however. This will be set by the focal boiler and turbine temperature capability, with an actively-cooled turbine a distinct possibility at temperatures above 1500 °F or thereabout. The incentive is, of course, increased system efficiency which permits a reduction in hardware size, and hence, costs -- assuming that this is not countered by the more expensive "advanced technology" equipment. In the interest of maximizing efficiency, the use of cold depth water for condenser cooling (41°F vs. 82 °F for the surface water) is very likely, since the gain far outweighs the cost of pumping the water up (favorable implications for marine farming).

Since dc power is required for the water electrolyzers (located in the depths to achieve high pressure gases and cell advantages, without the need for thick wall, expensive structures), generation of dc power by the turbine-generator is highly attractive. The alternative (conventionally done) of rectification of ac power is costly in terms of equipment and some loss of power. Fortunately, the acyclic (homopolar, unipolar) dc generator has this potential in the size range of interest (17).

With regard to the electrolyzers, it would appear that both unipolar (tank type) and bipolar (filter-press configuration) configurations should be examined for applicability; each has characteristic advantages and disadvantages. Applicable references are (18, 19). Depth storage of the hydrogen and oxygen at ambient generation pressure offers economic advantages as discussed for natural gas storage in (20).

The high-pressure (nominally 1500 psi) accumulator is essentially to smooth the flow of gas to the liquefiers and service power unit, and would be minimized for this function, since expensive heavy-walled containers will be required. The liquefaction plants would be of conventional design very likely, but would be so engineered to gain any synergistic benefits from the co-production of hydrogen and oxygen. Cryogenic storage at the surface of the type described in (20) would be located near the docking facility for convenient loading into the cryotankers (Ref. 8).

Macro System Cost Estimate

The macro system was broken down into 17 items of capital cost as listed in Table 2. Based on the anticipated distribution of these components within the macro system (i. e. whether associated with the 1 km modules, or with "central operations"), the number of items and the size were determined and listed. Cost factors, based on communications with specialists as well as open literature assessment were developed. Occasionally these were merely intuitive estimates. Using the "current" technology baseline, a total capital cost estimate was arrived at. To this was added ten percent for installation and testing services. The resulting rough estimate for the macro system was approximately $ 1.5 billion. (See Table 2).

At this level of cost associated with 1000 Mw continuous production of energy, it is of interest to compare the macro system with both present and alternative projected sources of energy. These three bases of comparison were examined, although none expressly matched the macro system's input/output: 1)Conventional electric energy generation systems, 2) Conventional hydrogen and oxygen production plants, and 3) Alternative solar energy utilization schemes which are of the same general scale as the subject one (11, 21, 22).

Summarizing the results of these three comparisons, the cost of energy produced by the macro system is indicated to be significantly higher than those conventional sources of electrical power and cryogenics, a factor of 4 to 5 being observed. On the other hand, the macro system's energy cost fell into the range estimated for representative solar energy alternative approaches, being at the lower or higher end, dependent on whether the end product desired was cryogenic or electrical.

It should be noted that considerable reductions in the macro system's energy costs would seem possible, however, through these principal avenues: 1) Optimized system design, 2) Technology advancements, and 3) Collateral production of salable products to spread costs over a broader revenue base. Further improvements in each of these areas will be complementary, that is, gains will compound one another. Based on the writer's judgement in assessing these potentials, a gross reduction of the cited factor of 4 to 5 is achievable if a number of the potential gains identified qualitatively could be brought to fruition. If so, the macro system would be quite competitive with conventional sources of energy, and considerably better than the alternative solar energy proposals. However, the depth of the investigation to date is not sufficient to make this other than a surmise.

Concluding Remarks

This paper has introduced and discussed yet another approach for harnessing solar energy directly (Ref. 11, 21, 22). Its novel approach of open-seas basing may offer substantial advantages over land-basing as in previous proposals. Sea-basing also embraces problems peculiar to the nautical environment, with a significantly lower clear skies factor than can be had in a desert location. Other concerns with forseen difficulties in locating a large solar array on the ocean may be countered through judicious marine engineering approaches, particularly that of oceanographic stable platforms (14, 15). It does appear that the concept of locating a stabilized, reasonably long-lived solar collector and attendant component systems of the subject macro system on the open sea is supportable.

But in at least an emotional way, the single most distracting characteristic of a solar utilization scheme of the magnitude presented is the enormous proportions of the solar collector. This is a reflection of the innate nature of the solar energy intensity at the Earth and it cannot be altered. At best, we can move the array into near-Earth space as proposed by Glaser (11) to maximize exposure duration and to eliminate atmospheric attenuation.

The approach taken here in view of the intrinsic collector area problem is straightforward: 1) Select the largest practical solar collector deemed "reasonable", and 2) Incorporate sufficient numbers of these as modules to make up the overall requirement. The objective of minimizing the cost of the collector goes without saying.

If the technical feasibility of the subject concept is accepted, the singular issue is that of energy cost. Although "fuel" cost and the required investment in property are zero, the overall capital cost appear very high by today's utility and chemical industry standards. As a result, energy cost is very high based on the rough assessment performed. But as noted above, there are avenues for cost reductions which are definitely promising. These should be evaluated quantitatively.

What will be perhaps more difficult to evaluate is the dollar-worth of the macro system's "benevolent environmental interaction" characteristic. This, with the fact that no natural resources potentially in short supply are consumed. These two areas of national and global concern must enter into the decision-making process in future energy systems.

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TABLE 1

Results of Macro System Sizing Calculations

Rated Production of Macro System (Daily Basis) (1000 Mw, continuous equivalent)

Liquid Hydrogen	1.34×10^6 lb 670 Tons	0.609×10^6 kg 609 Tons-metric
Liquid Oxygen	10.72×10^6 lb 5360 Tons	4.89×10^6 kg 4890 Tons-metric
Total Cryogenics	12.06×10^6 lb 6030 Tons	5.499×10^6 kg 5499 Tons-metric

Results of Sizing Calculations (Daily Basis)

	Technology Bases	
	"Current"	"Projected"
Hydrogen liquefaction energy	6.03×10^6 kwh	5.36×10^6 kwh
Oxygen liquefaction energy	2.68×10^6 kwh	2.14×10^6 kwh
Hydrogen required for service power	0.405×10^6 kg	0.298×10^6 kg
Oxygen required for service power	3.24×10^6 kg	2.39×10^6 kg
Service power level, continuous	400 Mw	343 Mw
Water to be electrolyzed	9.10×10^6 kg	8.15×10^6 kg
Solar still effective area	2.68×10^6 m^2	1.79×10^6 m^2
Electrolysis energy input	50.0×10^6 kwh	35.8×10^6 kwh
Average power level, 4 hours duty cycle	12.5×10^3 Mw	8.95×10^3 Mw
Peak power level, at local noon	16.6×10^3 Mw	11.9×10^3 Mw
Thermal energy to turbine	105.4×10^6 kwh	67.0×10^6 kwh
Incident solar energy required	137.8×10^6 kwh	78.3×10^6 kwh
Solar collector area required	47.3×10^6 m^2 47.3 km^2 (6.88 km square)	26.9×10^6 m^2 26.9 km^2 (5.19 km square)

TABLE 2

Rough Cost Assessment of Macro System

Item	Requirement	No. Units	Unit Size	Cost Factor	Item Cost Million $
Solar Collector	48 km^2	960	100x500m	$\$5/m^2$	240
Focal Boiler	500 km	960	500 m	$100/m	50
Turbine & Condenser	16,600 Mw (peak)	48	345 Mw	$20/kw	335
Generator, dc	16,600 Mw (peak)	48	345 Mw	$7/kw	115
Electrical Conduits	990,000 Mva-mi	96	0.62 mi	$20/kw	20
Depth water System	$7x10^6$ T/day H_2O	48	36,000 gpm	?	5
Solar Still	$2.7x10^6$ gal/day	--	--	$\$1.00/ft^2$	30
Water Electrolyzer	$560x10^3$ lb/hr, H_2	48	12,000 lb/hr	$150/lb/hr	85
Gas Storage (depth)	$40x10^6$ ft^3 (actual vol.)*	48	$1x10^6$ ft^3	$1.00/gal	50
Gas Accumulator	$40x10^3$ ft^3 (actual vol.)*	1	$40x10^3$ ft^3	?	15
Service Power Unit	400 Mw	1	400 Mw	$100/kw	40
Hydrogen Liquefier	670 T/day	1	670 T/day	$\$25x10^6$ for 250 T/day	55
Oxygen Liquefier	5360 T/day	1	5360 T/day	$8/T/day	45
Cryogenic Storage	$18x10^6$ gal*	1	$18x10^6$ gal	$1.5/gal	30
Flotation Units	5 per L-3 module	240	--	@ $\$1x10^6$	240
Platform Structure	Forms L-3 module	48	1 km^2	@ $\$1x10^6$	50
Docking Facility	"Descartes" class cryo-tanker capability	1	--	@ $\$10x10^6$	10
			Delivered hardware subtotal		1415
Integration, installation & test services (@ 10%)					142
			Total rough cost estimate		$ 1557

Summary: Macro system sized for 1000 Mw continuous equivalent production of the cryogenic hydrogen and oxygen energy form is estimated to cost in the vicinity of $ 1.5 billion. This is for the "current" technology version without system optimization or refinements. No credit is taken for collateral product potentialities. Dollars are "today's".

* Total volumes for both hydrogen and oxygen; storage would be in separate containers.

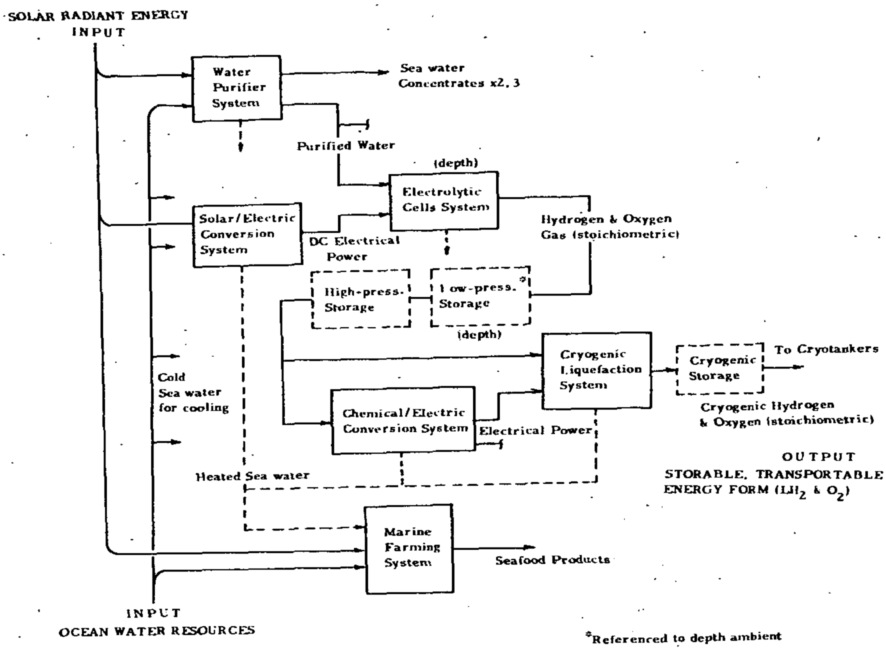

Figure 1 - Block Diagram of Macro System

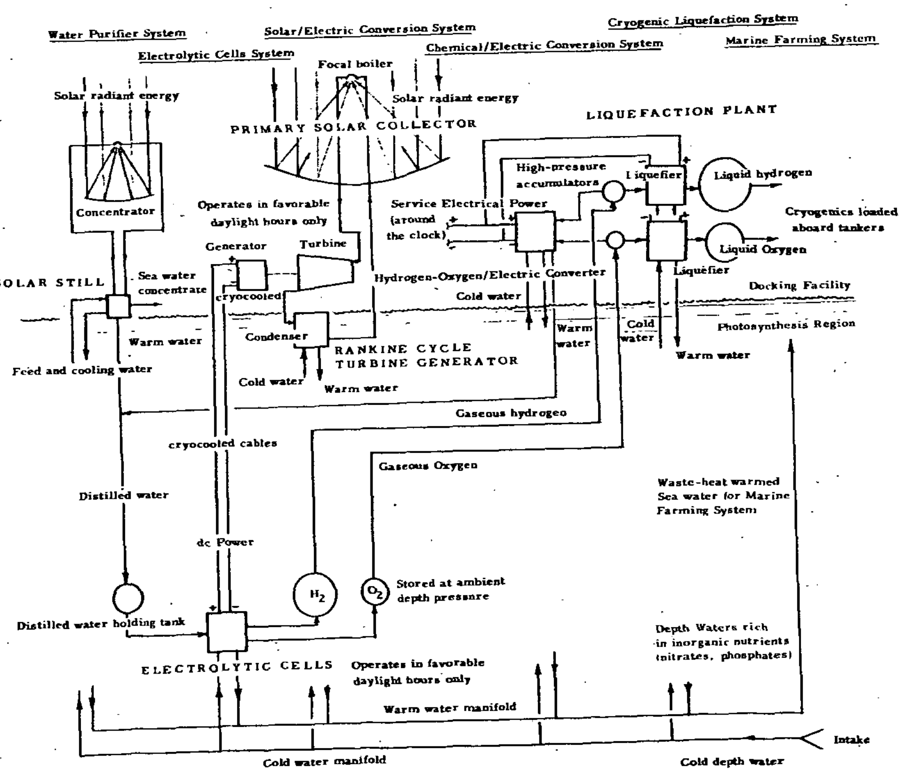

Figure 2 - Pictorial Schematic of Macro System

Figure 3 - Large Liquid Oxygen Storage Container

Figure 4 - Large Liquid Hydrogen Storage Container

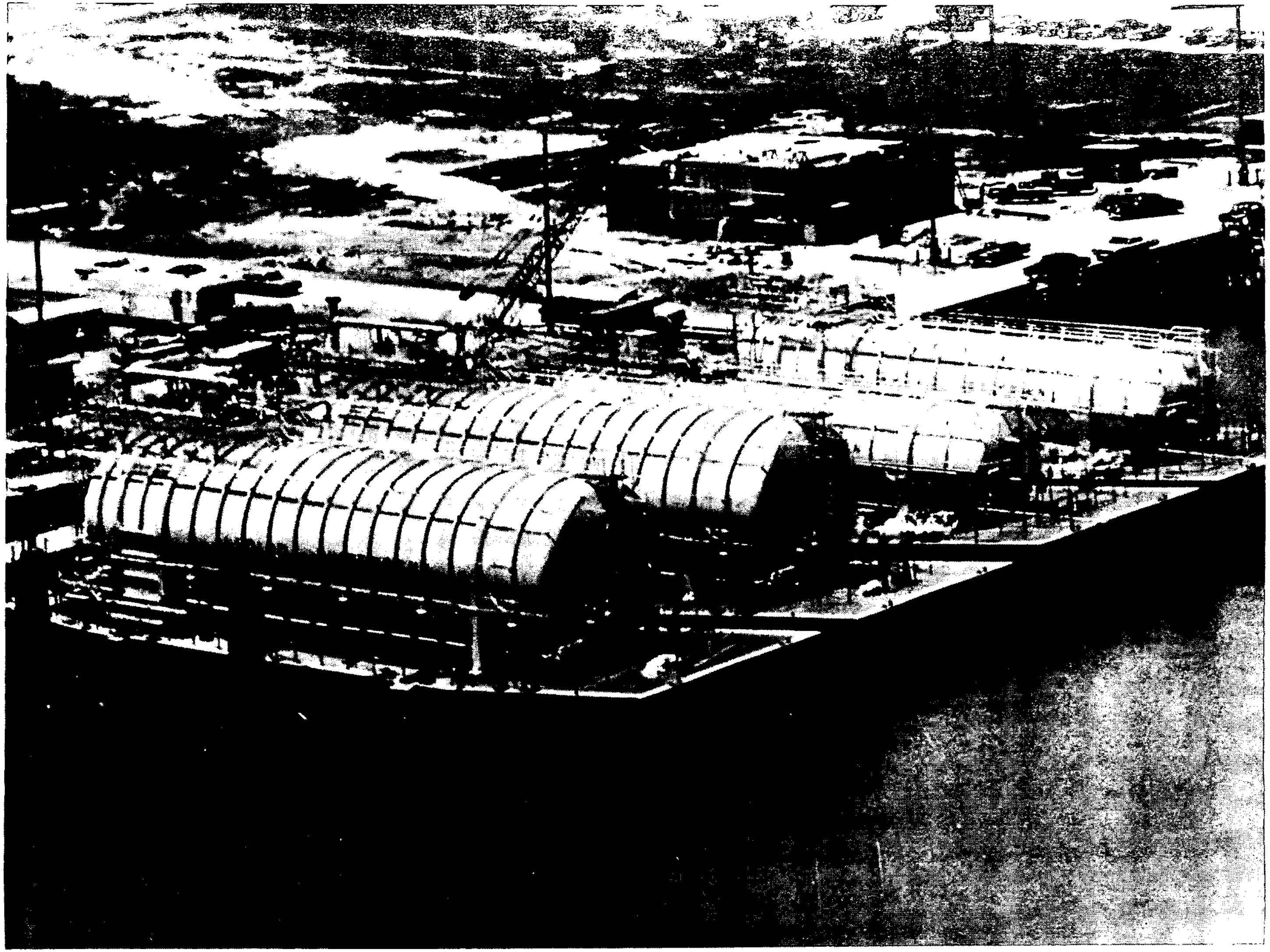

Figure 5 - Liquid Hydrogen (foreground) and Liquid Oxygen (background) Barges

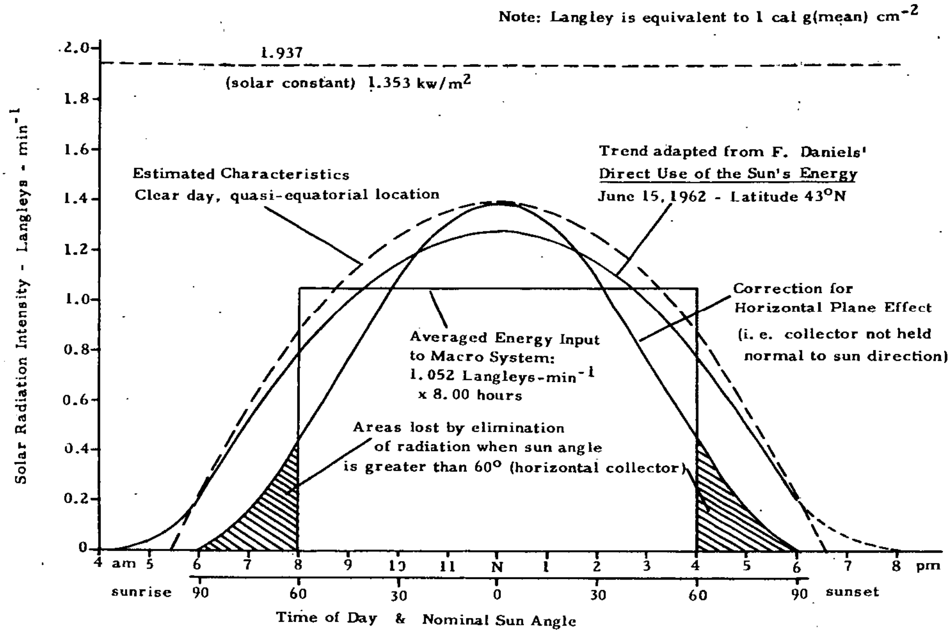

Figure 6 - Solar Energy Diurnal Characteristics

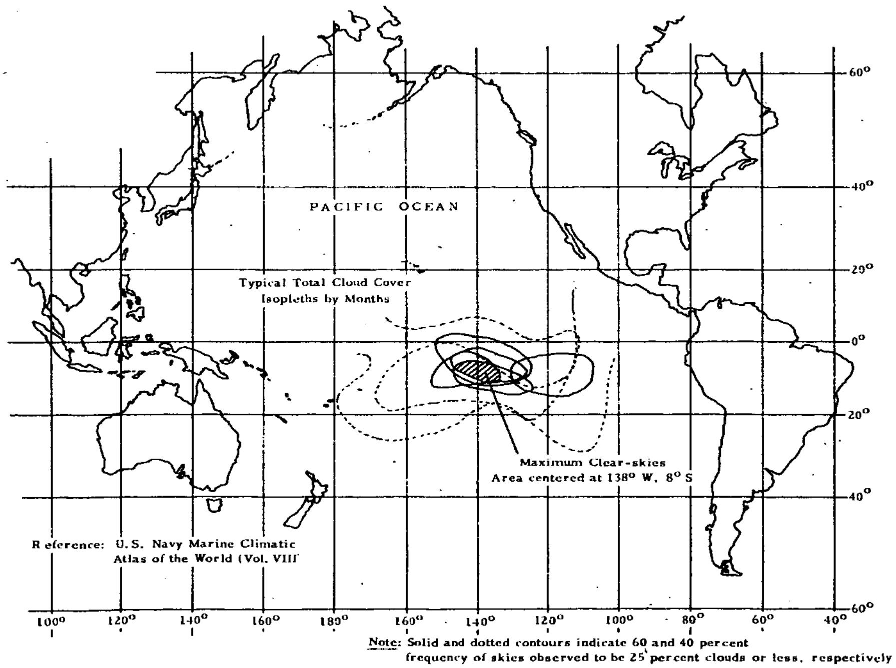

Figure 7 - Cloud Cover Minimization Trends for Mid-Pacific Region

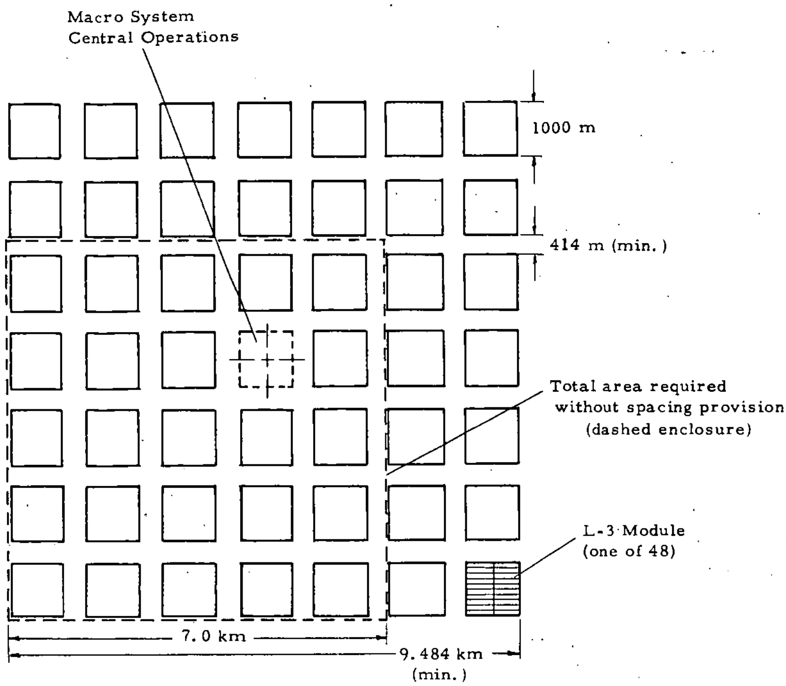

Figure 8 - Representative Overall Layout of Macro System

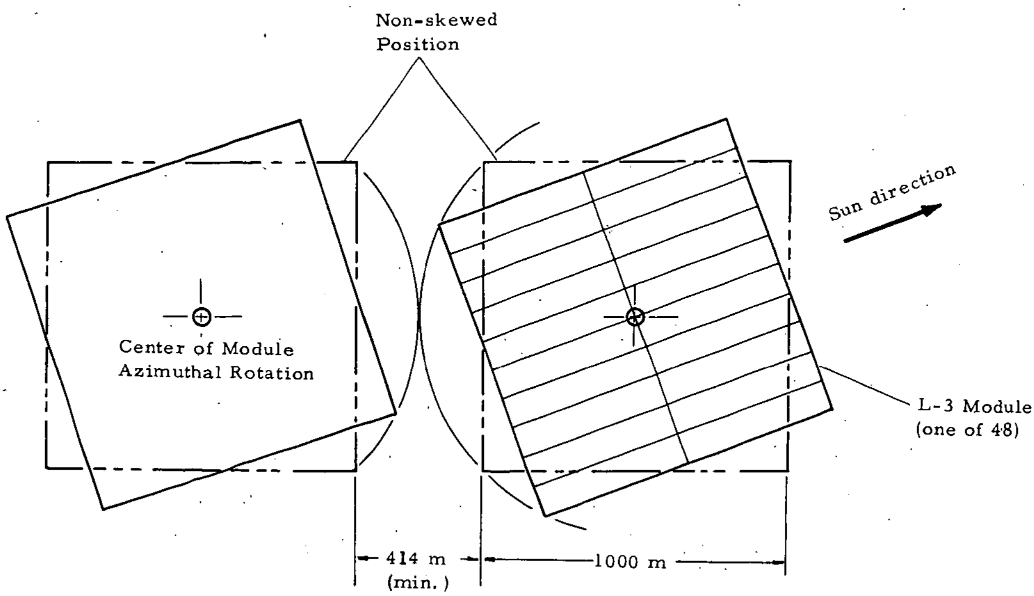

Figure 9 - Spacing Requirements Due to Azimuthal Rotation Capability

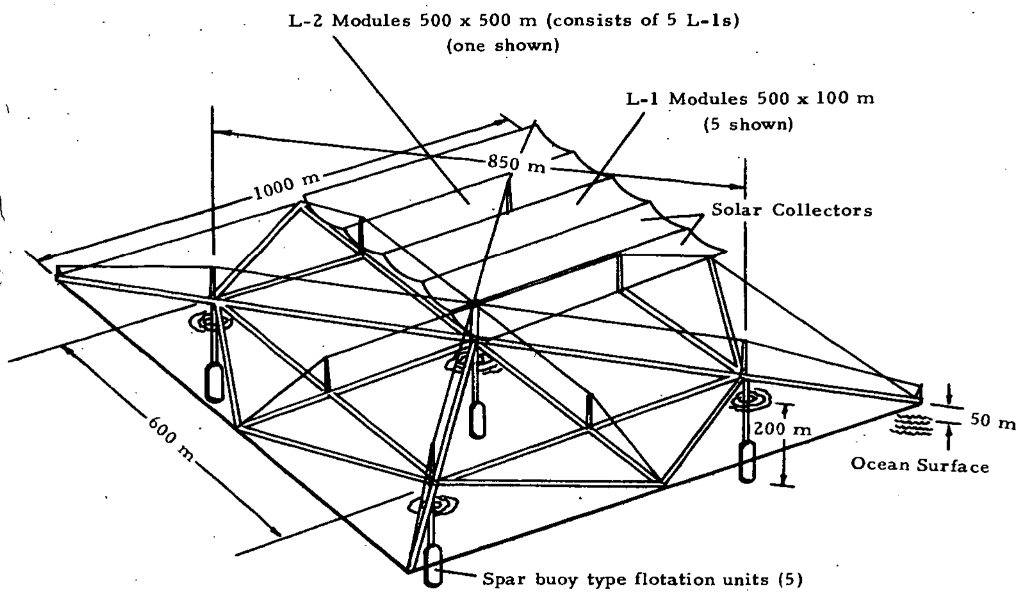

Figure 10 - Conceptual Configuration for Basic Macro System Module (1 of 48)

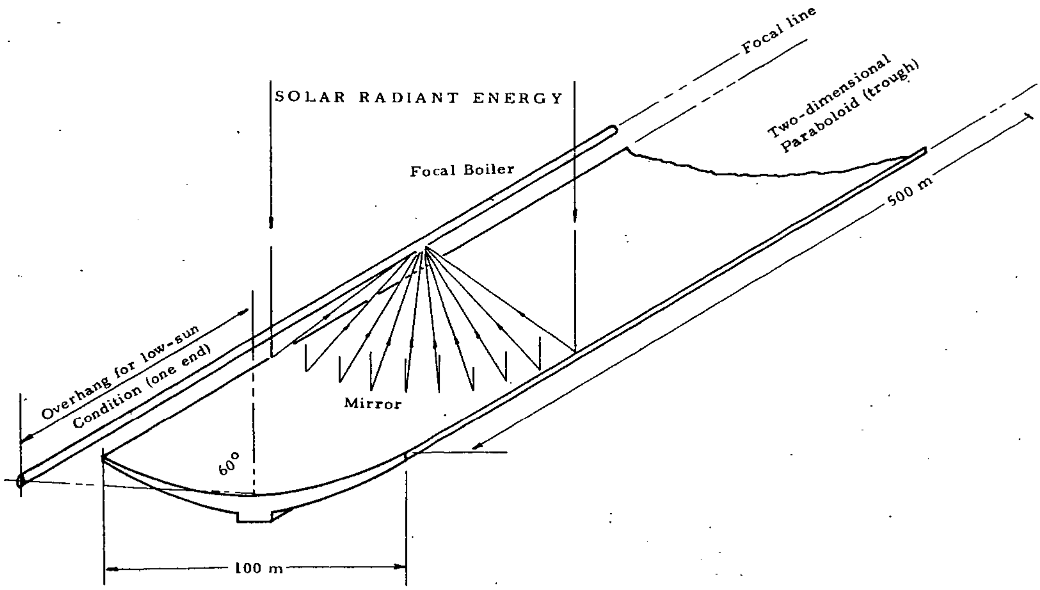

Figure 11 - Basic Geometry of Solar Collector Scheme