THE DUMAND POWER SUPPLY PROBLEM

by

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ABSTRACT

The interaction of the power supply design and the electrical characteristics of the shore cable have led to a review of the characteristics of both. The constraints of maximum reliability and the need to use existing power supply designs lead to the conclusion that the cable resistance should lie in the 40–60 ohm range (which implies an appreciable increase in cost), and the power should reach the array at 350 v., with 5.6 kw available. Only the shunt regulator for 350v should reside in the junction box; the power supplies will be in the SBC's. AC power transmission was reconsidered and ruled out because of unknown dangers from shark bite.

BASIC REQUIREMENTS

At the collaboration meeting of Jan. 1990, it became clear that a major decision was required to complete the design of the DUMAND shore cable. That design depends critically on the requirements placed upon it by the power supplies selected for the array. In particular, the cost of the cable rises rapidly with the amount of copper in the cable, which determines the cable resistance. In any power supply design, the internal impedance of the power source is always a significant factor, and DUMAND is no exception. Furthermore, increasing the copper area – in order to reduce the cable resistance – also increases the cable weight, diameter, and associated handling difficulties. It is thus desirable, insofar as possible, to keep the cable size to a minimum. Fig. 1 shows the estimated cost, resistance, and weight of the cable as a function of its diameter, based on trial designs from George Wilkins.

It is clear that the design of the power supply interacts strongly with the electrical properties of the electro–optical shore cable. Neither the cable design nor the power supply can be independently selected; each strongly affects the other. Thus, the cable as originally designed by Wilkins, to supply a load with a voltage regulation factor (VRF) of unity, has a resistance of 133 ohms. Supplying a 5–kw load over this cable is difficult, if the power must be delivered at a high current. In that case the cable power loss is high, and the shore voltage will have to be high as well, and regulation in the face of a varying load is difficult. A high–resistance cable thus strongly favors a high–voltage, low–current load, for a given power requirement. The design objective is then to strike a reasonable balance among all these requirements and constraints.

Let us now examine the power-supply considerations that affect cable design. The requirements for the DUMAND power supply, in addition to the usual ones of reliability, safety, and minimum cost, include some important operational points.

First, in order to use the cable most efficiently, the decision to supply DC rather than AC power was made some time ago. This means that we restrict ourselves to switching power supplies that convert DC to DC. These are now compact, highly efficient, and highly reliable, so we make no sacrifice in that regard.

CONSTRAINTS ON CABLE AND POWER SUPPLY PARAMETERS.

A major constraint on the power supply design is imposed by the fact that DC-DC power supply systems of the requisite reliability are not commercially available at present for input voltages much over 350 volts. (This is in part due to the fact that this is the output voltage from a 230-volt AC rectifier and filter, and there is little commercial need for higher input voltage supplies, except at much higher power levels than ours.) The absence of such supplies has been confirmed by talks to manufacturers and power supply consultants, both in Hawaii and Kiel. The time and engineering effort required to design a supply, test it, and guarantee its long life and reliability are simply not available, especially since the final cable design must be frozen within a few months.

Reconsideration of AC transmission.

Since the restriction to 350 volts at the ocean end of the cable implies either a relatively expensive redesign of the cable to lower its resistance, or to raise its operating voltage, it is worth while to re-examine the possibility of AC power transmission. The cable insulation, as originally designed, is good for 1970v with a considerable safety margin. Thus a 1250v supply could supply 5.0 kw to the array at an RMS current of 4.0 amp, and a power loss in the cable of only $(4.0)^2 \times 133 = 2.13$ kw. This would make a highly efficient supply. 230v stepdown transformers in the junction box could give us the 350v DC rectified output needed for further DC-DC conversion. (Power distribution to the array from the junction box should be at as high a voltage as possible; the 200m cables from junction box to strings become very heavy and expensive for high currents, as e.g. distribution at 48v.)

The major argument against this solution is the unknown possibility of damage to the cable by sharks (or other ocean inhabitants) who might be attracted by the electromagnetic field of the cable, which has no insulated shield, as in a coaxial cable. There has long been evidence of sensitivity of various organisms (including sharks) to electric and magnetic fields from power lines and power transformers. There is little or no experience with deep–sea unshielded AC power cables, and consequently only guesses are possible concerning the reality or seriousness of this concern. This problem could be eliminated by using an insulated outer conductor on the cable for the return, rather than seawater; but this would greatly increase the cable cost and resistance, and thus nullify the advantage of AC. Because of this uncertainty concerning shark–bite we arbitrarily dismiss this solution, attractive though it appears. (There are also technical arguments against AC transmission, which concern cable losses from current peaks if capacitative–input filters are used; but in view of the objections already raised, we need not concern ourselves with them.)

Additional Constraints.

1. Power failure of a module (either open or short) should not put a string out of commission; and failure of a string should not put the rest of the array out of commission.

2. This implies that the sudden change of power load due to a failure – be it an open or short circuit – must be automatically corrected for, in order to keep the array operating. The automatic correction is necessary both because we will not always have an operator on duty, and in order to prevent damage to the rest of the array by a fault. The same applies to the initial current transients at turn–on and turn–off.

3. As always, maximum reliability strongly favors having no major nodes in the junction box, where a failure can disable the entire array. In the case of the 350v power supply, this seems to be feasible; the power supplies can be in the SBC's and in the individual modules. The common shunt regulator and crowbar can be in the junction box, with suitable standbys.

CABLE DESIGN CONSIDERATIONS.

The required array power is 5.0 kw. At 350v, 5000 watts requires 14.29 amperes to be supplied by the cable.

Now, the smallest, least expensive cable design, originally intended by George Wilkins for a high–voltage supply with a VRF of 1, is less than 10mm in diameter, and has a resistance of 133 ohms. If we attempt to use this cable to supply 14.29 amperes to the array, the voltage drop in it will be 1901 volts, so that the shore power source will have to be 1901 +350 = 2251 volts, which at 14.29 amperes is 32.17 kw., of which over 84% is lost in the cable, and for which, at $.09 per kwh, a year's supply of 6000 hours would cost $17,400. (There is another constraint on this high-resistance cable, whose great virtue is its small size: if we need to use 2251 volts input to it, the thickness of the dielectric, which is rated at 1970 volts/mm, will have to be raised from 1.0 mm, its present value, to 1.15 mm, to stay within the rating.)

Fig. 2 shows the input power and annual operating cost as a function of cable resistance for the single 350v. power supply. The highest resistance cable that keeps the source voltage to 1970v or less, for a drain of 14.29a, is 113 ohms; it is the highest resistance we can use that keeps the 1.0mm dielectric thickness. Using this value would rule out any possible future increase of array current. Lower values are worth investigating, however, to see whether the advantages they offer may not compensate for the additional cable cost they require.

POWER SUPPLIES IN SERIES.

One obvious method for reducing cable current, with supplies that are designed for 350 volts input, is to put two power supplies in series, thus increasing the output voltage to the array to 700v, and correspondingly cutting the current in half to maintain the same 5000 watt load. For a high-resistance source like the 133-ohm cable, this is a much better match. The cable voltage drop is now 951 volts, half of what it was, and the power loss only a quarter. We now demand a power source of 1651 volts at 7.15a or 11.8 kw, which will cost us only $7.15K/yr, and is well within the voltage allowance of the minimum diameter cable. The input power and annual cost vs. cable resistance are shown for this system in Fig. 3. (It can be shown (see Appendix) that for reasons of stability this economical solution is infeasible for the 133-ohm cable; but by then it will have been ruled out on other grounds.)

Unfortunately, putting power supplies in series has two major disadvantages. One is that it is considerably more complex; one must take pains to keep the loads balanced, and we have roughly doubled the amount of equipment.

The other is even more serious. If we do not use a single 700v supply in the junction box – a highly disagreeable choice from the standpoint of system reliability – but instead put several (lower-power) supplies in series in each SBC, we find ourselves with the problem of keeping all the power supplies operating independently even though they are strongly coupled together. It is not trivial to keep series supplies operating properly when each has an independent load, as they would in this case – one of them supplying the string, the others the SBC. It may well be possible to design power supplies for such operation; series power supplies have been successfully used occasionally. It does not appear possible, according to our present information, to obtain such power supplies off-the-shelf. It may be that further investigation of this point is warranted.

This problem does not arise if we use 350v supplies in each SBC. For reasons of stability (see Appendix), we need to have a common regulator for this voltage, which clearly belongs in the junction box. Having supplied this, we can now regard the shore supply, cable and regulator as a fine low impedance source which is (within limits) relatively impervious to load changes.

Thus, with series supplies, we find ourselves constrained to put them into the junction box. If we make the output of each 175v, and put their outputs in series, we can then distribute 350v to all the SBC's, and run the SBC supplies independently in parallel, just as we would with a 350v supply. The load division problem is then restricted to the two JB supplies which have series inputs and series outputs, and load division should be possible to maintain.

It is thus technically possible to use either solution; the chief argument in favor of the 700v series supply solution is its economy in cable construction. The chief argument against it is the added vulnerability to total system failure of having a complex major component at the junction box node. This is a sufficient argument; there is no need to consider additional ones.

These solutions have one important property in common; they would both benefit greatly from a reduction of the shore cable resistance from 133 ohms to something around 60 or below: 40 ohms has become an unofficial value espoused by both Kiel and Hawaii advocates.

OTHER CONSIDERATIONS

Just what does a reduction of the cable resistance to the 40–60 ohm range cost us? Fig. 1 shows the direct cost of the cable and the increase in weight, which makes handling problems somewhat more difficult in deployment. Against this we have a reduced operating cost – a much bigger saving for the 350v solution than for the 700v one. Since this does not make up for the increased out-of-pocket initial cable cost, we ask what other advantages does it give. To answer this we must carefully examine the other operating requirements of the array.

Figs. 2 and 3 show the power consumption and power cost for 350v and 700 v supplies, respectively. The latter is clearly more economical.

Fig. 4 shows the load line for a 133-ohm cable (which, we recall, was intended for a much higher input voltage supply) operating with a source voltage of 2251 volts, as required by the 350v 5000w load. The load line of a 5000-watt load is also shown; it is a hyperbola. The two intersections of the two lines are both mathematically possible; but the higher-voltage one is not feasible, since the load voltage is too high. Load lines are also shown for 40- and 60-ohm cables. In each case there are two intersections of the load line and the 5000-watt hyperbola; although the higher voltage intersection is stable as long as the VRF remains well above one, we restrict ourselves to the lower voltage case, and rely on a careful design of the shunt regulator to stabilize the operating point.

Fig. 5 is a similar diagram for a 700v load on the shore cable. Of the two intersections of the load lines with the 5000w hyperbola, we note that the 40- and 60-ohm load lines operate at the stable higher-voltage intersection, while the 133-ohm line, nearly tangent to the hyperbola, operates at the lower one. As shown in the appendix, the operating point is stable for the lower resistance cables, but unstable for the 133-ohm.

VOLTAGE REGULATION

The operating point we have selected, of 350v, 14.29 amps, is readily stabilized by a shunt regulator and crowbar. If the line voltage rises, the shunt regulator increases the current drain until the voltage drops to its proper value; conversely, if it falls, the regulator decreases the current drain to restore the operating voltage. The single shunt regulator thus controls the input voltages on all nine strings. The crowbar is a voltage-limiting SCR that prevents the input voltage from exceeding the maximum safe value, should the shunt regulator lose control.

The shunt regulator will work only over a limited range. If the load varies a large amount – e.g. if we turn off half the strings, then, to avoid overheating the regulator, there should be a return signal from the junction box to the shore power supply to tell it to reduce the cable input voltage to the value appropriate for the new value of the current drain. Such a sense signal can be transmitted via the C2 optical link. This is necessary to keep the regulator operating within its safe current limits. Note that if the shunt regulator current drops – even instantaneously – to zero, the negative impedance of the operating point will cause the system to immediately collapse to zero input voltage.

Figs. 6 and 7 show the operation of the 350v system under different conditions of load, as the number of strings changes from 1 to 9. Fig. 6 shows the delivered string power and input power as a function of the number of strings. Fig. 7 shows the total array current and the regulator current, as well as the source voltage, as a function of the number of strings. Fig. 8 shows the operating points of the system for 3- and 9-string operation. Fig. 9 is a table summarizing the power supply characteristics for both 350v and 700v supplies.

JUNCTION BOX ENVIRONMENTAL MODULE

We have not discussed the environmental module attached to the junction box, since its design is still nebulous. There are some features that deserve mention, however. If the module is to contain a low-light-level TV system, it must also include a light for illuminating the scene. In the ocean one needs lots of light. The power for the light may well be as large as a kilowatt. Of course, when the light is on, the strings have to be turned off, so that this is not an additional power drain but an alternative one. The power requirements for the other instruments are not likely to exceed 100 watts. Until the contents of the EM are better known, its power supply cannot be determined.

The EM is a convenient location for returning, via the C^2 optical link, the sensing signal from the JB regulator.

MAXIMUM DELIVERABLE POWER.

For any given value of dielectric thickness there will be a limiting source voltage; for 1mm, the present value, it is 1970 volts. For a given cable resistance and a fixed voltage - 350v in our case - delivered to the load, we can calculate the maximum current and power that can be delivered. They are as follows:

Cable Res. ohms	Max delivered power, kw	Source power, kw
117	5.0	20.15
60	9.45	53.2
40	14.2	79.8

OVERALL POWER SYSTEM LAYOUT

Fig. 10 shows a block diagram of the 350v power system envisaged in this paper. We have assumed a cable in the 40-60 ohm range, thus implicitly increasing the cable cost and weight. Detailed calculations of the true cost of a given resistance choice have not yet been made. They will have to include both cable costs and power equipment savings.

We have not discussed the control system implied by this choice of power supply. It is clear that a rather complex and carefully designed system of fail-safe controls will be required to prevent damage to the major system components and allow complete flexibility in operation.

SUMMARY

We have reviewed the cable and power supply design interactions, and find, because of the 350v maximum input voltage of available supplies, that we need a relatively low-resistance cable – 60 ohms or less. While such a cable is perhaps 20% larger than the minimum for the required 5kw delivered power, it meets the stability and reliabililty needs of the array power system. The design chosen also has good flexibility; if future power needs at the array increase, the cable can deliver several times the design load (at the price of more power dissipated in the cable.)

ACKNOWLEDGMENTS

This paper represents the work of many DUMAND-associated people. In particular George Wilkins and Kim Born have done innumerable cable design calculations, Peter Koske of Kiel first directed our thinking in the direction of low-voltage input supplies operating at VRF's less than 1.

APPENDIX A.

The question arises as to why a central shunt regulator is required in the JB, when all the power supply loads are themselves regulated. The answer lies in the fact that regulated power supplies are designed to work from variable-voltage sources of zero or low internal impedance. When the input voltage to the regulated supply changes, the regulator portion of the power supply varies its current in such a way as to keep the power to the load constant. However, if the source impedance is not small, this change of current will change the available voltage. If the load line of the source has a flatter slope than the hyperbola representing the constant power load (as in Fig. 4), the source cannot keep up with the required change, in either direction; the operation is therefore intrinsically unstable, and the voltage at the load will either drop to zero or rise until the crowbar shuts it off. (The constant power load line, a hyperbola, does not actually go to infinity at zero voltage for a real load; it turns around and drops to zero.)

The cure, obviously, is to reduce the apparent internal resistance of the source. The dynamic resistance of the fixed load of 5000 watts is given by its slope, which is, since $E = P/I$,

$$dE/dI = -P/I^2 = -R.$$

For the operating point, $E=350$v, $I=14.29$a, and $-R = -24.5$ ohms. If the slope of the source load line is more negative than this (i.e. a higher source internal resistance) the system will be unstable. That is the case for the proposed 60-ohm cable. If the internal impedance of the source is (algebraically) greater than -24.5 ohms, (corresponding to a VRF>1) the system will be stable. Thus a (very expensive) 20-ohm cable would not require a regulator for this operating point. A regulated source has an internal impedance close to zero, and thus the junction box regulator will protect the system as long as the regulator current remains within the operating range. If it falls to zero, the regulator stops working and the current drops to zero. If the load drops far enough, the regulator safe voltage will be exceeded, and a suitable signal to the power source will be needed to reduce the input voltage to the cable; the crowbar will also protect the regulator and array from damage from overvoltage.

We note that for a 700v series supply (see Fig. 5) the operating point is stable for a 40- or 60-ohm cable, but not for 133 ohms.

EXAMPLE

We illustrate with a numerical example the instability of a 60-ohm source with the array load of 5000 watts at 350 volts, 14.29 amps. We take the array load as equivalent to a single regulated supply of these ratings. Thus

$V_{out} = V_{in} - IR$, where R is the cable resistance and V_{in} is held constant. Then

$$dV_{out}/dI = - R$$

Assume the system operating at its nominal values, and an instantaneous voltage rise of 10 volts at the load. Because the source resistance is -60 ohms, there will be a current change $dI = dV/R = 10/-6 = -.1667$a. (The negative resistance is because the load line for the 60-ohm source constrains the current to drop in order to produce a voltage rise.)

The response of the regulated supply to this change can only be to change its current, since it cannot influence the line voltage. Now a regulated supply keeps its output power constant over a wide range of input voltages; this can only be accomplished by varying the input current to keep the power drain constant, or nearly so. Thus the response of the power supply to the voltage increase is to decrease the input current to keep the power drain to 5000 watts. Thus the current drops to 5000/360 = 13.89a., 0.40a below the nominal value.

But now the source impedance makes itself felt: a drop of .40a in source current means a rise of .40 x 60 = 24 volts. The line voltage rises to 374 volts. But at 374 volts, the regulated power supply is constrained to reduce the current to 13.37a to keep the load to 5000 watts. It is now clear that the process is divergent, and the voltage will rise until the crowbar stops it.

An entirely similar process occurs if the initial process is a voltage decrease of 10 volts. In this case the source current increases by 10/60 = .1667a. The regulated supply, now receiving only 340 volts, raises its current to 5000/340 = 14.71a., an excess current of .42a. This in turn drops the line voltage to 350 - .42 x 60 = 324.8v. Again, the process is divergent, and ends up with the voltage dropping to zero.

The reader can readily show, by the same reasoning, that if the cable resistance is less than 24.5 ohms, the process converges, instead of diverging, and the proper operating point is restored. Thus, the junction box regulator serves the function of reducing the source resistance to a low value, and thus allowing stable operation. We note that the case of the cable resistance equalling the source impedance corresponds to a VRF of 1.0, and the operating point we have selected, whose VRF is less than 1, requires a shunt regulator to stabilize it.

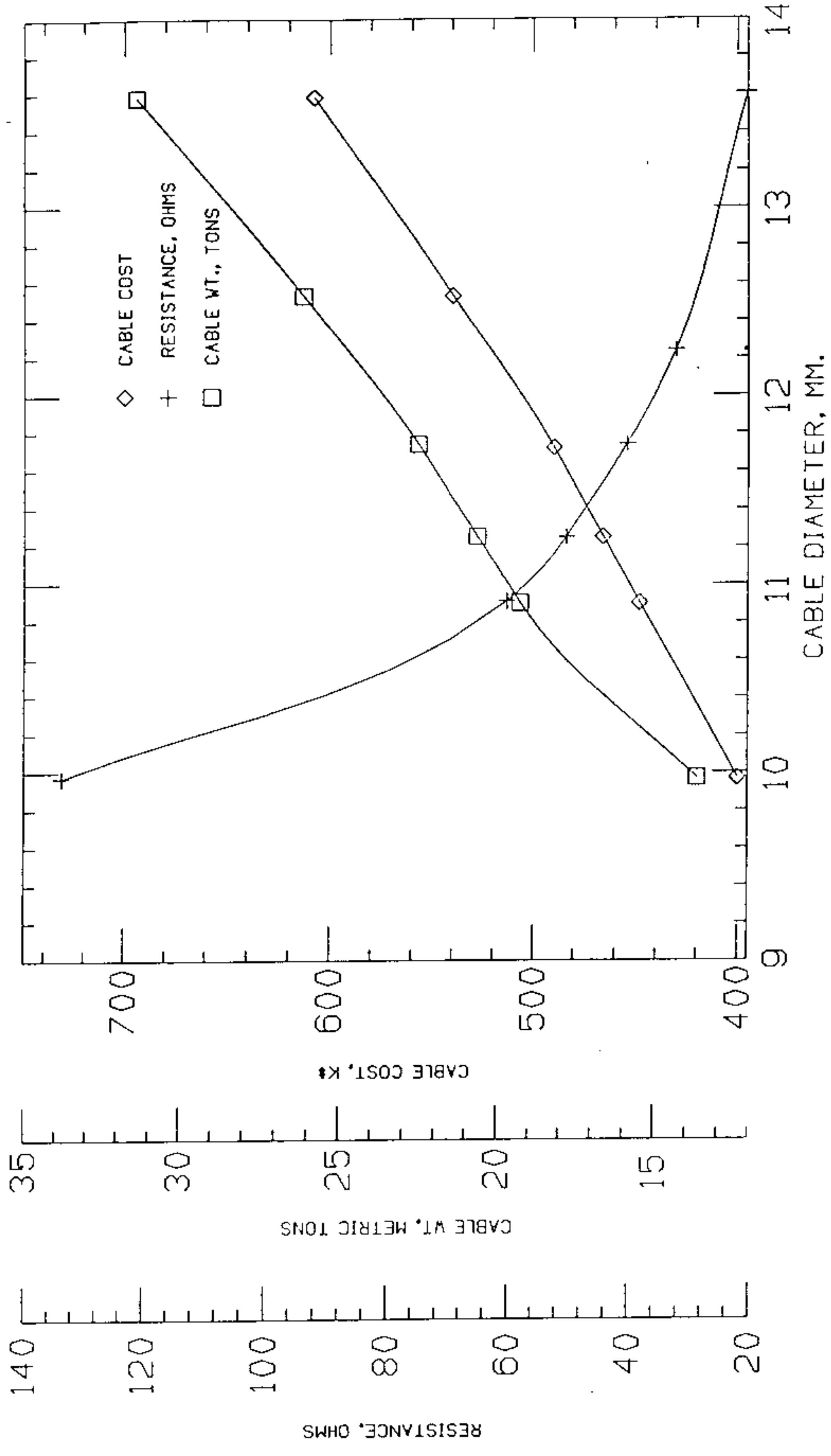

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Fig. 1. Electrical, physical properties of Shore Cable

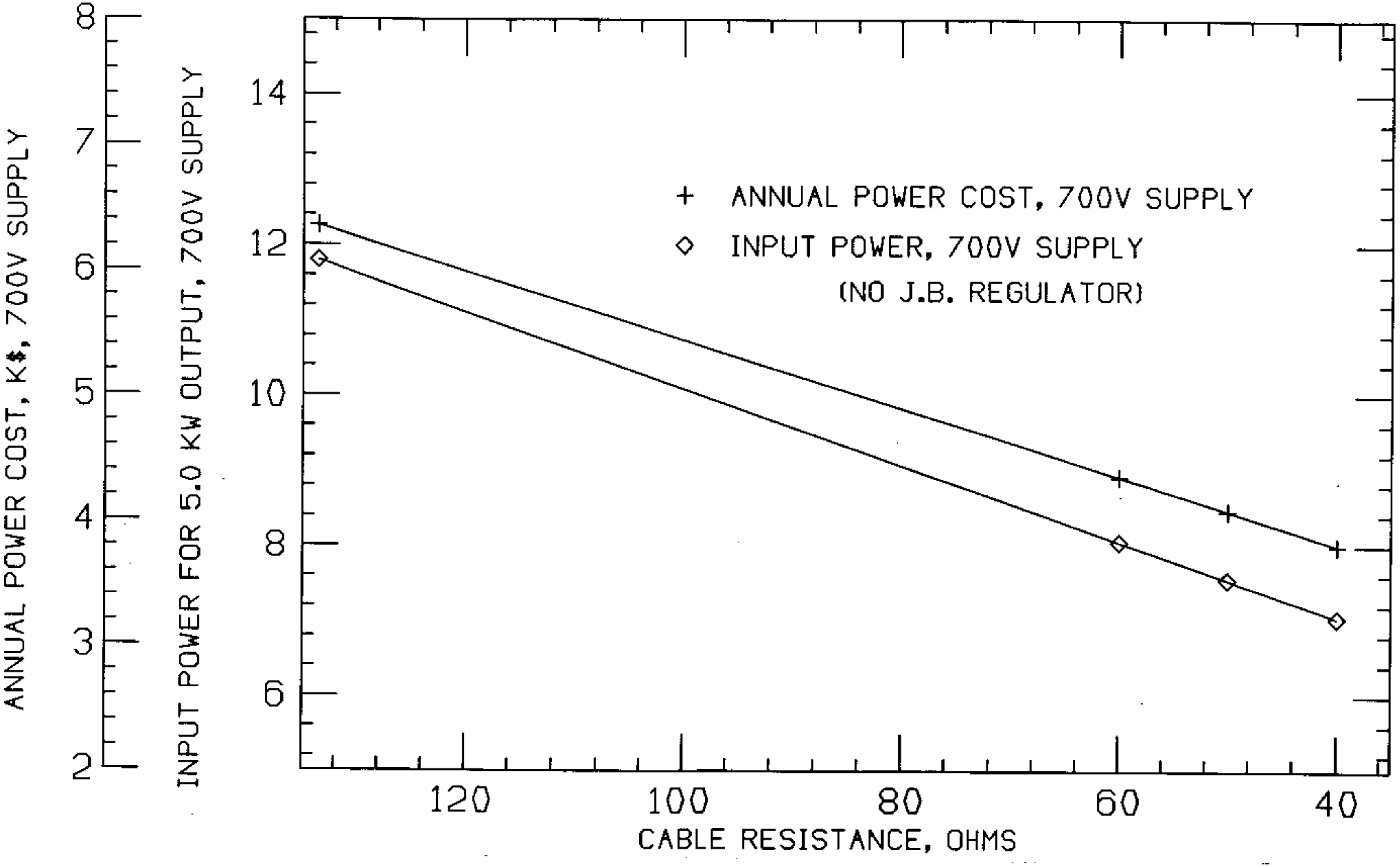

Fig. 3. Power Requirements and cost vs. cable resistance, 700v supply.

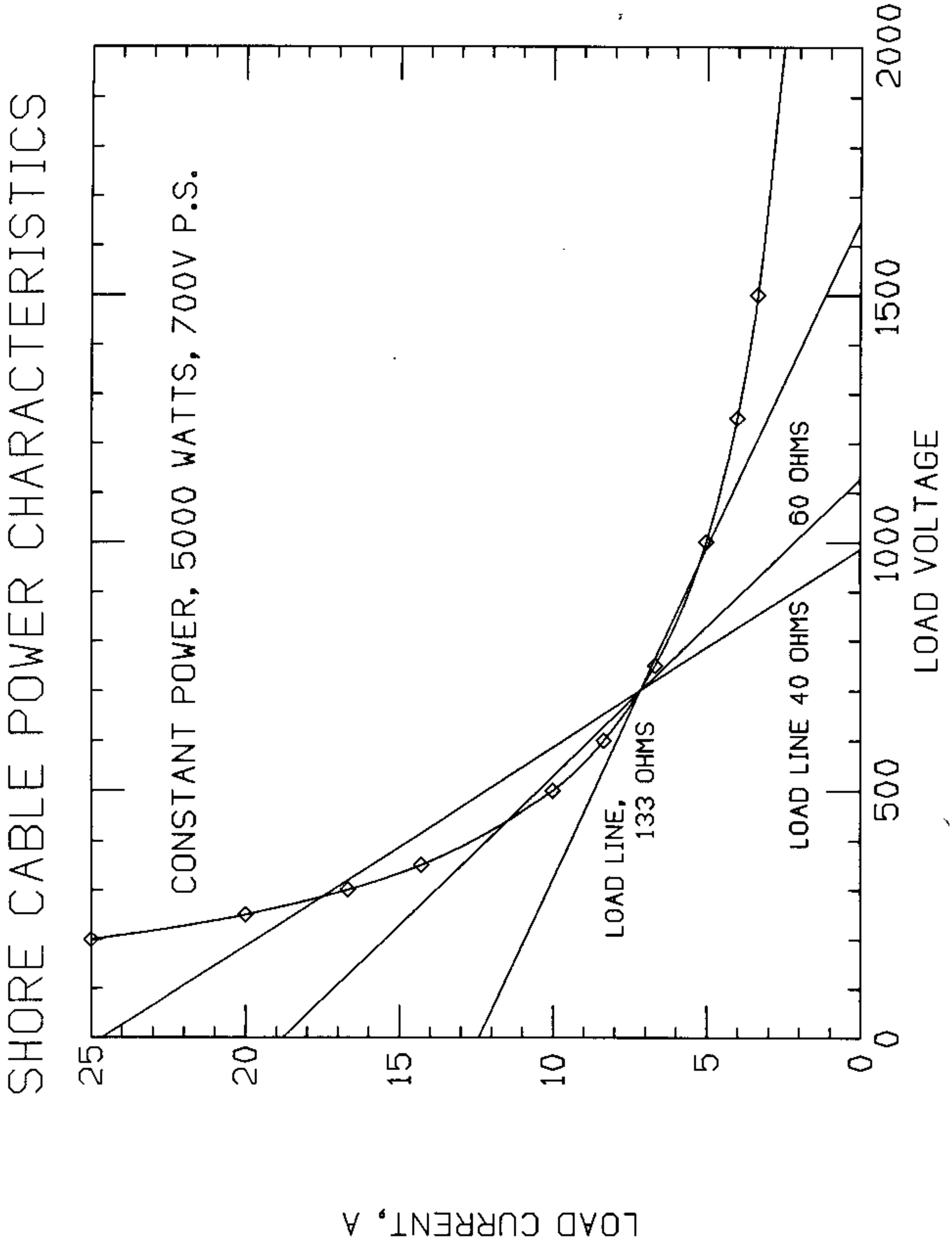

Fig. 5. Shore cable operating characteristics for 700v supply.

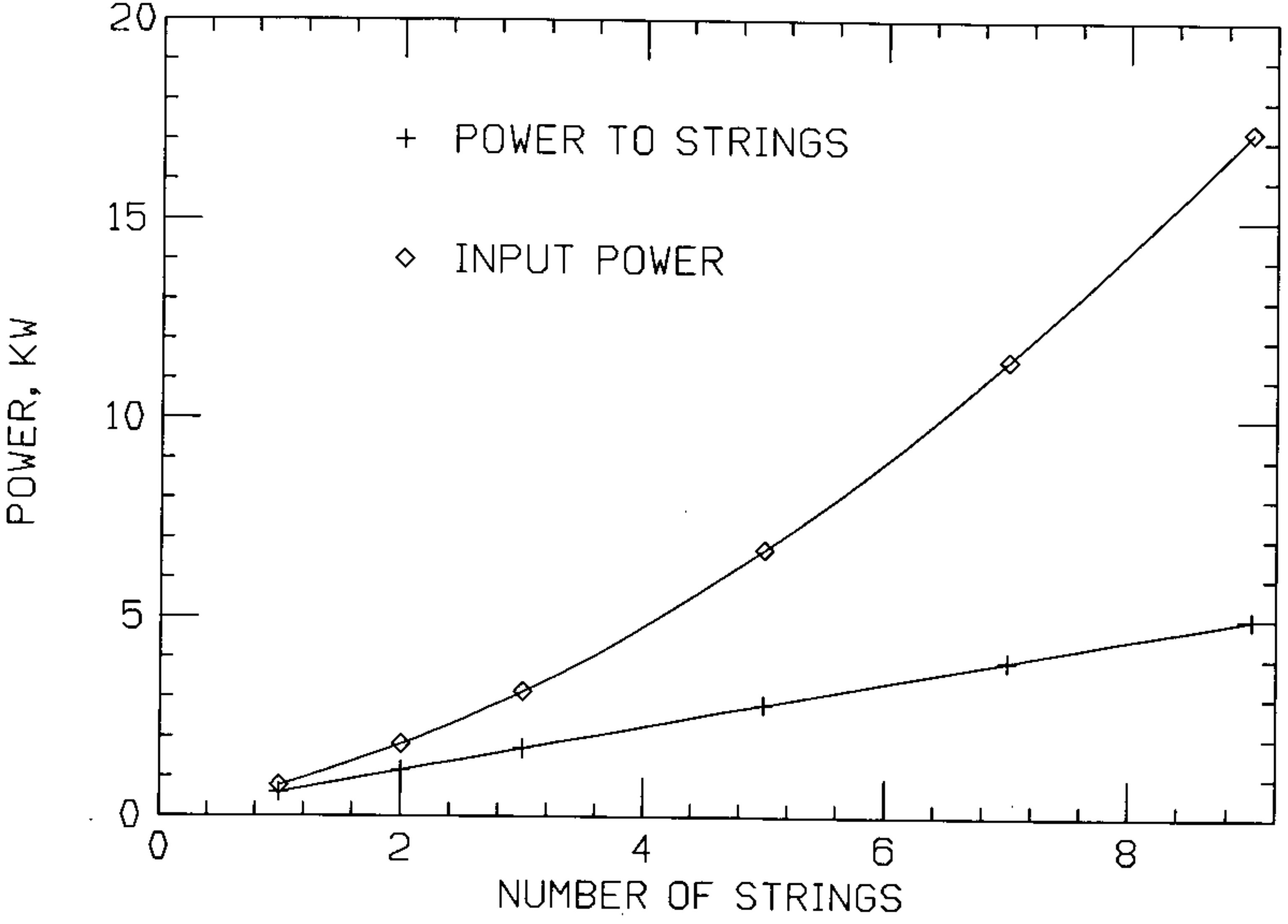

Fig. 6. Input power and power to strings vs. number of strings, 350v supply

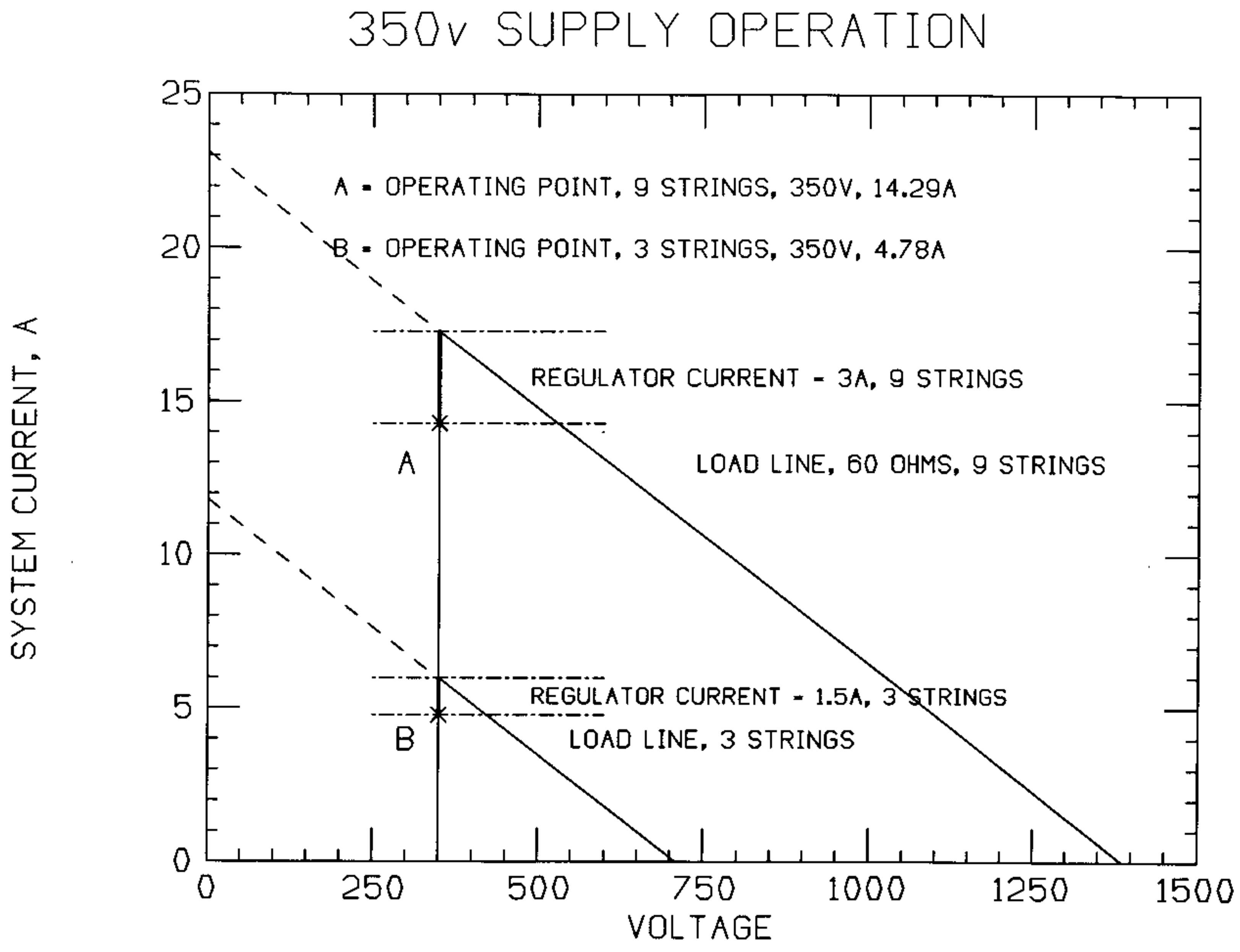

Fig. 8. Operating characteristics of the array, with 3 or 9 strings, showing regulation range.

COMPARISON OF 350- AND 700-V POWER SYSTEMS.

ARRAY POWER	CABLE REQUIREMENTS	EQPT IN JB	POWER OUT
350V 14.29a ca 5.0 kw	Resistance ca. 60 ohms Addnl cable cost ~$50K Source power: 1387v. 17.29a, 24.0 kw.	Crowbar, Voltage reg. (3.0 amp reg. current at full load.)	350v, 5.0 kw
700v 7.15a 5.0 kw; (Two 350v supplies in series.)	Requires <98 ohm cable for stable operation without external regulator. For 60-ohm cable Source power = 986v 9.15a, 9.0 kw.	Two series 350v P.S. plus spares; also crowbar. Voltage reg. optional	350v, 5.0 kw.

Fig. 9. Summary of power supply characteristics.

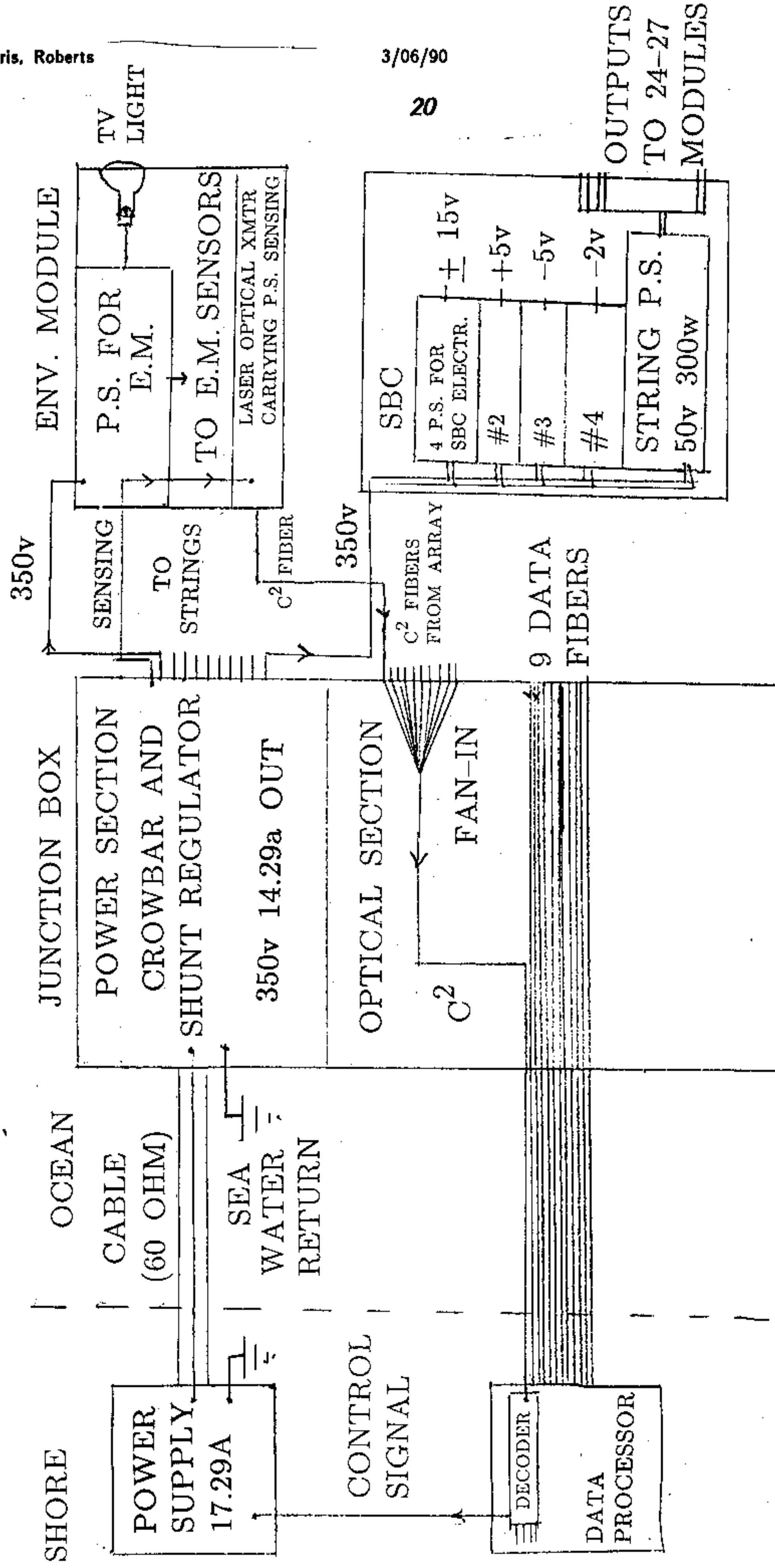

Fig. 10. Tentative Layout of DUMAND Power System