ASSESSMENT OF ECONOMIC FACTORS AFFECTING THE SATELLITE POWER SYSTEM

Volume II

THE SYSTEMS IMPLICATIONS OF RECTENNA SITING ISSUES

final report

CONTRACT NO. NAS8-33002

(NASA-CR-161186) ASSESSMENT OF ECONOMIC FACTORS AFFECTING THE SATELLITE POWER SYSTEM. VOLUME 2: THE SYSTEMS IMPLICATIONS OF RECTENNA SITING ISSUES Final Report (Little (Arthur D.), Inc.) 66 p HC A04/MF G3/44

N79-21552

Unclas

17301

MARCH 8, 1979

Arthur D. Little, Inc.

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VOLUME II

The Systems Implications of Rectenna Siting Issues

Contract No. NAS8-33002

March 1979
Final Report

Prepared by

Arthur D. Little, Inc.
Cambridge, Massachusetts 02140

Prepared for

ECON, Inc.
Princeton, New Jersey 08540

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Arthur D Little, Inc.

THE SYSTEMS IMPLICATIONS OF RECTENNA SITING ISSUES

by

Philip K. Chapman
(Study Manager)
Beverly J. Bugos
Katinka I. Csigi
Peter E. Glaser
Gerald R. Schimke
Richard G. Thomas

Arthur D. Little, Inc.,
Cambridge, Massachusetts

ACKNOWLEDGEMENT

The authors wish to acknowledge the advice and help received from many people interested in the Solar Power Satellite, but especially from Milt Page and Chuck Guttman, Marshall Space Flight Center, Allan Kotin at Kotin Associates in Los Angeles, and Ron Guttmann at Rensselaer Polytechnic Institute.

"So twice five miles of fertile ground
With walls and towers were girdled round:
And there were gardens, bright with sinuous rills,
Where blossomed many an incense-bearing tree ..." S.T. Coleridge

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SUMMARY

The work reported here was a study aimed at evaluating the feasibility of finding potential sites for Solar Power Satellite (SPS) receiving antennas (rectennas) in the continental United States (CONUS), in sufficient numbers to permit the SPS to make a major contribution to U.S. generating facilities, and to give statistical validity to an assessment of the characteristics of such sites and their implications for the design of the SPS system. It is found that the cost-optimum power output of the SPS does not depend on the particular value assigned to the cost per unit area of a rectenna and its site, as along as it is independent of rectenna area. If however it turns out that the total cost of a rectenna is not proportional to its area (because of terrain features, availability of land, etc.) then it is possible that changes in the baseline unit power output of the system would reduce costs. In any case, it is clear that many characteristics of the sites chosen will affect the optimum design of the rectenna itself.

After an examination of a wide variety of factors affecting choice of appropriate rectenna sites, a simple site-selection process was implemented, using fairly readily available data; this resulted in preparation of a list of 100 nominal CONUS sites. Examination of the similarities and differences of these sites led to the following conclusions:

1. There can be little doubt that it will be possible to find a sufficient number of rectenna sites for any conceivable implementation scenario.
2. There is however considerable difficulty in finding appropriate sites in the Northeast and Mid-Atlantic states, not only because of regional differences in terrain but because the best sites have generally been pre-empted by other productive land uses. If it is assumed, as in this study, that the density of rectennas should be roughly proportional to population density, then the problem is compounded because nearly 50% of CONUS rectenna sites should be found in these states.
3. There are a number of options available for dealing with siting difficulties in crowded areas. These include: long transmission lines from more remote sites (mostly west of the Mississippi); construction of rectennas off-shore; rectennas designed for multiple land uses; rectennas built in rough or otherwise undesirable locations, at increased cost; or acceptance of the direct and societal costs of displacing presently productive land uses. Evaluation of the best trade between these options requires more comprehensive study of rectenna engineering.
4. Many different terrain types are found amongst the nominal sites, suggesting that it will not be feasible to design a universally applicable rectenna construction technique. It is recommended that rectennas should be designed in modular form, with commonality at the billboard level, so that the modules can be assembled in a variety of site-specific ways.

It should be noted that the nominal locations in this study were selected only to exemplify generic constraints which might influence engineering design of the solar power satellite or rectenna systems. Many considerations were ignored which were not of direct engineering interest but which might prove essential to actual siting decisions. For these reasons, none of the listed locations should be construed as suggestions as to where rectennas might actually be built, if an when the SPS becomes operational.

CHAPTER I

RECTENNA SITING AND SYSTEM DESIGN OF THE SOLAR POWER SATELLITE

1.1 INTRODUCTION: THE PURPOSE OF THE STUDY

Most studies to date[1,2,3,4] of the Solar Power Satellite (SPS) have concentrated on the engineering issues of system design, because of the need to develop confidence in the technical feasibility of the concept. As in any system study, there has of course been an implicit or explicit set of assumptions about the broad effects of the system on society and on the environment, but these have not generally been regarded as involving parameters which could be varied. The reason for this approach is primarily that the complex of issues related to integration of the SPS into the energy supply of this and other countries towards the end of the century can be evaluated only in terms of the characteristics of the specific SPS design. Accordingly, the system design effort, which is continuing under NASA sponsorship, has been directed towards setting up a baseline SPS design which can be used as an input in societal and ecological studies of the type which have recently been funded by the Department of Energy (DOE)[5].

In many cases, it is however impossible to make a clean separation between engineering design issues and broader concerns. In particular, the choice of even such basic parameters as the unit power output of the SPS may result in sub-optimal values if the interfaces between the system, the electric utilities which market the energy generated, and the eventual consumers are taken as given, not subject to change when system design parameters change. Conversely, those concerned with broader impacts of the SPS may draw unnecessarily adverse conclusions if they regard the baseline system as immutable.

The principal objective of the present study was to explore the relationship between the problems involved in finding suitable sites for SPS receiving antennas (rectennas) and the system design. Rectenna siting, like that for any major energy facility, entails a host of complicated considerations, ranging from environmental impact analysis to local economic and demographic effects, engineering aspects, regulatory problems, and even political and ideological issues: most of these are unsuited to useful discussion in the abstract. For this reason, and to ensure maximum realism in the results, the approach chosen here was to undertake the task of selecting a set of nominal rectenna sites in the continental United States (CONUS), based on as nearly objective a selection process as possible; the sites found could then be examined to see whether they exhibited common characteristics, or a wide variation in characteristics, which might have an effect on the system design of the on-orbit (satellite) or ground (rectenna) parts of SPS. In making site selections, the preliminary assumption, perhaps subject to change in the light of the study, was that each SPS was designed to deliver five gigawatts (5 GW) to its terrestrial power grid. The number of sites selected in CONUS was one hundred, a number chosen both to give some statistical validity to the results and to represent a total installed capacity which was not unreasonable in terms of possible SPS market penetration.

It must be emphasized that *the purpose of the present study was* **not** *to identify potential sites which might be recommended for actual installation of rectennas.* As discussed in Chapter III, preliminary screening of sites was carried out using a short list of selection criteria, those

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which seemed most likely to be significant in terms of the objectives of *this* study — i.e., those which might have the most effect on SPS system design. Many questions which might be very important in choosing actual rectenna sites were deliberately ignored in preliminary screening, being taken into account, if at all, only in the *ex post facto* examination of chosen sites. A more complex selection process, or one intended to elucidate other issues (e.g., public acceptance of rectennas) could and probably would lead to a quite distinct set of sites from those presented here. However, it is unlikely that the implications for SPS system design, drawn from such a selection, would differ very significantly from those obtained here.

As an example, one of the issues *not* taken into account in the screening process was that of radio-frequency interference (RFI) with systems in the vicinity of the rectenna. The microwave flux levels from the SPS power beam at the periphery of the rectenna site are designed to be low enough to meet applicable standards for long-term exposure of biota, but there is no doubt that they are high enough to threaten serious RFI with local communications equipment, radar, etc., especially those which operate at S-band (although it should be noted that the lead time for development of the SPS is such that nearly all presently existing equipment of this type will have been replaced before the system is operational, and thus it would be possible to minimize the RFI-sensitivity of equipment near potential rectenna sites). The RFI problem may well be serious for the SPS, but it seems very unlikely that it will be solved *by system design,* for this would entail heroic measures — getting the first few side lobes of the power beam down to communications levels might require major increases in the diameter of the SPS transmitting antenna, phase- as well as amplitude-taper across the transmitting aperture, and substantial improvements in phase control. It is almost certainly more cost-effective to attack the problem by some combination of (i) choosing rectenna sites away from major concentrations of RFI-sensitive equipment; (ii) designing new equipment which must be installed near rectennas to be insensitive to SPS RFI; and (iii) establishing RFI easements in zones around rectennas, such that all activities would be permitted but freedom from RFI would not be guaranteed. If this be true, two sites which differ only in the present concentrations of RFI-sensitive equipment near them are *identical* from the viewpoint of the SPS system designer which was adopted in this study.

There were three reasons for restricting the screening criteria in this way: (i) it was necessary to limit the scope of the investigation to make it manageable within available resources and to allow focussing on the relationship between rectenna siting and system design, an important subject. (ii) These limits conform to established policy regarding DOE and NASA SPS study responsibilities. (iii) In the present state of knowledge regarding the SPS, an attempt to construct a thorough screening procedure for rectenna sites would be of dubious realism and, at most, temporary utility.

Ideally, it might be supposed that one could set up an exhaustive list of rectenna siting criteria, together with an objective procedure for applying them. If a sufficiently extensive CONUS data base were available, detailed to the level of tens of square kilometers, one might then hope to define unambiguously the hundred (or more, as required) best rectenna sites. It should be apparent, however, that such a process is impossible, even in principle, firstly because many siting criteria are incommensurable (the problem of trading economic, ecological, societal and aesthetic costs is common to many major projects, especially in energy technologies), and secondly because there is rarely consensus about the relative weight to be given different criteria, even when the penalties can be expressed in similar units. These difficulties are hardly unique to the SPS: the democratic process can be regarded as a mechanism for dealing with such situations.

It is virtually certain that, in practice, rectenna sites will not be chosen as a result of a comprehensive national planning process, but instead will be selected on a case-by-case basis, as sites for other energy facilities have been. The first rectenna will presumably be installed in some location where the balance between perceived benefits, or costs of the SPS system, and costs of alternative energy supplies is particularly (but not necessarily maximally) favorable — somewhere in the Southwest is a good guess, near a major load center. Later rectennas will be built as demand dictates, the particular sites being selected in the final analysis by an essentially political process in which such factors as the charisma of leading proponents and opponents may be as important as the economic or technical considerations.

A national rectenna siting plan would also be premature because it is very probable that technical developments will change the basis for decisions. For example, present indications[6] are that the ionospheric microwave flux density limit to avoid thermal runaway may be significantly higher than the baseline assumption of 230 W/m^2; if it is increased, the rectenna area required for a 5 GW system will be reduced in proportion, making it easier to find sites. As another example, rectenna designs may be developed which not only "sit lightly on the land," but permit such multiple uses (e.g., a greenhouse under the rectenna in desert areas) that the local desirability of a site is greatly improved, compared to that for the baseline rectenna design.

As long as it is recognized as essentially a paper exercise, development of a national siting plan, with updates as conditions change, could serve the useful purpose of determining whether siting constraints impose limits to projected SPS capacity growth scenarios. Moreover, it might eventually provide a rational framework for evaluating the national impact of siting decisions, as well as a tool for educating decision-makers and the public about the trade-offs involved. Before undertaking such a plan, it is however recommended that the realism of a proposed siting procedure be assessed by undertaking a detailed study of a specific proposed site, including preparation of a full Environmental Impact Statement (EIS) and development of construction plans and costs. A serious evaluation of a rectenna site of medium difficulty (e.g., in the Mid-West) could provide a wealth of new and realistic information about site selection criteria as well as rectenna engineering.

In any case, it is reiterated that development of a national rectenna siting plan and/or detailed evaluation of a particular site are both beyond the scope of this study. In choosing specific sites for inclusion, it was often found that realism required judgment rather than the blind application of a rating system, and the basis for that judgment undoubtedly involved conceptions (if not prejudices) about issues not directly related to system engineering. Moreover, it is to be hoped that the results of the study will be useful, at least as statistical indications or rectenna site characteristics, to the broader SPS community: until a more thorough study is available, it would perhaps not be unreasonable to use the sites listed herein as a "strawman" set in assessing other problem areas (for example, in evaluating the impact of the RFI problem). In any such use, it is however essential to bear in mind that the nominal locations in this report have been selected only to exemplify generic constraints which may influence engineering design of the SPS or rectenna. No claim is made regarding the suitability of any particular site as actually representing a potential rectenna location. Failure to observe this important caveat can result in misinterpretation or misuse of the data.

1.2 SYSTEM IMPLICATIONS OF RECTENNA SITING CONSTRAINTS

1.2.1 Unit Power Output.

In most studies to date, the cost-optimum power output of the SPS has been determined quite simply by diffraction limits to the microwave power transmission system (MPTS) and flux density limits at the transmitting antenna and in the ionosphere. The power delivered at the utility grid may be expressed in the following forms

$$P_o = \eta_1 I_r A_r = \eta_1 \eta_2 I_t A_t \quad (1.1)$$

where

- η_1 is the power conversion efficiency of the rectenna, including reflection losses, etc.
- I_r is the average microwave flux density in the beam near the rectenna (or in the ionosphere).
- A_r is the projected area of the rectenna, perpendicular to the beam.
- η_2 is the fraction of the transmitted power which is intercepted by the rectenna.
- I_t is the average microwave flux density at the aperture of the transmitting antenna.
- A_t is the area of the transmitting antenna.

A_r and A_t are not entirely independent – the diffraction-limited relationship is

$$A_r A_t = A_o^2 = \left(\frac{\pi}{4} k\lambda x\right)^2 \quad (1.2)$$

where λ is the wavelength of the radiation, x is the distance from the satellite to the rectenna, and k is a constant which depends on the transmitting antenna power taper and the fraction of the total beam power which is intercepted by the rectenna. Since the wavelength is fixed by other constraints (transparency of the atmosphere and availability of microwave components), A_o may be taken as a constant. Using [1.2] in [1.1] then gives

$$P_o = \eta_1 A_o (\eta_2 I_r I_t)^{1/2} \quad (1.3)$$

$$A_t = A_o (I_r/\eta_2 I_t)^{1/2} \quad (1.4)$$

$$A_r = A_o (\eta_2 I_t/I_r)^{1/2} \quad (1.5)$$

These basic parameters of the system are thus determined as soon as the operating flux densities I_r and I_t are given. Choosing the optimal flux densities requires a simple cost model: there are a number of costs for both the rectenna and transmitting antenna which depend on their areas (and of course some which depend on other factors — for example, the cost of microwave transmitting tubes may depend on the power level rather than antenna area). Considering only the area-dependent costs, one may write the total cost of these parts of the MPTS as

$$C = \gamma_r A_r + \gamma_t A_t \tag{1.6}$$

where γ_r is the cost per unit (projected) area of the rectenna, including site acquisition and preparation as well as rectenna engineering, and γ_t is the cost per unit area of the structure, waveguides, and other area-dependent parts of the transmitting antenna, including transportation to orbit, amortization of construction facilities, etc. The cost per unit power output of these components of the system may then be written in the following three ways:

$$C/P_o = \frac{1}{P_o}(\gamma_r A_r + \gamma_t A_o^2/A_r) \tag{1.7a}$$

$$C/P_o = \frac{1}{\eta_1 I_r}(\gamma_r + \gamma_t A_o^2/A_r^2) \tag{1.7b}$$

$$C/P_o = \frac{1}{\eta_1 \eta_2 I_t}(\gamma_r A_r^2/A_o^2 + \gamma_t) \tag{1.7c}$$

These three relations give the dependence of the specific cost (i.e., the cost per unit power) on the rectenna area when (a) the power output is fixed; (b) the ionospheric flux density is fixed; and (c) the transmitting antenna flux density is fixed. The peak ionospheric flux is limited by thermal runaway, the present baseline limit being 230 W/m², and the peak transmitter flux is probably limited by radiative cooling constraints, the present baseline limit being 22 kW/m² (note that this is an engineering, not a physical limit, and might be increased by using more efficient power conversion devices, reducing the waste heat, or perhaps by active cooling). While I_t and I_r are averages across the beam, the antenna power taper is constrained by sidelobe suppression requirements, etc., so that the peak limits imply rather lower limits for these parameters. In any case, it is clear that the curves obtained from [1.7b] and [1.7c] with I_r and I_t at their maximum values, represent lower bounds on the achievable specific cost. Using baseline values for the parameters yields the solid curves shown in Fig. 1.1, with arbitrary cost units.

If γ_r and γ_t are constants, [1.7b] is a monotonic decreasing function of A_r and [1.7c] is a monotonic increasing function. Since the accessible cost regions lie above both curves, the minimum cost point is then at their intersection, giving an optimum rectenna area of 79 km² in the example shown. The corresponding power output may be obtained from [1.3].

It is interesting to note that the values of A_r, A_t and P_o found in this way do not depend on the numerical values of γ_r and γ_t (although the value of the minimum specific cost of course does). Changing these values will change the shape of the two curves, but they will still intersect at the same value of A_r. In other words, since [1.3], [1.4] and [1.5] depend only on I_r and I_t, the areas and power are determined as soon as it is recognized that these parameters should be given their

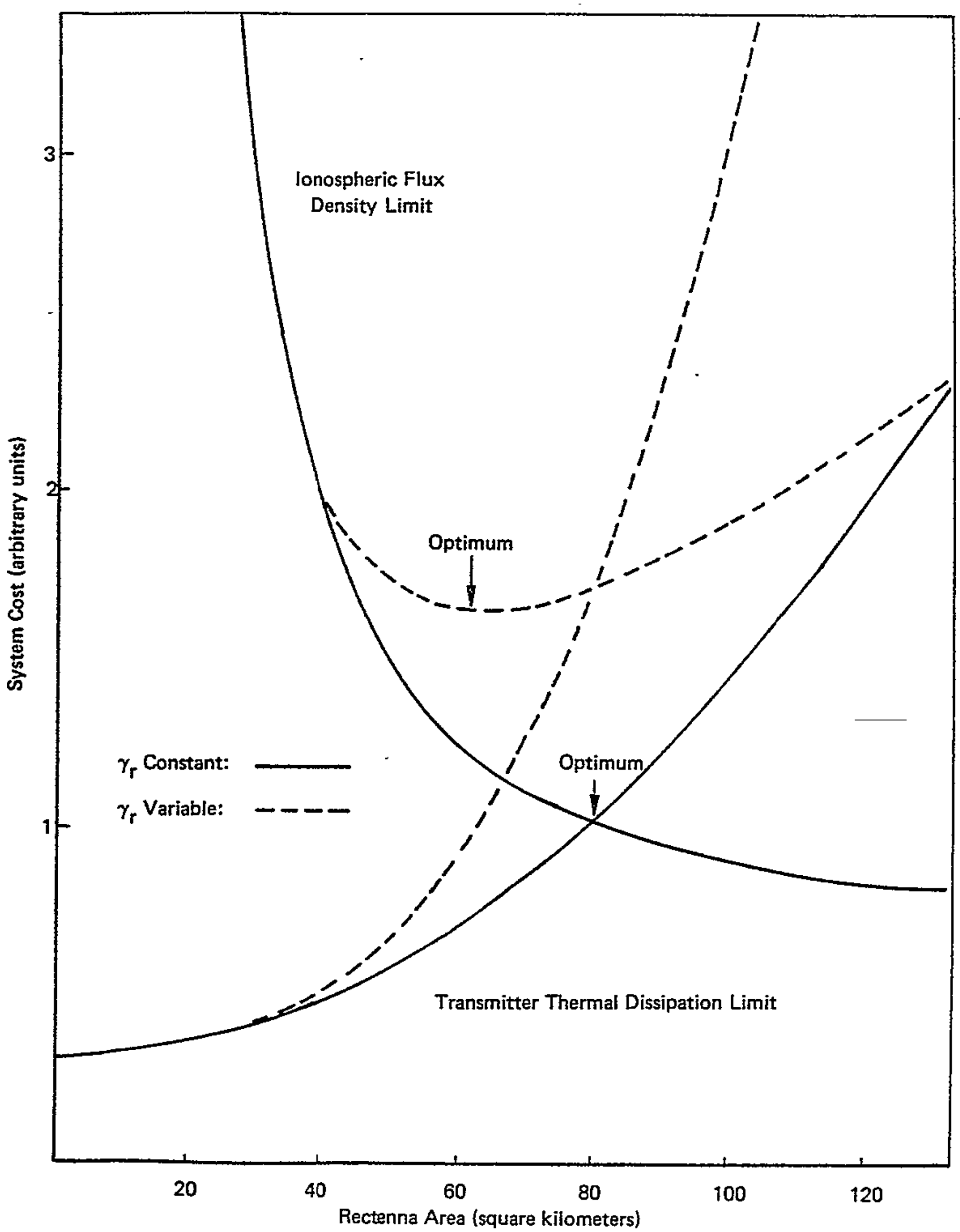

FIGURE 1.1 DETERMINATION OF SPS RECTENNA AREA

maximum values to minimize costs. This is an important point for the present study, for it means that SPS design changes are not required if a higher-cost rectenna site is considered. As will now be shown, this conclusion however depends on the assumption that γ_r and γ_t are independent of the rectenna area.

Suppose for example that γ_r is a monotonic increasing function of A_r. This is not an unreasonable supposition, as there are certainly areas where the difficulty (and hence cost) of putting together a large parcel of land increases rapidly with its size. Alternatively, there may be sites including a relatively small area of flat land, where rectenna construction costs may be minimized, surrounded by a region of increasingly difficult terrain. In such cases, it is clear that the function [1.7b] will exhibit a minimum value at some rectenna area A_{rm}. If this value is less than the area A_{r1} where the ionospheric- and transmitter-flux limit curves cross, then it is easy to show that the minimum-cost point is A_{rm}, not A_{r1}.

This behavior is exemplified by the dashed curves in Figure 1.1, which shows the effect of modelling γ_r by a function

$$\gamma_r = \gamma_{ro}(1 + A_r/A_1) \qquad (1.8)$$

where $A_1 = 10\ km^2$ and γ_{ro} is a constant chosen so that the rectenna cost per unit area matched the baseline value at about $A_r = 35\ km^2$. All other parameters were given their baseline values.

As expected, the dashed curves intersect at $A_{r1} = 79\ km^2$, the same value as in the previous example. The lowest point of the region above both curves is however no longer at the intersection, but at a value $A_{rm} = 63\ km^2$. Since the minimum point of course lies on the same curve at constant ionospheric flux as the intersection, the power output is reduced in proportion to the area. The minimum point lies above the maximum transmitter flux curve, and therefore the cost-optimum condition for this case is operation of the transmitter below its flux limit.

The physical significance of these results is simply that, in cases where rectenna costs increase rapidly with area, it may be cost-effective to limit the size of the rectenna (and hence the power output), even though this implies a larger transmitting antenna.

Whether or not rectenna costs per unit area can be assumed to be independent of rectenna area is clearly a question that can be answered only with reference to specific potential sites. If this characteristic is common to many sites (for example, if it is often necessary to build in valleys whose dimensions are comparable to those of the baseline rectenna), then it is possible that system studies to date have significantly overestimated the optimum unit power output of the SPS. Because this parameter is an important factor, not only in further engineering studies, but in assessing the initial capital requirements, the integration of the system into utility power pools, and a variety of societal issues, the question needs to be resolved as soon as possible. Some relevant data were generated during the present study, but explicit evaluation of the effect on costs of varying rectenna areas at selected sites needs further investigation.

1.2.2 The Multibeam SPS

The above discussion applies to the "conventional" SPS, of the baseline type, in which there is one transmitting antenna for each rectenna. There is however and interesting alternative proposal[17], in which a single large transmitting antenna directs power beams to a number n of rectennas. This is certainly feasible, although at the cost of considerable increase in the complexity of the retrodirective phase control system; the technique is used now in multibeam phased-array radars, and has been proposed for the multi-footprint Public Service Platform[8]. For the SPS application, problems may arise with sidelobe suppression in the complex diffraction pattern of the system, with interference between nearby rectennas and with the grating lobe pattern due to the finite size of the transmitter subarrays. However, this alternative does provide a means for reducing the area of rectennas and their unit power outputs.

For this system, the equations of the previous section are modified as follows. The power output from a single rectenna may be written

$$P_o = \eta_1 I_r A_r = \frac{1}{n} \eta_1 \eta_2 I_t A_t \tag{1.9}$$

which, together with the diffraction constraint [1.2] gives

$$P_o = \eta_1 A_o (\eta_2 I_r I_t / n)^{1/2} \tag{1.10}$$

$$A_t = A_o (n I_r / \eta_2 I_t)^{1/2} \tag{1.11}$$

$$A_r = A_o (\eta_2 I_t / n I_r)^{1/2} \tag{1.12}$$

The total cost, including η rectennas and one transmitter, is

$$C = n\gamma_r A_r + \gamma_t A_t \tag{1.13}$$

so that the cost per unit power may be written in the forms

$$C/nP_o = \frac{1}{\eta_1 I_r} [\gamma_r + \gamma_t A_o^2 / n A_r^2] \tag{1.14a}$$

$$C/nP_o = \frac{1}{\eta_1 \eta_2 I_t} [\gamma_r n A_r^2 / A_o^2 + \gamma_t] \tag{1.14b}$$

If γ_r and γ_t are constant, for fixed I_r and I_t, respectively, these relations are monotonic decreasing and increasing functions of A_r. The minimum cost point is thus again at the intersection of the flux-limit curves. Using maximum flux values in [1.10] to [1.12], it is found that the power output from each rectenna decreases as $n^{-1/2}$; the total power output (and hence the area of the solar array in orbit) thus increases as $n^{1/2}$. The optimum transmitting antenna has an area which increases as $n^{1/2}$, and the area of each rectenna, like the unit power output, decreases as $n^{-1/2}$. When the optimum rectenna area [1.12] is inserted in [1.14] it is found that the specific cost is independent of n. Since no allowance has been made for the cost of extra phase-control complexity, etc., it is probable that the specific cost of power would in practice be higher with this system.

The primary appeal of the multibeam SPS is the smaller rectennas and unit power outputs which it permits. The latter may ease utility integration problems, but whether or not small rectennas are desirable is clearly a siting question. It may well be easier to find a large number of small sites than a few large sites, for the same total installed capacity. A realistic siting survey is thus essential to determining the effort which should be devoted to the multibeam SPS; data is needed, not only on the possible benefits of smaller sites (in terms of land acquisition, public acceptance, rectenna engineering, etc.), but also on whether the geographic distribution of significant load centers, relative to a proposed network of rectennas, is such that smaller rectenna power output can provide useful reductions in power transmission costs.

1.2.3 Rectenna Engineering

The final and most obvious example of the implications of siting studies to SPS system design is the question of designing the rectenna itself. Until rectenna siting problems are better understood, it will not be possible to provide realistic answers to at least the following questions:

i. Some rectenna designs[9] are intended to be built in a continuous weave back and forth across the site, perhaps using a mobile factory, mounted on a large crawler. Are there a sufficient number of sites (in CONUS or elsewhere) with suitable terrain to justify development of this approach? Is it usually possible to avoid areas which are rough, swampy or otherwise unsuited to continuous extrusion of the rectenna?

ii If modular (e.g., billboard) rectenna designs are preferable, can they always be set up perpendicular to the power beam (as in the baseline rectenna), in a sawtooth array? In some cases (particularly if it is necessary to suspend the rectenna well above the ground, perhaps on cables, for safety reasons, to permit use of the ground beneath, or to cross gullies) it may be preferable to use horizontal billboards, even at the expense of increased billboard area. In other cases, where the ground is flat and dry, it may be cheaper to use billboards lying directly on the ground than to install the structure required to support them perpendicular to the beam.

iii. In what fraction of sites will it be necessary to give serious attention to multiple use of the land, because of the value of the land, because desirable and profitable facilities can be installed at modest additional cost under the rectenna (e.g., greenhouses in some desert areas), because the waste heat from the rectenna is of agricultural use (e.g., for preventing frost damage) or because of a need to improve public acceptance of the facility? How should the rectenna be designed to permit such uses?

iv. What weather conditions must the rectenna be designed to endure? To what extent is it possible to avoid areas with heavy snow cover, frequent freezing rain, or high probability of damage due to lightning, tornadoes, etc.? Is it realistically possible to design a universal rectenna, or must the design be site-specific?

v. Is it necessary to consider off-shore sites, either for use by the United States or in other areas (e.g., Japan)?

vi. What is the trade-off, in terms of the difficulty of finding sites, between rectennas located close to their intended loads and those in remote areas? What are the implications in terms of design of the rectenna for multiple use, security of the facility, and public safety?

The study reported here is a preliminary attempt to develop a data base useful in answering some of the system-design questions discussed above.

CHAPTER II
GUIDELINES FOR RECTENNA SITING

2.1 RECTENNA LAND REQUIREMENTS

One of the most notable features of the SPS system is the large tract of land which must be reserved for each rectenna. It is not the total land requirement which is especially significant, for in fact the SPS compares favorably[10] to most other power generation technologies in this respect (taking into account the areas required in other cases for fuel extraction, processing and transportation, waste disposal, etc.), but the fact that it is concentrated in quite large, discrete parcels. It is this feature which may well make land use a controversial issue in deployment of the SPS, so much so that it may become a major determinant of whether or not the system is implemented.

In the present electric generating system of the United States, the land devoted to power transmission lines alone amounts to more than 4,000,000 acres[11]. If collected into suitable tracts, this would be sufficient land to build more than a hundred rectennas, each providing 5 GW; this would more than double the existing national generation capacity. It should be noted, however, that there is increasing resistance to the installation of new transmission lines, and it must be expected that much of this opposition will be transferred to the rectenna siting issue. There are conceivable technological fixes for land use problems in terrestrial power transmission (e.g., underground cryogenic lines), but the only possibility of reducing the *total* land requirement for a network of SPS's of given total capacity is through increasing the average flux density over the rectenna site. There are a number of possible avenues towards this end:

i) Modest improvements may be achievable by locating rectennas as far south as possible, to reduce cosine effects (see Section 2.3.1).

ii) The intensity distribution in the power beam at the rectenna could be improved, giving it more nearly a "top-hat" shape. This would increase the ratio of average to peak flux over the rectenna, improving conversion efficiency as well as reducing land area directly, and it would also provide a more rapid drop-off in flux at the periphery, reducing the needed exclusion area around the site. It would however require better phase control (perhaps including phase taper across the transmitting aperture) and a larger transmitting antenna, which are not negligible costs.

iii) If recent experimental results[6] are confirmed by planned tests, the theoretical model which has resulted in the baseline ionospheric flux density limit of $230 W/m^2$ will have been shown to be invalid. It is uncertain how much of an increase this would permit. In any case, there will presumably be limits to the peak flux over the rectenna because of effects on birds flying over it or because of possible constraints to aircraft operations.

iv) Laser power transmission[12] from the SPS, if shown to be feasible and economic, offers a radical reduction in receiver land requirements.

All of these techniques would reduce the area of each rectenna as well as the total area. If optimal scaling is used, then Eqs. (1.3) and (1.5) show that increasing the rectenna flux density reduces the number of rectennas required (by increasing unit power output) as well as decreasing the size of each rectenna. There may also be ways to reduce the unit rectenna size without reductions in total area, the most obvious being:

v) Operation at smaller rectenna areas than are obtained from narrowly-defined optimizations such as that shown in Fig. 1.1 — in other words, it may be desirable to trade some increase in direct system costs for some perceived land-use benefit.

vi) The Multibeam SPS, discussed in Section 1.2.2, is a system whose primary purpose is to reduce the scale of each rectenna.

In connection with (v) and (vi), it is to be noted that it is not necessarily desirable to reduce the area of each rectenna, at the cost of an increased number of rectennas. If this is the trade-off, then (defining cost as including regulatory delays, public opposition, etc.) the definition of the optimum size may depend on whether one is more concerned with the marginal cost of one more rectenna, or the total cost of a large number of them. Moreover, the dependence of the various costs on the area of the tract in question may differ, and the balance between them may be different in different regions of the country. A general statement of the optimum rectenna area, from these points of view, is clearly not possible.

There is presently no coherent, clearly defined and universally applied procedure for making land-use decisions in the United States. Especially with respect to siting of new energy facilities, the present process involves a chaotic jumble of local, state and Federal regulations, ad hoc responses to special-interest groups, and a host of bureaucratic agencies, in which the public interest may or may not be served. Until a rational national land-use policy has been developed, it is hardly possible to define what is meant by the best set of potential sites for rectennas, let alone to specify where they might be.

As noted in Section 1.1, the primary purpose of the present study was to investigate those generic characteristics of rectenna sites which could be important to system definition of the SPS. From this point of view, the process of identifying specific sites is essentially equivalent to the selection of an experimental sample from a large population of potential sites, in order to assess their characteristics. The simple and narrowly-focussed selection methodology discussed in Chapter III was deemed adequate for this purpose, but it would be absurdly presumptuous to assume that it could serve as a substitute for the long and arduous analysis, the detailed data-gathering, and the careful resolution of controversy which will be necessary before any definitive recommendation can be made concerning actual sites for rectennas.

2.2 CLASSIFICATION OF SITING ISSUES

The first step in the site selection process was to draw up a list of issues needing consideration, questions to be answered and, where possible, criteria for choosing one site over another. Although the resulting list could not be considered exhaustive, it soon became clear that the factors were so complex, involved so many disparate and frequently subjective elements, and included so many unknowns that development of a comprehensive numerical site-ranking scheme would be a futile exercise. Numerical rating methods were developed for some of the simpler and more quantifiable attributes of sites, and these did prove useful in making choices between sites when they were not obvious without such analysis. This rating procedure is described in the next Chapter.

Examination of a broad range of siting considerations, even those which were not explicitly involved in preliminary site screening, was an essential part of this study. Firstly, it was of course necessary to define that sub-set of criteria which was to be used in the actual initial site choices. Secondly, familiarity with the issues provided a necessary background — difficult choices were sometimes resolved by bringing up broader questions. Finally, an understanding of how well the sites meet the listed criteria is important in assessing how realistic a sample of potential sites has been obtained.

Site selection criteria can of course be categorized in many ways. The following Sections present tables listing siting issues according to a classification which proved useful in practice, together with a discussion in the text of some of the more significant or less obvious items. For each issue, the following judgmental factors are given in the tables:

Class: A Class I issue is one which is significant because of its possible effect on the feasibility, acceptability or system design of the SPS, whereas a Class II issue refers to possible effects of the SPS on external interests.

Importance: This is a (necessarily rather subjective) estimate of the importance of the issue to siting decisions.

Unique?: This refers to whether or not the issue is one which is unique to the SPS system, or common to other energy facilities.

2.3 RECTENNA SITING ISSUES (GENERAL)

2.3.1 Low Latitude Sites Reduce Area

Figure 2.1 shows the geometry of the power beam from an SPS in geosynchronous equatorial orbit (GEO) to a rectenna at latitude L. Assuming for simplicity that the SPS and rectenna are at the same longitude, the angle between the local vertical at the rectenna and the power beam is

$$\alpha = \phi + L \qquad (2.1)$$

where ϕ is the angle between the power beam and the equatorial plane, given by

$$\tan \phi = r_0 \sin L/(r_s - r_0 \cos L) \qquad (2.2)$$

where r_o is the radius of the Earth and r_s that of GEO.

The major effect of latitude on the rectenna site is the increase in the north-south diameter of the required area because of the cosine effect of the inclination of the power beam to the vertical. There is also a minor effect on both north-south and east-west diameters, due to the slow increase in range from the satellite with latitude, which is given by

$$x = r_s \sin L/\sin(L + \phi) \qquad (2.3)$$

TABLE I

RECTENNA SITING ISSUES (GENERAL)

Siting Issue			Class	Importance	Unique?
1.	Low latitude sites reduce area		I,II	Medium	Yes
2.	High latitude sites reduce satellite RFI		II	Medium	Yes
3.	Low pre-existing on-site population		II	High	Yes
4.	Compatible pre-existing land use		II	High	Yes
5.	Cheap land		I	Medium	Yes
6.	Federal lands where possible		II	Medium	Yes
7.	Close to existing utility tie-point		I	Medium	No
8.	Rectenna area not limited by land availability		I	High	Yes
9.	Enough land for several nearby rectennas		I	Medium	Yes
10.	Site not clost to Federal airways		II	Medium	Yes
11.	Site in or adjacent to existing Restricted Area for aircraft		II	Medium	Yes
12.	Site in region with major load centers		I,II	High	No
13.	Site should not encompass:				
	i.	National monuments	II	High	Yes
	ii.	Major historical sites	II	High	Yes
	iii.	Important archaeological or paleontological sites	II	Medium	Yes
	iv.	Airports (except minor strips)	II	High	Yes
	v.	State or local parks and recreational lakes	II	High	Yes
	vi.	Major railroads or highways	II	Medium	Yes

TABLE II

RECTENNA SITING ISSUES (PHYSICAL FEATURES AND ENGINEERING)

	Siting Issue	Class	Importance	Unique?
1.	Railroad access to site without major construction	II	Medium	No
2.	Highway access to site without major construction	I	Medium	No
3.	Low or gentle terrain relief	I	High	Yes
4.	Sloping sites need southern exposure	I	High	Yes
5.	Surface needs adequate bearing strength for construction	I	High	No
6.	Vehicular access to all areas	I	High	Yes
7.	Adequate water available for construction	I	Medium	No
8.	Few lakes or other obstructions on site	I	Medium	Yes
9.	Minimum disturbance to existing forests	II	Medium	No
10.	Good drainage of surface water	I	High	No
11.	Good emergency access to site	I	Medium	Yes
12.	Earthquake or subsidence-prone areas to be avoided	I	Medium	No
13.	Site preparation and construction problems	I	High	No

TABLE III

RECTENNA SITING ISSUES (CLIMATOLOGICAL)

Siting Issue	Class	Importance	Unique?
1. Frequency of lightning strikes	I	Medium	Yes
2. Probability of tornadoes	I	Low	No
3. Probability of hurricanes	I	Medium	No
4. Effects of heavy rains	I	Low	Yes
5. Effects of snow cover	I	High	Yes
6. Effects of freezing rain	I	Medium	Yes
7. Effects of dust storms	I	Low	No
8. Effects of seasonal temperatures and weather	I	Low	No
9. Microclimatic effects of rectenna heat island	I,II	Low	No
10. Probability of heavy cloud cover	I	Low	Yes

TABLE IV

RECTENNA SITING ISSUES (LOCAL IMPACT)

Siting Issue	Class	Importance	Unique?
1. Local economic and demographic effects of rectenna construction and operation	II	High	No
2. Microwave flux densities outside rectenna reservation	II	High	Yes
3. RFI with equipment in surrounding area	II	Medium	Yes
4. Uses of surrounding land	II	Medium	No
5. Local aesthetic impact of rectenna	II	Medium	No
6. Regional cultural differences and public perception of the rectenna	I,II	Medium	Yes
7. Possibilities for multiple uses of site	I,II	High	Yes

TABLE V

RECTENNA SITING ISSUES (ENVIRONMENTAL AND ECOLOGICAL IMPACT)

Siting Issue	Class	Importance	Unique?
1. Proximity to designated wilderness areas	II	High	No
2. Proximity to major scenic areas	II	High	No
3. Impacts to endangered species	II	High	No
4. Roosting or nesting of birds on rectenna	I,II	Medium	Yes
5. Proximity to major migratory bird flyways	II	Low	Yes
6. Disturbance of existing (surface and burrowing) fauna	II	Medium	No
7. Local insect species and populations	I,II	Low	Yes
8. Preservation of existing vegetation	.II	Medium	No
9. Preservation of features important to biota (wetlands, etc.)	II	High	No
10. Ozone production and other air pollution from rectenna	II	Medium	No
11. Water pollution by leachates from rectenna	II	Low	No

TABLE VI

RECTENNA SITING ISSUES (LEGAL, REGULATORY, SOCIETAL, ETC.)

Siting Issue	Class	Importance	Unique?
1. Conformity to Federal regulatory constraints	I	High	No
2. Conformity to state and local regulatory constraints	I	High	No
3. Land ownership and means of acquisition	I	High	No
4. Networking of rectenna installations	II	Medium	No
5. Institutional and administrative arrangements	I	Medium	No
6. Plans for eventual decommissioning of rectenna	I	Low	No
7. Site security	I	Medium	No
8. National defense: strategic significance	I,II	Medium	No
9. Societal constraints	I,II	High	No

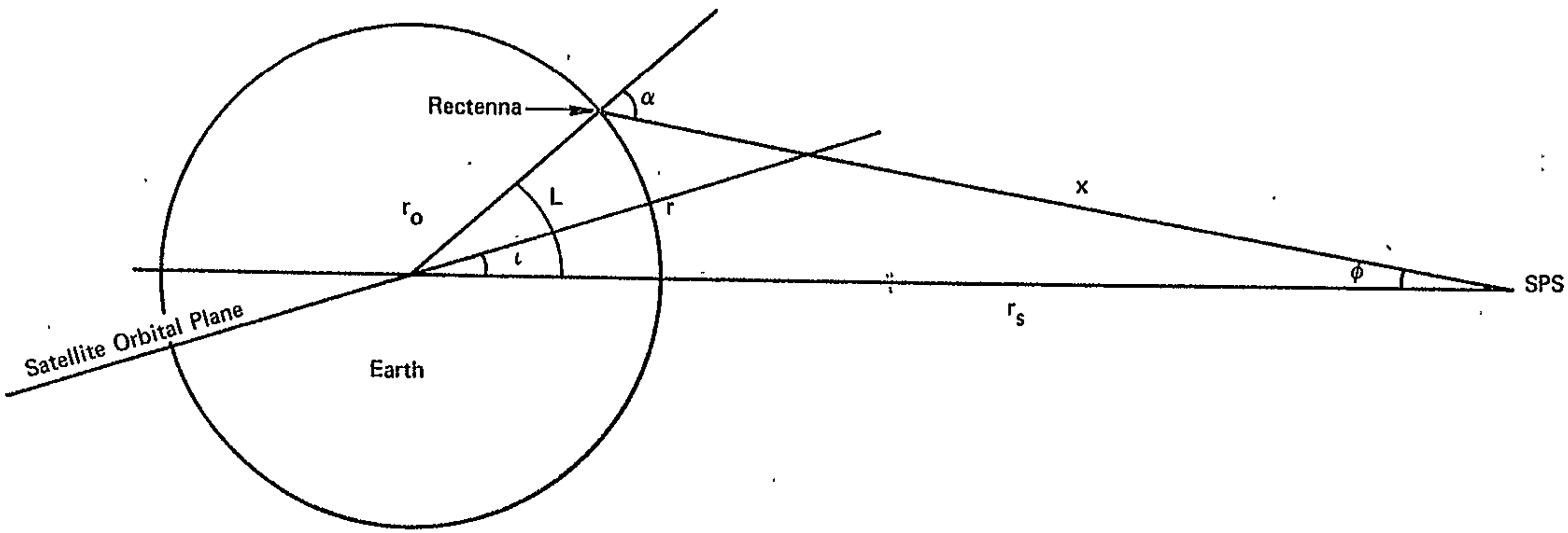

FIGURE 2.1 SPS POWER BEAM GEOMETRY

Figure 2.2 shows the variation of the two diameters of a rectenna with latitude, along with that of the total area. In this particular figure, the radius of a rectenna site on the equator was taken to be 5.7 km, the distance at which the flux density in the baseline system reaches 0.1 mW/cm^2, two decades below the current U.S. standard for long-term public exposure to microwaves.

Also shown in the figure are the CONUS latitude limits, from Key West to the 49th Parallel. The site area ranges from about 30,000 acres at the southern limit to nearly 55,000 acres at the northern limit, so that, other factors being equal, there is a significant benefit from southern sites. It should be borne in mind, of course, that land values in CONUS vary from region to region by much more than the area factor due to latitude. From this point of view, if it were possible to find an area reasonably free of lakes and muskeg in Quebec near 50° north, it might be cheaper than many in the Eastern United States. The Churchill Falls and James Bay projects of Quebec Hydro have demonstrated the feasibility of major electric power facilities in that area, but nevertheless the climatological factors discussed in Section 2.5 are likely to provide more important reasons for preferring southern sites than does the area factor alone.

2.3.2 High Latitude Sites Reduce Radiofrequency Interference with Satellites

Consider the intersection between the SPS power beam and the orbital plane, of inclination ℓ of a satellite in low Earth orbit (LEO). It is easy to show[12] that the locus of the beam intersection with this plane is a conic section, in most cases a hyperbola: it starts at GEO altitude at the time when the SPS passes through the right ascension of the ascending node of the lower satellite (assumed posigrade), sweeps down to a minimum altitude six hours later, and then back up to GEO at the right ascension of the descending node. The minimum altitude of the intersection may be obtained from the simple planar geometry of Figure 2.1, where the inclined orbit plane is shown, being given by

$$h = r - r_o = r_s \frac{\sin \phi}{\sin(\phi + \ell)} - r_o \qquad (2.4)$$

Satellites in this orbital plane whose altitude is less than this value will never encounter the power beam to the rectenna at the latitude shown in the figure. Figure 2.3 shows this maximum safe altitude as a function of latitude, for orbital inclinations of 10°, 20°, 28.5° (Kennedy launch) & 40°. The steepness of these curves is impressive — it is clear that small increases in rectenna latitude can greatly reduce encounters with satellites in relatively low-inclination orbits. The possible significance, in terms of RFI with satellite operation or perhaps actual damage, of such encounters between satellites and SPS power beams is under study[12]. From the present point of view, the problem provides some motivation for high-latitude rectennas. For example, if there were no rectennas below 40° latitude, satellites launched due east from KSC to altitudes below 1700 km would never encounter the beam.

2.3.3 & 2.3.4 Low Pre-Existing On-Site Population and Compatible Pre-Existing Land Use

It is clear that the disruption caused by the rectenna installation, and hence the cost and difficulty of obtaining the required parcel of land, will be minimized if there are few on-site dwellings and if the previous use is either unimportant (desolate areas) or compatible with possible multiple uses of the land.

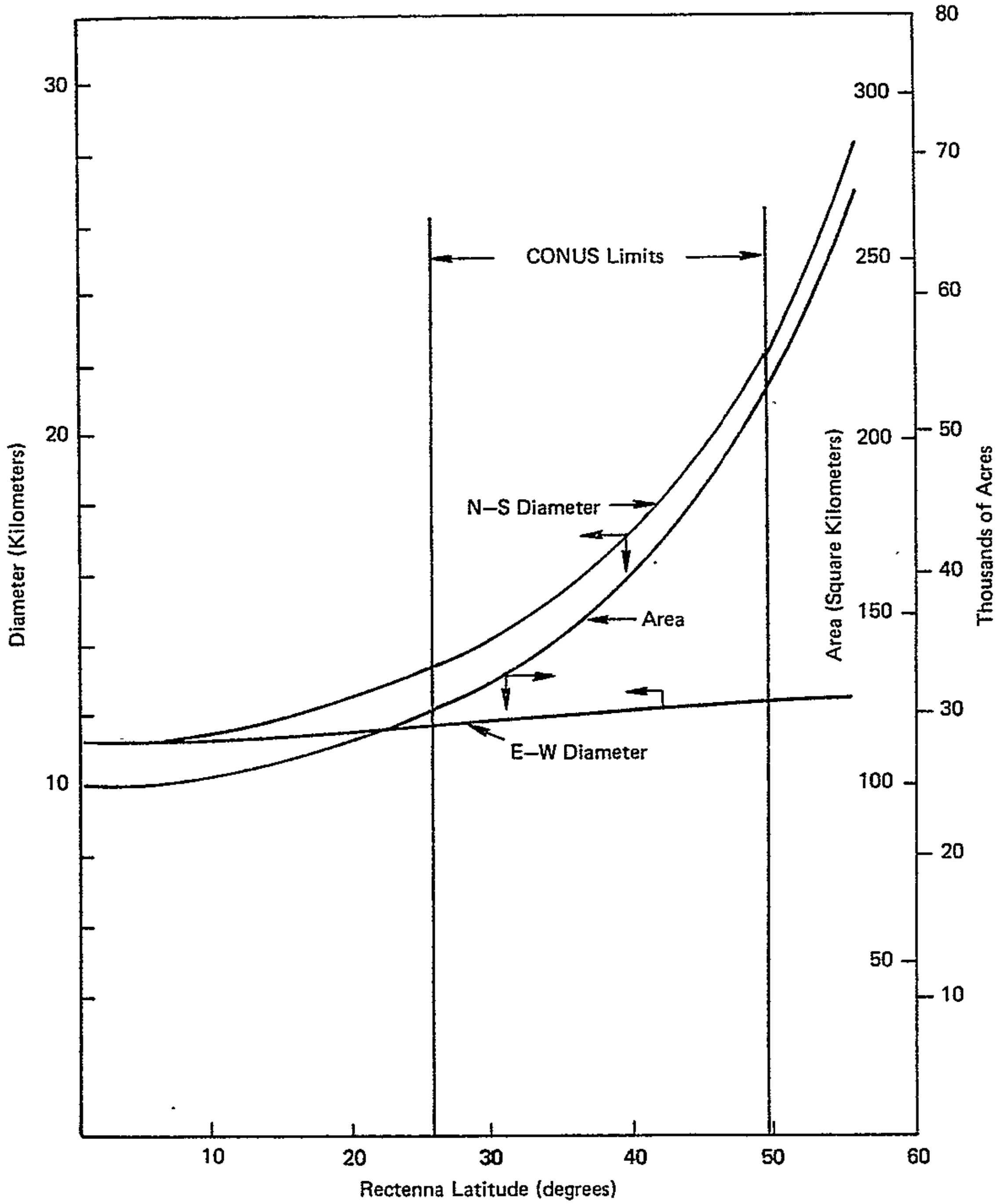

FIGURE 2.2 VARIATION OF RECTENNA DIAMETERS AND AREA WITH LATITUDE

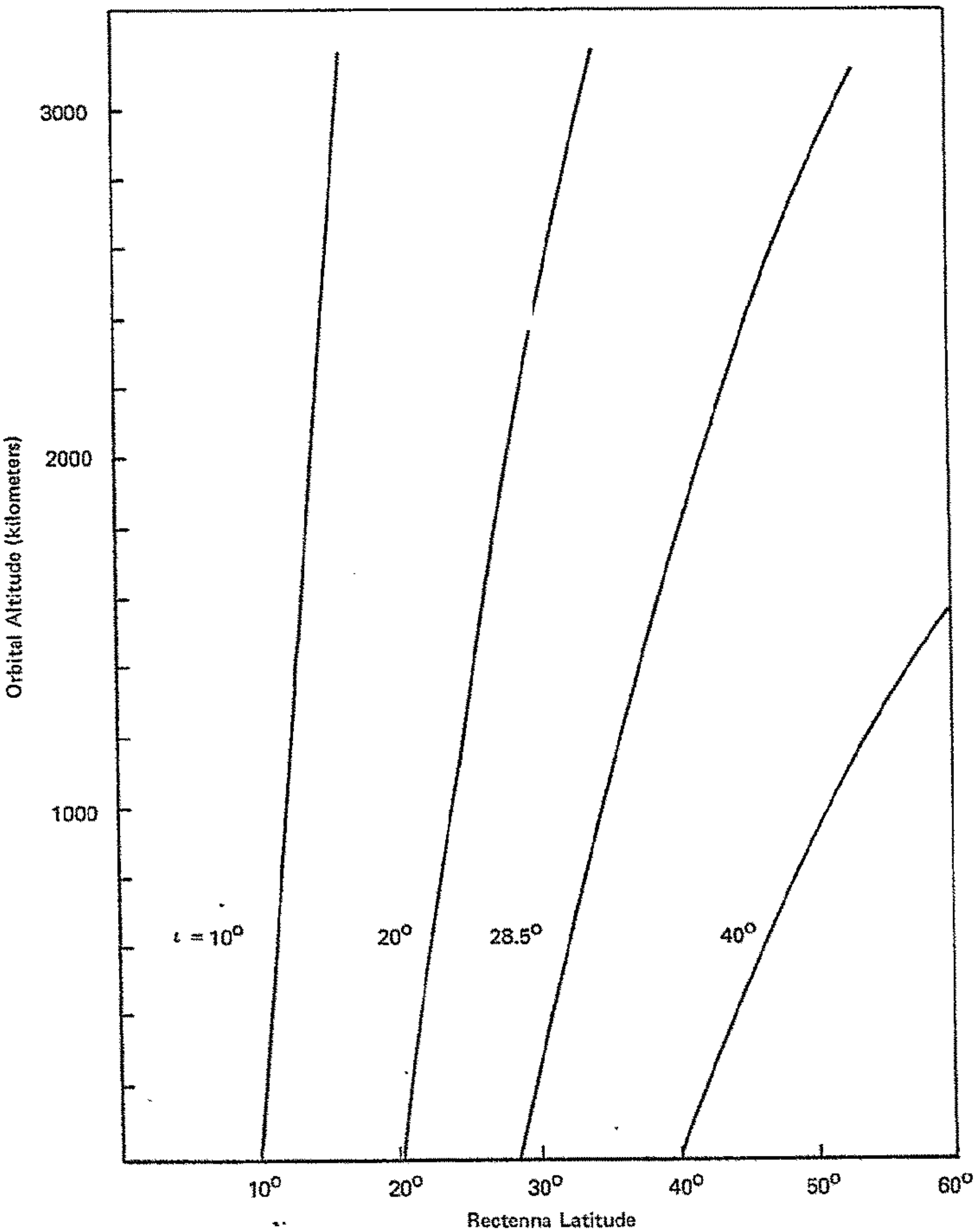

FIGURE 2.3 MAXIMUM SAFE ORBITAL ALTITUDES

2.3.5 & 2.3.6 Cheap Land; Federal Lands where Possible

An SPS installation delivering 5 GW. with a 95% plant availability factor, will produce about 42 billion kwh per annum. If the busbar price of electricity is, say, \$0.03/kwh, the gross revenues from the rectenna will amount to \$23,000/acre for northern CONUS sites to \$42,000/acre for southern sites. Although of course only a small fraction of these sums can be assigned to amortization of the cost of the land, it is significant that the figures are an order of magnitude higher than those typical of even intensive agriculture. It therefore appears that the SPS system may be quite competitive with agricultural uses of land, but that it will not be possible to purchase land at prices comparable to those found in residential areas near cities. To put the matter another way, if the cost of the land at the rectenna averages (say) \$2500/acre, land acquisition will represent a capital cost to the system of \$15-\$25 per kilowatt, depending on latitude. These are relatively small costs, but of course not negligible — they represent from \$75 to \$135 million for the rectenna as a whole, so that a considerable effort to find cheap land is justified.

The idea that sites should be sought on Federal lands is of course based on the supposition that it would be easier to find suitable tracts in such areas. It is not entirely clear that this is true, or will be in the Nineties. Federal lands are controlled by a broad variety of Government agencies which do not necessarily have a common policy regarding the land uses which can be permitted. Whether or not a rectenna will be allowed in a particular Government-controlled area is basically a political decision, even if (or perhaps especially if) the organization proposing to build the rectenna is a Federal power authority rather than a private company. There may in fact be more effective opposition from public interest groups to a rectenna on Federal land ("our land") than to one on land acquired from private owners.

2.3.7 & 2.3.12 Site Close to Existing Utility Tie-Point and in Region with Major Load Centers

These characteristics are desirable, not only to minimize transmission costs, but to avoid additional land use problems. It is instructive to note, for example, that the transmission lines required to transport several gigawatts from the coal-fired plants in the Four Corners region of the Southwest to the West Coast (a distance of just over 1000 miles) will pre-empt a total of about 100,000 acres[13] . If it were possible to locate rectennas closer to the intended load, up to 15 GW might be available from the same land area. In general, using above-ground EHV lines, the land required for transmission line right-of-way will exceed that for the rectenna if it is located more than about 500 miles from its intended load.

2.3.8 & 2.3.9 Rectenna Area Not Limited by Land Availability; Enough Land for Several Nearby Rectennas

It is clearly desirable to have ample room for the rectenna in the area of the chosen site. As the noted previously, the variation of the number of sites in a given region with the required area is an important subject for research, because it can influence quite strongly the system design of the SPS.

There are several reasons for considering the possibility of installing more than one rectenna in a given area (subject to limitations concerned with interference between side lobes from adjacent systems). The power park concept is one way of reducing public opposition to new generation facilities; in the remote areas where more than one rectenna could be installed, it is probably not much harder to obtain regulatory approval and local agreement to several rectennas than it would be for one. Moreover, adjacent rectennas may improve the possiblity of load-sharing in the event of outage of one SPS; this would be particularly attractive if the rectennas in the park all fed different power pools. Since the total output of such a park would be large compared to the power requirements of even major cities, a probable cost of the concept is that the average distance to the intended loads would be larger than in the case of single rectennas. The concept would thus be of increased interest if improved transmission lines (especially underground, perhaps superconducting lines) become practical.

2.3.10 & 2.3.11 Site Not Close to Federal Airways; Site In or Adjacent to Existing Restricted Areas for Aircraft

The purpose of these restrictions is of course to avoid cluttering the already crowded CONUS air space with additional restrictions to the free movement of aircraft. The proliferation of many new small (this is one context in which a rectenna is small) restricted areas is quite undesirable, not only because it increases the probability of accidental violations but because it can increase cockpit workloads and require additional communications with controllers, both of which decrease pilot attention to his primary tasks, perhaps adversely affecting flight safety. Naturally, these problems would not arise if it could be shown that passage through a microwave power beam, while perhaps not desirable, was not unduly hazardous to aircraft equipment, or if equipment modified to withstand such fluxes at S-band could be developed and installed in many aircraft. The required modifications might include Faraday cases around sensitive components, antenna grounding switches triggered by a flux sensor, etc. For jet aircraft, at least, straight-line passage through the beam should generally take less than a minute, and the crew and passengers would be largely protected by the metal fuselage, so that no serious health hazard is expected, at least as long as the baseline peak flux density (230 W/m^2) is not increased. There may be more problems with General Aviation aircraft, although they can of course be vectored around rectenna sites if they are in IFR conditions, just as in the case of airline or military operations; and, in most VFR conditions, the rectenna will be a quite obvious feature, readily avoided.

2.3.13 Site Should Not Encompass National Monuments, etc.

These restrictions are generally self-explanatory. It should be noted that the rectenna, while clearly incompatible with national monuments, major historical sites, conventional parks and recreation areas, and airports, does not preclude continued archaeological or paleontological work, although care might be required during construction to preserve stratigraphy. Major railroads and highways could be allowed to cross the site, at the expense of providing microwave shielding (wire mesh) over them.

CHAPTER III
SITE SELECTION METHODOLOGY

3.1 RATIONALE FOR PRELIMINARY SITE SELECTION

The interface between the satellite and rectenna in the SPS system is, of course, the power beam, which can be characterized by a small number of parameters: frequency, polarization, far-field flux density distribution, total power, directional stability, etc. The rectenna designer is not directly concerned with satellite design features (e.g., the solar energy conversion technique) which do not affect the nature of the power beam. Conversely, the characteristics of the rectenna affect the satellite system design only insofar as they affect the best choices for power beam perameters. In particular, while rectenna siting issues may be of fundamental importance to the basic design of the power satellite (e.g., in helping to determine the optimum power output), it is not surprising that only a few of the considerations discussed in the previous Chapter can be classified as significant from this point of view.

On the other hand, a high proportion of the listed siting issues can be directly important to rectenna design. Even if it could be shown that a single rectenna design was appropriate to all chosen sites, its characteristics would depend on the features common to the sites, and hence might change if another set of sites were selected. In practice, the capital cost of the rectenna will be sufficient (the baseline rectenna has a quoted cost[4] of $3.2 billion) to justify much site-specific engineering, and the number of repeated elements in the rectenna is sufficient to obtain manufacturing economies of scale on a rectenna-by-rectenna basis. The degree of commonality between rectennas is an important question (which is addressed in Chapter IV), but it is a safe assumption that the characteristics of each individual site will affect the design of the rectenna which is built there. It can thus be argued that even a limited study such as this cannot afford to ignore any significant siting criteria, even those which have no direct relevance to systems engineering, because taking them into account could result in a more realistic set of sites with different engineering characteristics.

The problem which immediately arises in any nationwide siting survey is that there is no established policy with respect to many of the land-use issues discussed in the previous Chapter, so that it is not always possible to set up unambiguous or universally acceptable criteria for choosing one site over another — in other words, many of the issues raised can presently be resolved only by subjective judgment. The only societal mechanism currently available (other than dictatorial fiat) for dealing with this situation is an adversary procedure applied to each individual siting decision, in which all parties affected by the outcome are given an opportunity to state their views and some reasonable degree of influence over the final result. It is attractive to consider a comprehensive national planning process which, when the time comes to begin installing rectennas, could deliver a list of sites which were "best," according to clearly defined criteria, but, in a democracy, this approach is probably unworkable and almost certainly undesirable.

The best that can be expected of a siting exercise of the type undertaken for this study is that it may provide a sample of sites which are reasonably representative of those which might be found in a centralized planning process; to this extent, the survey is inherently unrealistic. As discussed in Chapter I, it is however essential to take siting issues into account in planning for the SPS, and the survey technique at least provides a better guide in this area than can be expected of a merely intuitive estimate of what a typical rectenna sight might be like.

In any case, the procedure used in this study consisted of the following phases, which are discussed in more detail in succeeding Sections:

Phase 1: Research and discussion regarding issues important to siting decisions. The results of this phase were presented in Chapter II.

Phase 2: Establishment of an assumed geographic distribution of rectennas. For study purposes, CONUS was divided into ten regions, and a target number assigned for rectennas in each region.

Phase 3: Selection of tentative locations in each region, based on general principles, familiarity with siting issues, limited data (mostly maps) and a small set of specific criteria. The number chosen in this phase for each region was always larger than the target number for that region, by a greater factor in areas where siting difficulties were expected to be most severe (especially the Northeast).

Phase 4: Data-gathering regarding more detailed characteristics of the tentative sites, and comparison with the desiderata established in Phase I, leading to elimination of some sites and ranking of the remainder within each region. In many cases, rankings resulted from consensus among the study team, but in difficult cases the numerical ratings schemes discussed below were helpful.

Phase 5: Reduction of the candidate sites to the target number in each region, and consolidation of the data concerning them so that general conclusions could be drawn.

It cannot be claimed that the potential sites obtained by this procedure are optimal by any set of criteria, nor is there any necessary relationship between them and the sites which might actually be used for rectennas. It is expected, however, that consistent use of the procedure throughout CONUS should result in a sample of sites which are sufficiently representative of actual sites, at least in their statistical characteristics, to provide a useful guide for system design. As a practical matter, it was found that, if the criteria used in Phase 3 were too simple-minded, it was necessary to select a large number of tentative sites, because a high proportion of them would have to be excluded in Phase 4; but if the criteria in Phase 3 were too detailed, much effort was wasted in gathering data about at least some sites which would be eliminated. The two-stage iteration thus allowed a rough minimization of the workload, and provided flexibility so that it was not necessary to worry too much about mistakes in the early phases.

Finally, it must be pointed out that this was a preliminary general survey, using limited data sources. As a result, it is quite possible that more detailed investigation of any individual site listed here would reveal significant, perhaps insuperable objections to it as a location for a rectenna. Given several more iterations, carried out in greater detail, the basic procedure is however capable of providing an excellent list of potential sites, within the general limitations of any centrally-planned survey. It is clearly not yet warranted to carry out a nation-wide rectenna siting survey in the depth needed to give confidence about the feasibility of all the individual sites, for this might involve extensive site visits, polling of local residents, preparation of nominal Environmental Impact Statements, etc.; an alternative strategy, aimed at improving understanding of rectenna siting problems, is presented in Chapter 4.

3.2 STATUS OF AVAILABLE INFORMATION

For this study, information was obtained primarily from a number of general sources, and hence specificity is compromised by the level of detail and resolution which such sources are capable of providing. The most generally useful data was obtained from a variety of maps, including The National Atlas of the United States[14]; U.S. aeronautical charts, especially Sectionals[15]; U.S.G.S. topographical maps, especially the 15-minute series[16]; and U.S.G.S. detailed land-use maps[17] (these are not yet available for every CONUS area). Collectively, the different types of information available from these maps allow acquisition of a surprisingly good understanding of the physical features of specific areas, the uses of the land, local demographic and economic characteristics, and special activities occurring around locations of interest. The holistic approach afforded by map comparisons gives the analyst an opportunity to comprehend the totality of activities and features evident in particular areas, so that, even in the early stages of the survey, it is possible in some degree to take account of trade-offs between disparate siting criteria. This is a considerable advantage over the strictly exclusionary approach, in which each siting issue is used to delineate areas which should be rejected, with the results being simply overlaid in order to find areas permitted under all criteria — if carried out in sufficient detail, this approach can easily lead to the conclusion that there are no allowable rectenna sites.

General information can also be obtained from photographs and other imagery taken from orbit (especially Landsat) or from aircraft. These often reveal natural or man-made terrain features not necessarily evident from maps; more subtly, and perhaps more importantly, they lend a reality to the site-selection task which can be lost in concentration on the abstract symbology of maps. Synthetic-aperture (side-looking) radar imagery is particularly useful in studying terrain features, and Landsat photographs can be helpful in evaluating land use, especially in those cases where data reductions have been carried out for other purposes. In general, comparison of imagery with available maps alleviates the photo-interpretation problem.

Once specific sites have been identified, it is of course generally possible (in CONUS, not necessarily elsewhere) to find information in as much detail as desired, although considerable investment in time, cost and effort is often required. Complete information on a sufficiently detailed scale for a truly realistic evaluation of a potential rectenna site would, in most cases, require at least a cursory site visit, which was not feasible within the scope of the present study.

3.3 GEOGRAPHIC DISTRIBUTION OF RECTENNAS

In a previous rectenna siting study[18], which was concerned with quite elementary questions of site availability, the assumption was made that two sites should be assigned to each state in CONUS, a procedure which ignores the very large variability between states both in area and in energy demand. Moreover, the natural scale for grouping of rectennas is independent of state boundaries, being more concerned with power transmission — it could be defined as the distance at which the total area of transmission-line right-of-way, between the rectenna and its load, was equal to the rectenna area, or as the distance at which transmission costs became a significant contribution to the price of electricity from the system. Definitions of this type lead to a scale of 500-800 miles for the dimensions of regions in which rectenna sites can be regarded as essentially interchangeable, in terms of the load centers which they can feed economically.

Another approach to rectenna regionalization is to consider CONUS divisions presently used by the electric utility industry. For example, Figure 3.1 shows the regions established by the National Electric Reliability Council (NERC), an organization set up in the wake of the great Northeastern blackout in 1965, with the objective of rationalizing power-pool interties and load-shedding arrangements so as to increase reliability. The nine regions shown do not represent individual power pools, but are instead areas within which coordinating agreements exist between separate power pools (the important distinction is that a power pool is a group of electric utilities which are subject to unified control of generation facilities, not merely reliability agreements). The Councils shown are:

NPCC:	Northeast Power Coordinating Council
MAAC:	Mid-Atlantic Area Council
SERC:	Southeastern Electric Reliability Council
ECAR:	East Central Area Reliability Coordination Agreement
MAIN:	Mid-America Interpool Network
MARCA:	Mid-Continent Area Reliability Coordination Agreement
SPP:	Southwest Power Pool
ERCOT:	The Electric Reliability Council of Texas
WSCC:	Western Systems Coordinating Council

For rectenna siting purposes, it was considered that some of the eastern NERC regions are too small, and WSCC is too large. Moreover, the boundaries of the NERC regions do not all coincide with state boundaries, which is inconvenient because a great deal of statistical information which may be relevant to the siting process is tabulated by states. CONUS was therefore divided rather arbitrarily into the ten regions shown in Figure 3.2, with numbers assigned for reference purposes.

Originally, it was proposed to assign rectennas to each of these regions in proportion to the present electric energy consumption in them. However, there is naturally a correlation between the cost of electricity and its consumption, and the cost varies by about a factor of two between those states with cheap hydropower, particularly in the Northwest, and those which must import most of their energy needs, particularly in the Northeast. While rectenna costs may vary significantly across the nation, they are a relatively small component of the total cost of the SPS, and hence there is no reason to expect major regional variations in the price of electricity produced. As a matter of fact, one might expect that, everything else being equal, more rectennas would be built in areas with high electricity costs (and hence low present consumption per capita) than in areas where there are existing low-cost alternatives.

For these reasons, it was decided to assign rectennas to the various regions on the basis of their present population. Because of the uncertainties in predicting demand for satellite solar power, there seemed little point in taking into account demographic trends in order to predict regional populations around the end of the century. Furthermore, it is at least possible that introduction of the SPS could alter the regional development of industry and hence complicate predictions of population.

The resulting distribution of rectennas is shown in Figure 3.3. The numbers in each region are the percentage of population; since 100 rectenna sites were to be selected in this study, the numbers are also the target numbers of sites to be found in each region.

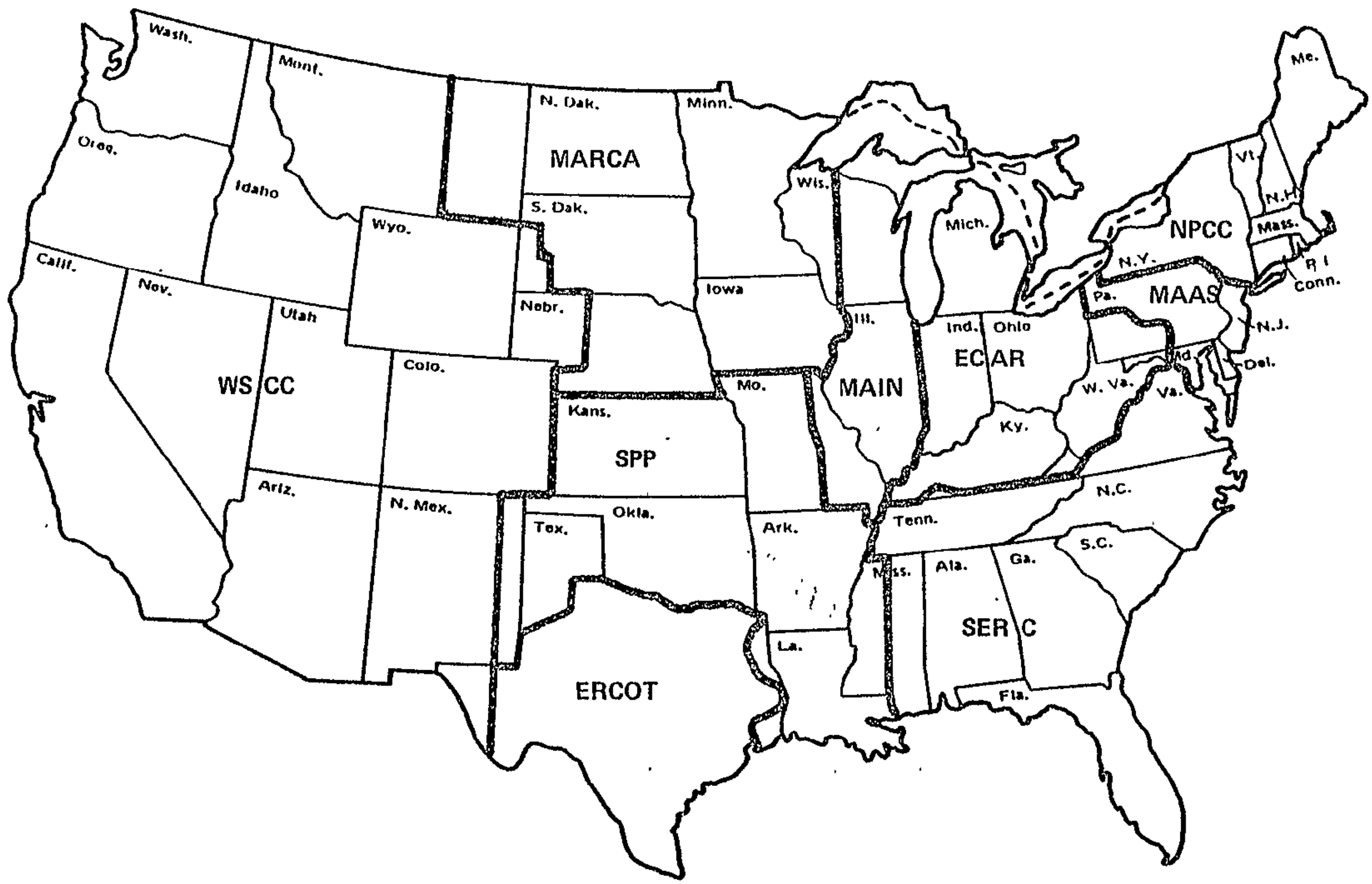

FIGURE 3.1 REGIONAL COUNCILS OF THE NATIONAL ELECTRIC RELIABILITY COUNCIL

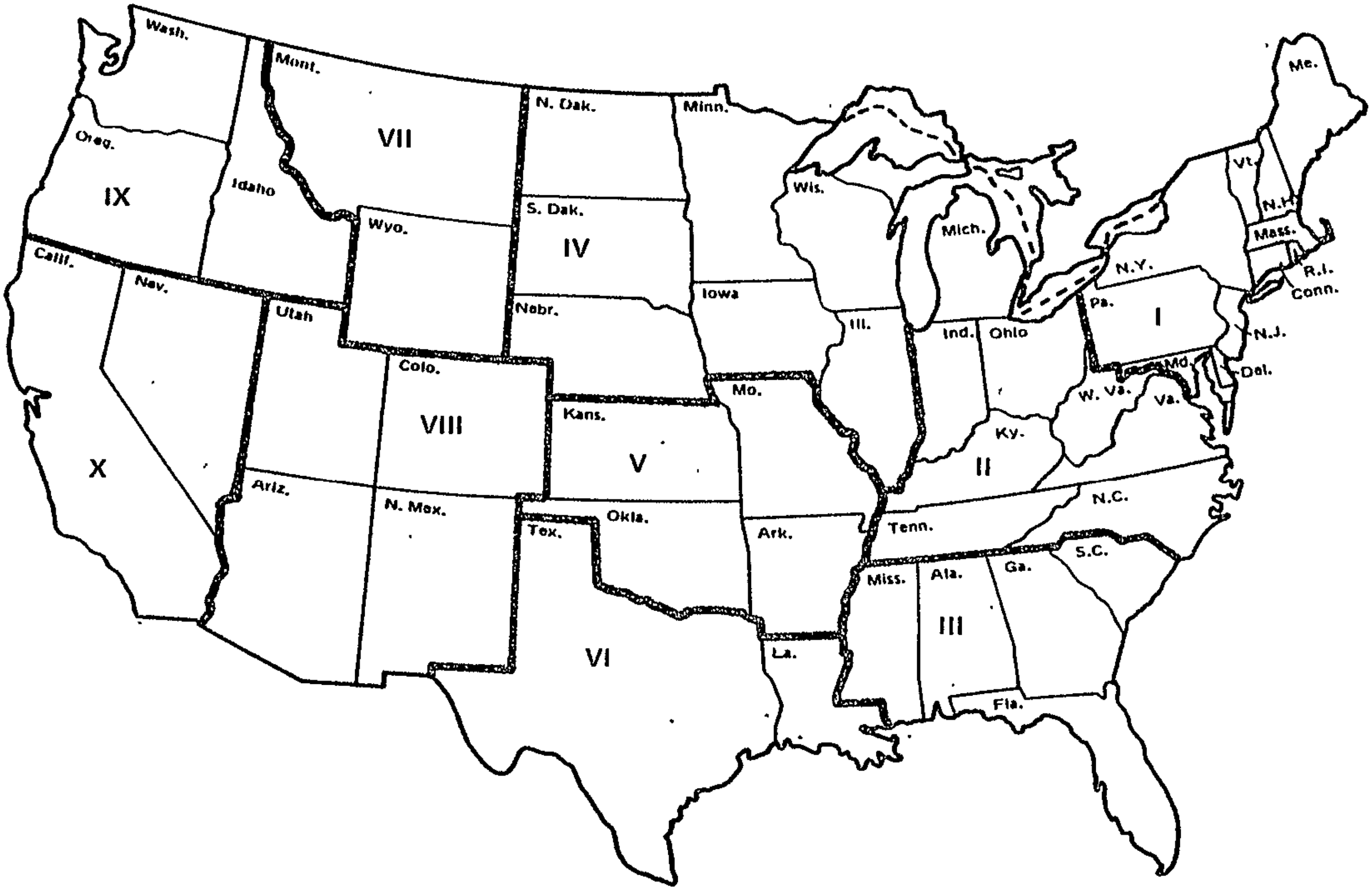

FIGURE 3.2 RECTENNA REGIONS AND NUMBERING SYSTEM

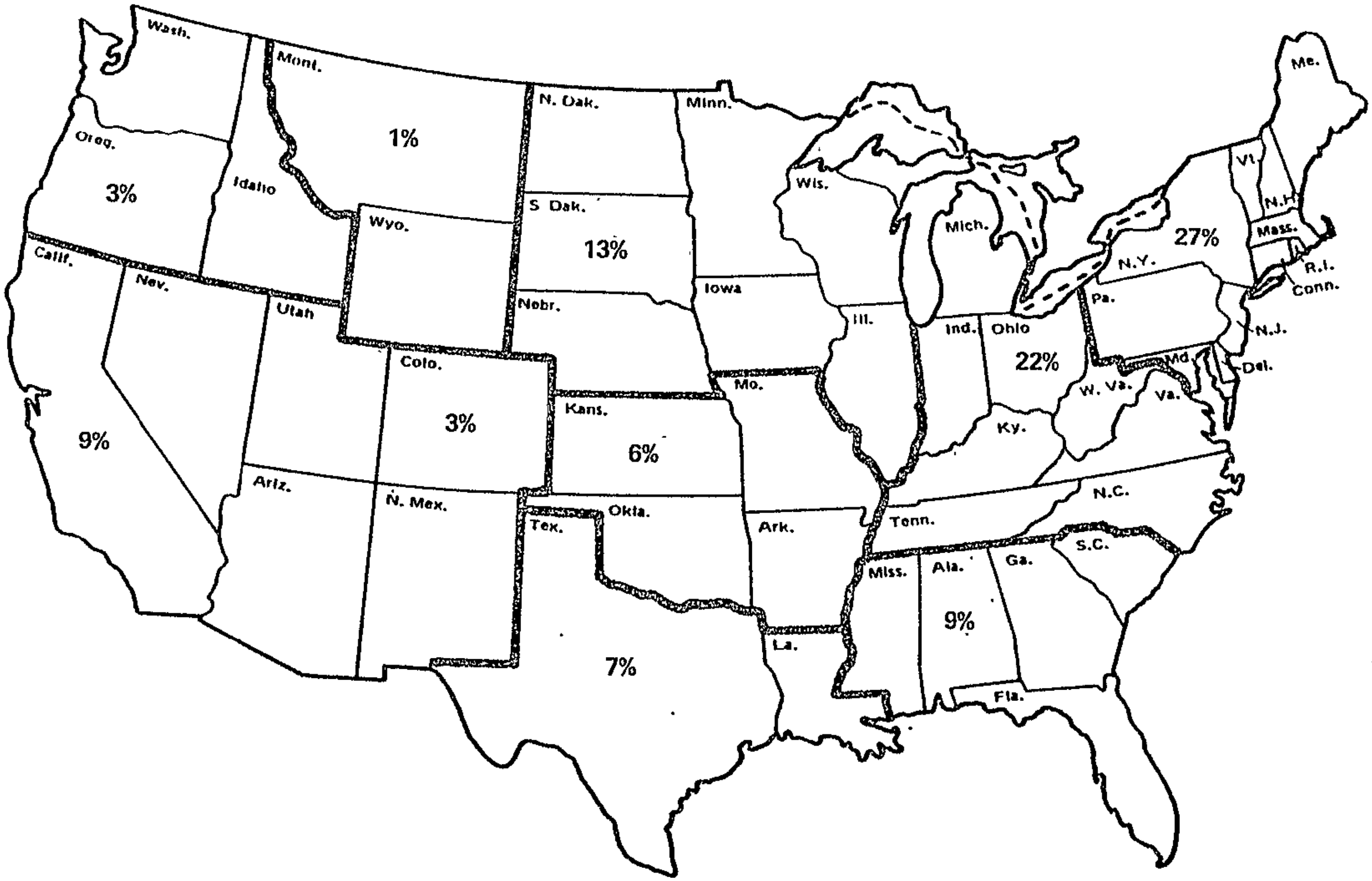

FIGURE 3.3 PERCENTAGE ALLOCATION OF RECTENNAS TO REGIONS, BY POPULATION

As can be seen from this map, approximately half the U.S. population is concentrated in Regions I & II, with 27% in Region I, occupying only about 6% of the total land area. The problem of finding a higher density of sites in these regions is compounded by the fact that, to a large extent, land suitable or desirable for rectenna sites in this part of the country is already intensively utilized for other purposes. Naturally, in these heavily populated areas, the land which has been left in a relatively undeveloped state (mostly in forest) tends to be that which is difficult to farm or settle, and often includes mountainous or swampy areas which pose obstacles to rectenna construction also.

3.4 SITING PROCEDURE

Given the target numbers for each region, site selection proceeded in the following steps:

1. Open areas of suitable size were found, mostly by reference to Sectional aeronautical charts, which were found to display an appropriate level of detail for initial screening. These charts show, amongst other things: roads, water features, cities and towns, airports, airways, air navigation facilities, terrain features, prominent landmarks, restricted flight areas, transmission lines, radio towers, wildlife refuges, political divisions, some parkland, railroads, and often some indication of vegetation. The first selection of tentative sites in each region was obtained from these open areas, mostly on the basis of land use and apparent human activity, often by cross-referencing Sectionals with other information sources, such as the National Atlas. The result was a large number of sites of uncertain acceptability.

2. All these preliminary sites were marked on a large-scale map, which served as a means of controlling and coordinating the wide variety of data which were to be accumulated. Using the rating schemes described in the next Section, scores were assigned to each site according to the following six characteristics: (i) water on site; (ii) terrain relief; (iii) roads on site; (iv) population in area; (v) nearby airports; and (vi) nearby airways. No attempt was made to combine these scores into a single indicator of the quality of the site, because there was little agreement about the relative weights to be given to them. However, the numerical scores did afford a profile of each site, according to these characteristics, allowing at least a qualitative distinction between "good" and "bad,' sites. These particular characteristics were chosen mostly because they involved significant factors and could be evaluated, at this preliminary screening level, using readily available data. In practice, the profiles provided a useful means of providing data on each site, an input to but not the primary determinant of the ranking of each site, which was settled in the final analysis by discussion amongst the study participants.

3. Based on the rankings developed, the target number of sites was selected for each region. For example, in Region III (the Southeast), some 25 sites were tentatively selected in preliminary screening, and the 9 highest-ranking sites were assigned to the primary list, for further investigation. The remaining sites were retained as alternatives, in case primary sites proved less desirable on the basis of additional data.

4. The sites on the primary list were then investigated more intensively, using other types of maps and data, including:

   - U.S.G.S. maps which break down land use and land cover into a number of categories, at quite high spatial resolution (40 acres or less). Unfortunately, as noted above, these maps are not yet available for the whole country.
   - Maps showing present power generating facilities and transmission lines, to find utility tie-points and to evaluate possible transmission-line right-of-way problems.
   - Large-scale topographic maps, showing transportation routes, towns in various population categories, topography, water, transmission lines, political jurisdictions, parks, forests (state and national), wildlife refuges, wilderness areas, Indian reservations, Federal lands, mines, quarries and many other features, at greater resolution than in Sectionals.
   - In some cases, aerial and Landsat photographs.

The primary difficulty which was found with these data sources was that some of them are quite out of date, perhaps twenty years old. This was of course of more consequence in connection with man-made features that with those of natural origin.

5. As a result of these studies, some of the sites were moved a few miles, and some of them were rejected. In the latter cases, replacements were obtained either from the tentative lists or from areas near the rejected site which seemed promising on the basis of the more detailed information. After a number of adjustments of this type, the final list of 100 CONUS sites was available, as presented in the next Chapter.

3.5 NUMERICAL RATING SCHEMES

3.5.1 Water On Site

The basis of this rating scheme was a judgment regarding the relative importance to rectenna design of various types of water feature, together with a means for accounting for the number and size of such features on each proposed site. Although the judgments involved are at best the result of a consensus between several subjective points of view, the procedure is at least internally consistent and, once the basis has been agreed to, it can be applied in an objective way to all sites.

To some extent, the judgments involved were based on experience gained during the site-selection procedure. For example, almost every site, except perhaps some in particularly arid areas, includes a number of small creeks or washes. These features are not expected to be of major consequence to rectenna design but, even if they were, they are so ubiquitous that discrimination between sites would not be aided by assigning high scores on them.

For present purposes, water features were divided into the following five categories, and each occurrence in a given site was assigned a score in the indicated ranges, depending on whether the particular feature was a small or large example of its type.

Feature	Small	Score	Large
Creeks	0	to	2
Ponds	1	to	4
Rivers	4	to	6
Wetlands	5	to	8
Lakes	6	to	8

The high score associated with wetlands was due, not only to engineering difficulties in such areas, but also to their importance to wildlife.

The raw source of each site was the sum of the scores for all the on-site water features. This was then converted to a rating between 0 and 10, using the nomograph shown in Figure 3.4. The slope of this graph was chosen after examination of the raw scores of many sites which were considered reasonable, so as to allow effective discrimination between them. The slope terminates at a rating of one because it was originally intended to combine ratings with respect to different characteristics into a single figure of merit and it was not desired to force outright rejection of a site merely because its water feature raw score was high.

3.5.2 Terrain Relief

For each site, maximum altitude change across the site was determined from topographic maps, and converted to a rating using the nomograph shown in Figure 3.5.

This simple rating scheme can be quite misleading because it does not include any indication of the roughness of the land, its general slope, or the orientation of the slopes. Particularly in the West, it may be possible to find sites with a smooth, uniform slope with a southern exposure, which would make quite desirable locations for rectennas but which would rate poorly because the south-to-north altitude change was large. Conversely, it is possible to find very broken areas (e.g., badlands) in which the altitude changes are quite small, but which would clearly make very difficult sites for rectenna construction. However, it is obviously possible to discriminate between these types of site by examination of contours, so that discretion in the application of this measure of terrain relief could improve its utility.

An improved measure of the difficulties with construction due to terrain could perhaps be found using a roughness coefficient, including some indicator of the horizontal extent of significant elevation changes. To make such a statistic meaningful, it would be necessary to take into account the ltype of rectenna construction which was to be used: sites which are very rought for some types of rectenna may be perfectly acceptable for others. These complications are sufficient to make any better terrain measure of doubtful utility in a preliminary survey.

3.5.3 Roads on Site

An attempt was made to quantify the number of roads in or about each proposed site, breaking them down into two general categories: primary roads (two or more lanes, paved, used as major highways) and secondary roads (gravel and dirt roads, some minor two-land paved roads). It was found that most sites have either a few (two to five) secondary roads crossing them, in areas lacking intensive land use, or else many roads crisscrossing the site every mile or two, in farmland or other reas of well-established uses. The number of sites with intermediate numbers of secondary roads was quite small.

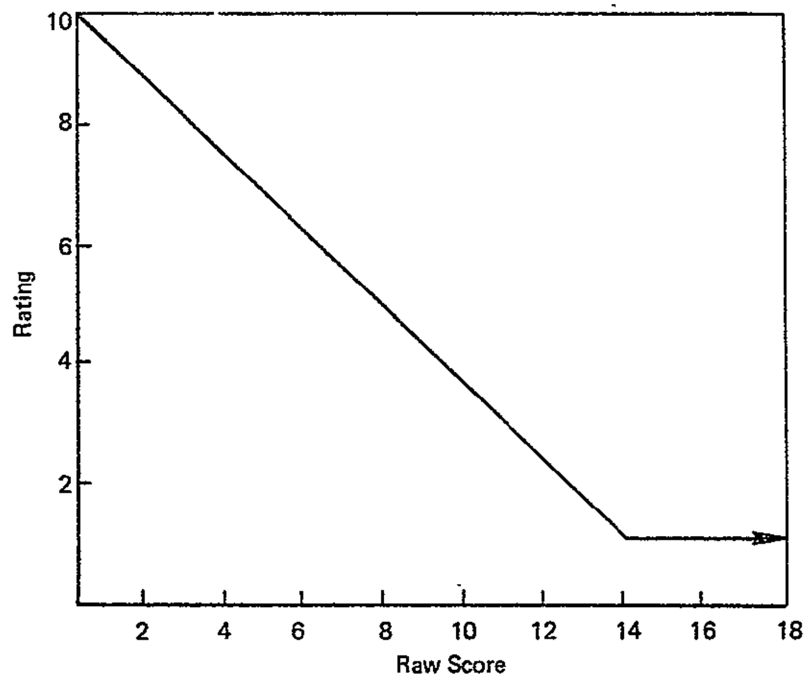

FIGURE 3.4 **SITE RATING NOMOGRAPH (WATER FEATURES)**

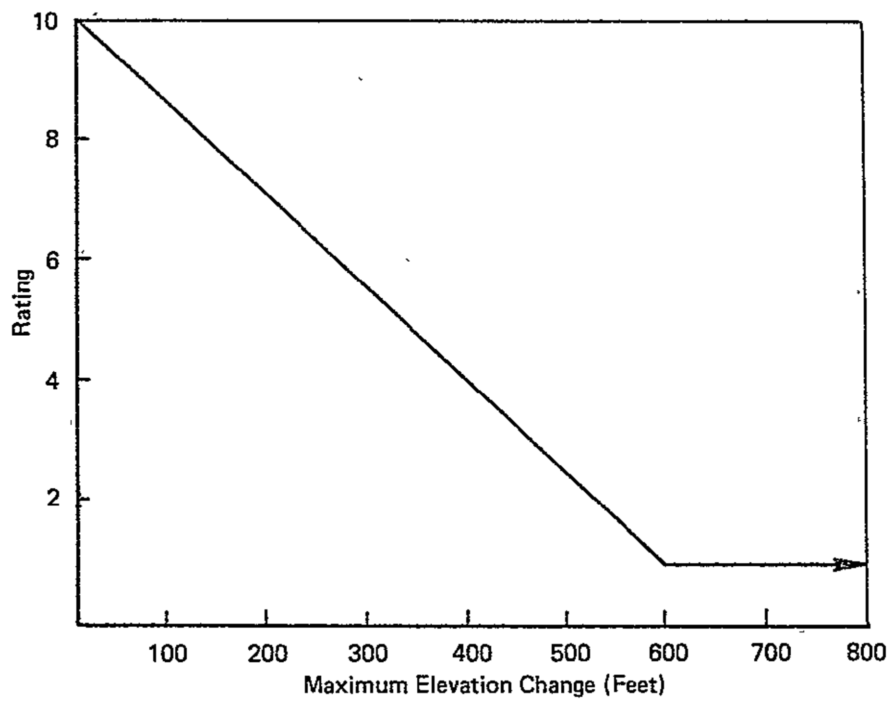

FIGURE 3.5 **SITE RATING NOMOGRAPH (TERRAIN)**

The raw score assigned to each site was calculated as the sum of twice the number of primary roads and a term which ranged from three to five, depending on the number of secondary roads. The score was then converted to a numerical rating, using the nomograph in Figure 3.6.

One of the difficulties with taking into account roads on site in evaluating potential sites is that it is not clear whether they should be regarded as an advantage or a disadvantage. It is certainly true that roads will be necessary for access to the site during construction and for maintenance thereafter, so that few roads means greater expense for obtaining rights of way and roadbuilding. On the other hand, there is a correlation between the number of roads and the existing activities on site, so that roads may be an indicator of conflicting land-use priorities. A more sophisticated rating scheme might be able to take account of these problems, perhaps by giving a maximum positive rating to a site with some, but not too many roads.

A different type of difficulty arises with respect to through roads, especially those which are of economic importance to surrounding towns, which is that of assessing the cost of either re-routing them or else protecting travellers on them from exposure to microwave radiation while crossing the site. It is clearly possible to shield all roads by erecting a wire-mesh roof over them, and it may or may not be justified to capture the energy incident on them by building elevated rectenna sections over them. The energy derived from a square meter of (horizontal) surface at the center of a rectenna at 40° latitude amounts to about 1150 kwh/year, with a value of perhaps $35 (@ 3¢/kwh). It may therefore be justified to spend several hundred dollars per square meter to avoid wasting the energy incident on roads.

3.5.4 Local Population

This is one of the most difficult characteristics to quantify in a meaningful way, at least without seeking information at the local level. Population density is usually reported on a county basis, which means that it is difficult to construct a spatial distribution of population on anything less than a scale of tens of square miles. If sufficiently detailed data were available, it would be possible to weight the population density by some appropriate function of distance from the site, and then to calculate an unambiguous score for rating purposes.

Because of the difficulty of obtaining detailed rural population data, an alternative scheme was used to get rough measures of population in the area of proposed sites. The number and distances of towns from the center of the site were noted, together with best estimates of their populations (crude data could often be obtained from maps, and in other cases census data were useful). For each town, the population was divided by the distance from the nearest site boundary, and the resulting people/mile figures were summed to give a raw score, which was then converted to a rating using the nomograph shown in Figure 3.7.

In some cases, there were small towns (never more than a few hundred people) actually within the proposed site boundaries; because there was no reason to discriminate between such towns on the basis of their position, they were always assigned a "distance" of one mile. At the other extreme, no towns were counted which were more than 20 miles from the site boundary, because it was assumed that such towns would be of little significance to an actual siting process — indeed, it can be argued that population centers at moderate distance are advantageous, providing a source for workers during construction and then operation of the facility as well as consuomers for at least come of the power generated.

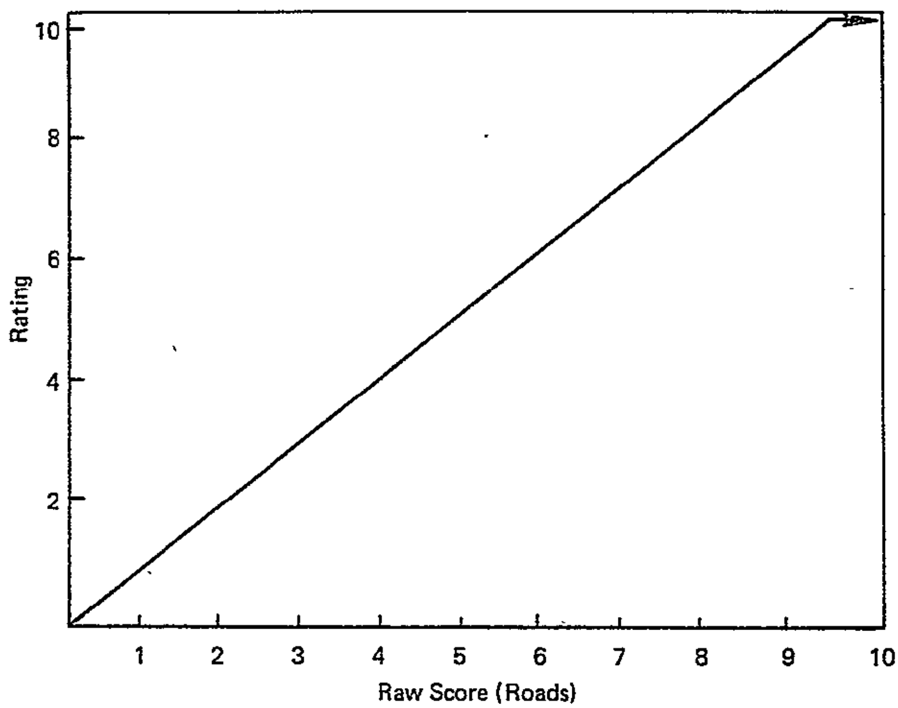

FIGURE 3.6 SITE RATING NOMOGRAPH (ROADS)

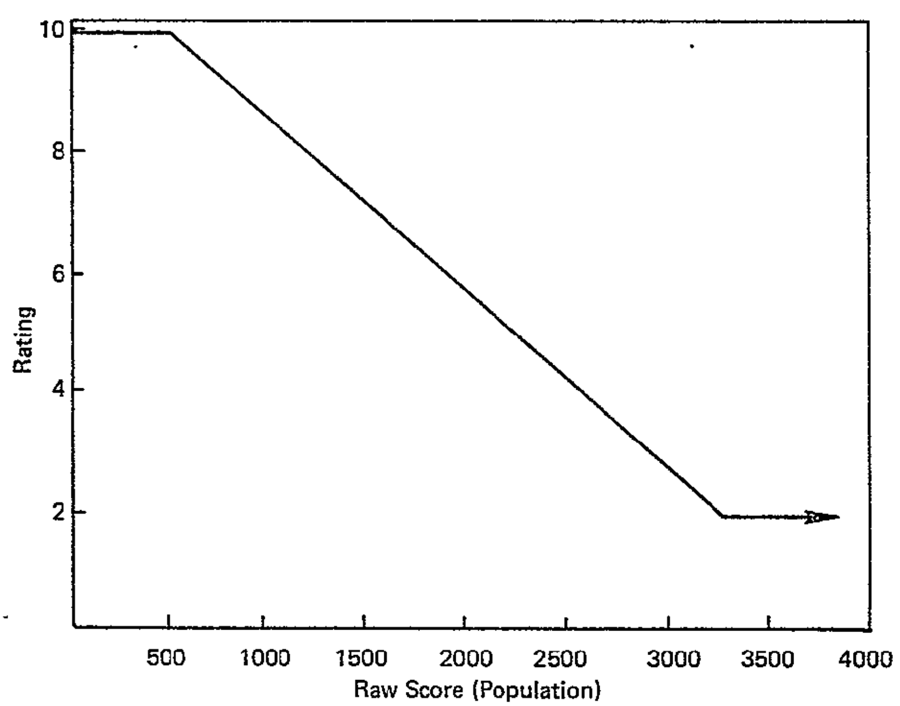

FIGURE 3.7 SITE RATING NOMOGRAPH (POPULATION)

3.5.5 Nearby Airports

In almost all the final site selections, it was possible to avoid locations which included any airfields actually within the proposed site boundaries, but many had small fields (mostly private, unpaved strips) within three or four miles. In rural areas, the public airfields within about ten miles were generally not more than short, paved stris, although larger fields were found in a few cases. In order to give a rough measure of the importance of the fields involved, the raw score consisted simply of the number of fields within ten miles of a site boundary (15 miles for airports with more than one runway), with paved strips being given a weight of two unpaved strips. The rating was then obtained from the nomograph in Figure 3.8, the slope of which again reflects experience with the siting process.

3.5.6 Nearby Airways

The raw score for this characteristic consisted of the number of airways sufficiently close to the proposed site to give concern about aircraft straying into the power beam, even when under IFR control. Airways whose centerline was within about 8 miles of a site boundary were counted, except those to the south, where airways up to 15 miles away were counted, the reason of course being that the power beam is inclined to the vertical at an angle α, greater than the latitude, given by Eq. (2.1). The score was converted to a rating using the nomograph in Figure 3.9.

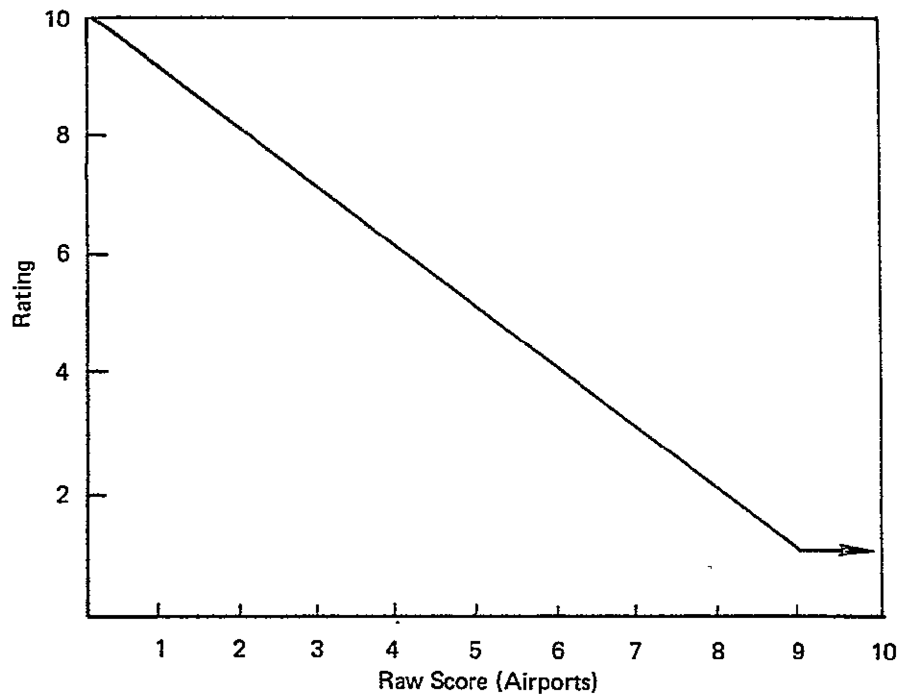

FIGURE 3.8 SITE RATING NOMOGRAPH (AIRPORTS)

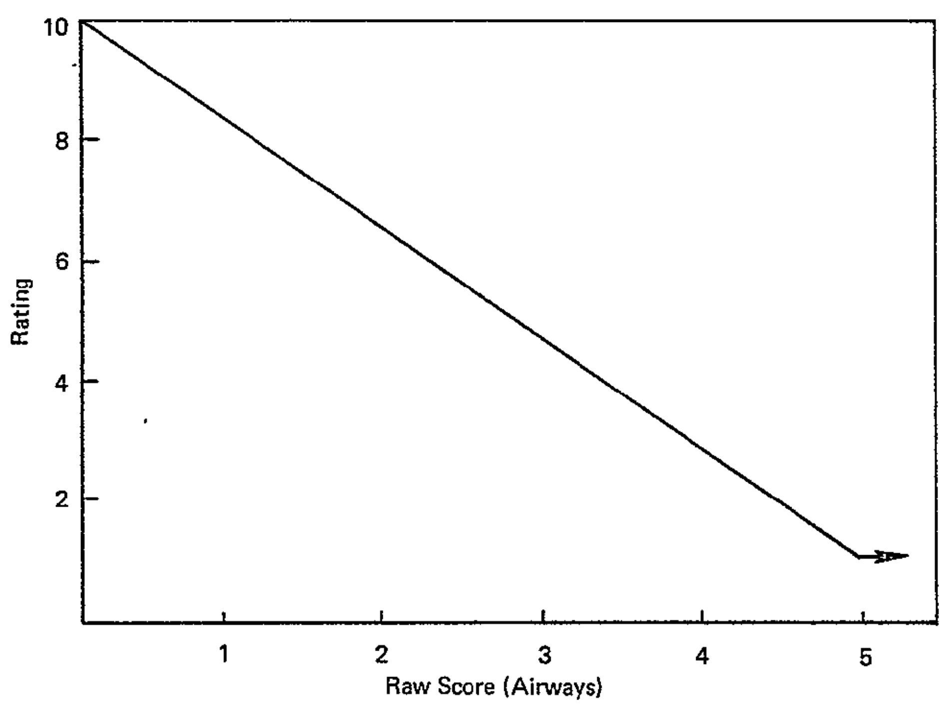

FIGURE 3.9 SITE RATING NOMOGRAPH (AIRWAYS)

CHAPTER IV
RESULTS OF THE STUDY

4.1 THE FINAL SAMPLE: ONE HUNDRED CONUS SITES

The siting procedure described in Chapter III provided, as its eventual output, a list of 100 nominal rectenna sites, each with its associated data sheet. The survey was too limited in scope to allow any claim to be made concerning the realism of any individual site selected, but, taken as a whole, the list provides a reasonable cross section of possible site characteristics. From the point of view of this study, the reason to go through the site selection process was to force a degree of realism in considering the SPS system design implications of rectenna siting problems. Identification of each site was necessary in order to compile information about typical site features; but, apart from this, the specific geographic locations are irrelevant.

The general nature of the siting problem is however exemplified by the broad geographic distribution of the selected sites, which is shown in Figure 4.1. The basic assumption that rectennas should be assigned to different regions of the nation in proportion to their populations is of course equivalent to the proposition that most rectennas should be located in areas which are already crowded, with well-developed patterns of land use. In the West, where sites are plentiful, the chosen locations are widely scattered; but the rectenna density is high in the Northeast, where siting is most difficult (in the figure, each dot covers about five times the area needed for a rectenna). It is clear that the siting problem would be greatly eased if economical long-distance power transmission became feasible — it might then make sense to locate virtually all rectennas west of the Mississippi.

In order to allow this set of sites to be used as a "strawman" in other studies, Table VII gives the coordinates of the centers of all the nominal rectenna locations. It is possible that publishing this list will permit misinterpretation, but it is hoped that the caveat given will be noted and will allay concern.

4.2 CHARACTERISTICS OF RECTENNA SITES

In order to examine the question of the regional variability of those characteristics of the nominal sites which may be directly important to the basic rectenna design, several sets of relevant data were tabulated by the rectenna regions shown in Figure 3.2.

4.2.1 Terrain Variation

The distribution of the maximum differences in elevation within individual sites is shown in Figure 4.2 for each of the regions and for CONUS as a whole. Although there is considerable spread within regions, it is clear that there are, as one would expect, characteristic differences between regions. In the Northeast, for example, the average variation in elevation across sites is 300-400 feet; in the Southeastern and Central regions, it is closer to 100 feet; and the Western regions have a great deal of spread, ranging from 300 to 1400 feet. In every region, it is possible to find fairly flat sites, but it is much easier in some areas than others.

TABLE VII

COORDINATES OF NOMINAL RECTENNA SITES

	Latitude	Longitude		Latitude	Longitude
1.	40° 51′	79° 10′	40.	43° 47′	86° 04′
2.	41° 40′	75° 15′	41.	37° 47′	82° 37′
3.	41° 16′	75° 00′	42.	36° 25′	78° 48′
4.	39° 10′	79° 22′	43.	39° 44′	85° 22′
5.	43° 22′	70° 50′	44.	38° 59′	85° 25′
6.	43° 40′	70° 42′	45.	41° 04′	87° 02′
7.	44° 51′	75° 46′	46.	35° 34′	86° 37′
8.	44° 28′	74° 31′	47.	36° 41′	87° 46′
9.	45° 53′	68° 05′	48.	39° 23′	78° 38′
10.	45° 08′	68° 30′	49.	32° 45′	82° 27′
11.	41° 42′	75° 52′	50.	30° 40′	88° 50′
12.	41° 11′	77° 42′	51.	31° 50′	88° 49′
13.	41° 28′	76° 16′	52.	33° 16′	88° 21′
14.	42° 33′	76° 46′	53.	26° 34′	80° 54′
15.	42° 37′	78° 19′	54.	33° 45′	86° 40′
16.	40° 40′	77° 05′	55.	31° 52′	83° 38′
17.	39° 17′	75° 46′	56.	30° 23′	85° 16′
18.	38° 51′	75° 40′	57.	31° 37′	81° 35′
19.	42° 43′	72° 44′	58.	34° 02′	88° 17′
20.	42° 26′	75° 43′	59.	42° 10′	92° 13′
21.	42° 45′	75° 24′	60.	45° 39′	99° 05′
22.	43° 13′	74° 49′	61.	41° 54′	98° 55′
23.	43° 35′	75° 17′	62.	40° 39′	88° 38′
24.	43° 34′	75° 37′	63.	41° 27′	89° 47′
25.	43° 39′	75° 46′	64.	40° 22′	90° 32′
26.	44° 42′	75° 15′	65.	44° 38′	90° 48′
27.	45° 07′	73° 52′	66.	42° 46′	95° 04′
28.	36° 05′	88° 40′	67.	44° 09′	89° 43′
29.	36° 18′	84° 50′	68.	43° 37′	98° 40′
30.	36° 40′	84° 24′	69.	47° 35′	100° 11′
31.	36° 55′	85° 31′	70.	41° 24′	94° 35′
32.	36° 00′	84° 53′	71.	45° 39′	95° 06′
33.	35° 36′	85° 26′	72.	37° 12′	96° 37′
34.	40° 21′	86° 13′	73.	39° 24′	96° 00′
35.	37° 22′	86° 53′	74.	35° 44′	99° 06′
36.	39° 12′	87° 48′	75.	34° 08′	97° 45′
37.	34° 30′	78° 30′	76.	34° 48′	96° 10′
38.	39° 00′	81° 30′	77.	33° 28′	91° 42′
39.	37° 24′	78° 16′	78.	37° 23′	90° 50′

TABLE VII (Continued)

	Latitude	Longitude		Latitude	Longitude
79.	33° 27′	100° 10′	90.	47° 32′	119° 10′
80.	29° 23′	96° 30′	91.	43° 15′	120° 25′
81.	32° 54′	91° 35′	92.	36° 38′	114° 23′
82.	31° 10′	95° 33′	93.	34° 21′	115° 02′
83.	32° 09′	94° 01′	94.	37° 49′	118° 06′
84.	28° 09′	99° 43′	95.	39° 39′	122° 22′
85.	46° 35′	109° 23′	96.	40° 17′	122° 27′
86.	34° 06′	103° 57′	97.	35° 30′	117° 58′
87.	36° 11′	104° 09′	98.	35° 40′	116° 11′
88.	38° 35′	104° 03′	99.	35° 25′	120° 02′
89.	43° 12′	113° 26′	100.	40° 34′	120° 15′

NOTE: The nominal locations for rectennas listed here have been selected only to exemplify generic constraints which may influence engineering design of the solar power satellite or rectenna systems. Many considerations have been ignored which are not of direct engineering interest but which may prove essential to siting decisions. For these reasons, none of the listed locations should be construed as suggestions as to where rectennas might actually be built if and when the SPS becomes operational.

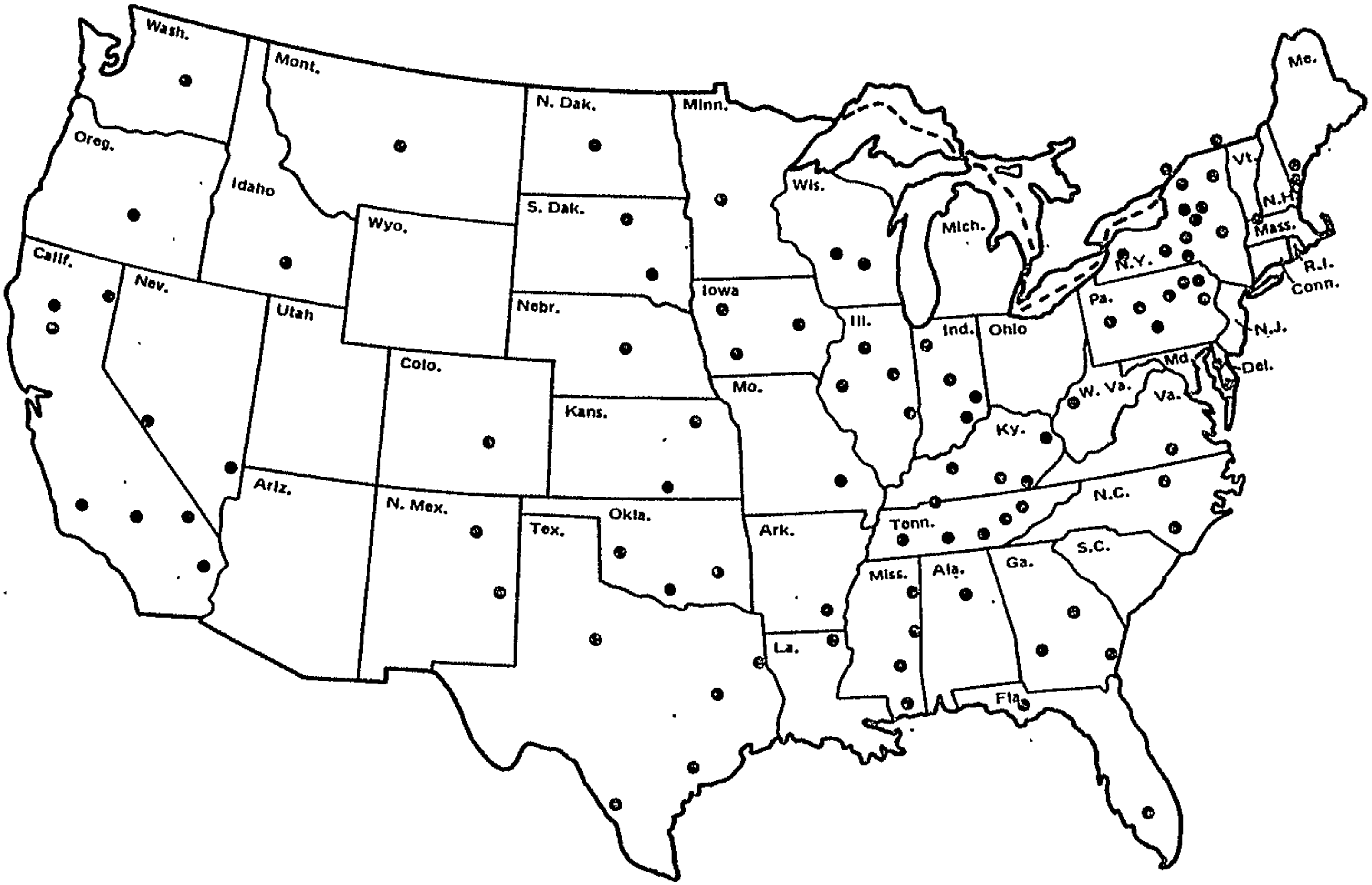

FIGURE 4.1 APPROXIMATE LOCATIONS OF NOMINAL RECTENNA SITES

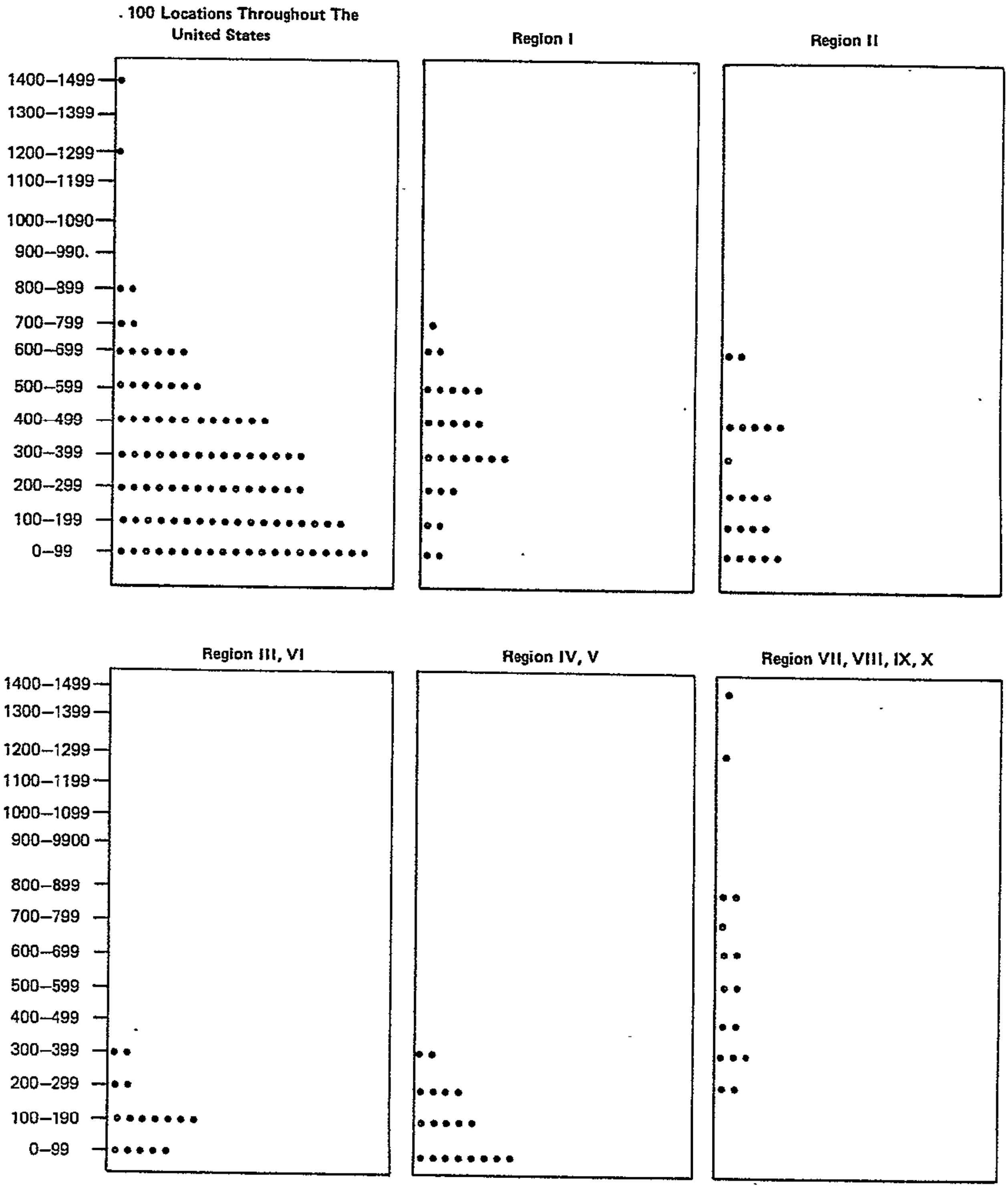

FIGURE 4.2 DISTRIBUTION OF TERRAIN VARIATION (MAXIMUM ELEVATION DIFFERENCE WITHIN RECTENNA SITE (Feet))

It is important to note again that elevation differences take no account of the horizontal scale of terrain relief, so that the distributions shown must be combined with other data to give meaningful interpretations. For example, it is not obvious from the figure that the Northeast is almost certainly a more difficult area, in terms of on-site terrain relief, than are the far Western regions, because of the much greater scale of the landforms in the latter areas.

4.2.2 Water Features

Figure 4.3 shows the percentage of the nominal sites having the indicated types of water feature within their boundaries. Ninety percent of the locations throughout CONUS have creeks or streams on site; 20% have small lakes; 19% have wetlands and 6% have rivers or canals. It is noteworthy that the Northeastern region has a higher percentage of sites with each of these features than in any other regions. The area of water, as a percentage of total area, is twice as high in the Northeast as the national average[19], and four times that in the West, so these results are not surprising.

4.2.3 Rainfall

Heavy rainstorms can be significant to the rectenna designer in several ways. There may be a minor reduction in the power output during such storms, due to absorption of microwave power; both erosion and flooding are more likely in areas with high rainstorm potential, factors which can be important both during rectenna construction and in affecting maintenance requirements; and heavy rain could result in increased leaching from the rectenna, leading to contamination of groundwater. The maximum rainfall during a 24-hour period, over a century of records, was examined for each site, giving the results shown in Figure 4.4. In most locations, rectenna installations must be designed to cope with 24-hour rainfalls of 5 to S inches. Unsurprisingly, there are Gulf Coast sites with considerably higher than average rainfall potential, and Western sites with considerably less. This is one area in which the Northeast region does not appear to be significantly worse than the national average, from the rectenna designer's point of view.

The possibility of soil erosion is related to the terrain relief as well as the rainfall, so a crude index was calculated by multiplying together the rainfall figures from Figure 4.4 and the elevation differences from Figure 4.2. As shown in Figure 4.5, this index exhibits a good deal of scatter, suggesting that realistic evaluations of erosion potential would require better data, relating actual slopes rather than elevation differences to rainfall.

4.3 CONCLUSIONS

Based on this study, there can be little doubt that a sufficient number of rectenna sites can be found to permit the SPS to make a major contribution to U.S. generating capacity, although social and political concerns will of course have a bearing on the number of acceptable sites and on their distribution. There is however a serious (and perhaps inevitable) mismatch between the regions where sites are readily available and those with high existing population density (and hence energy demand).

In the West, it is easy to find large numbers of what appear to be acceptable sites, mostly in desert areas. In many cases, rectennas could be built on flat, hardpan land of little present use, which would also minimize construction problems (the mobile factory, continuously weaving a rectenna as it moves back and forth across the site, might be quite feasible) and allow easy

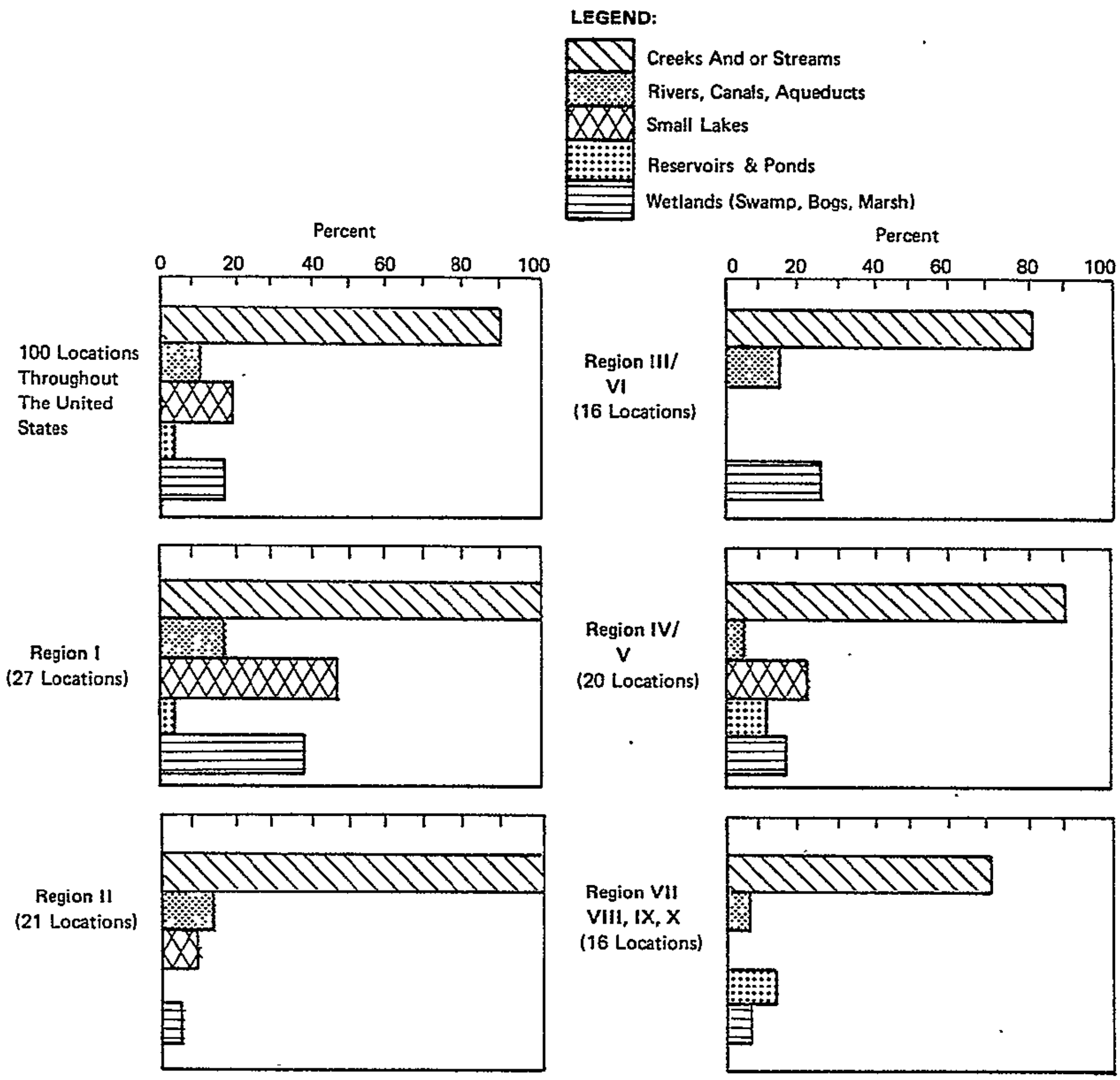

FIGURE 4.3 PERCENT OF LOCATIONS WITH VARIOUS WATER RESOURCES

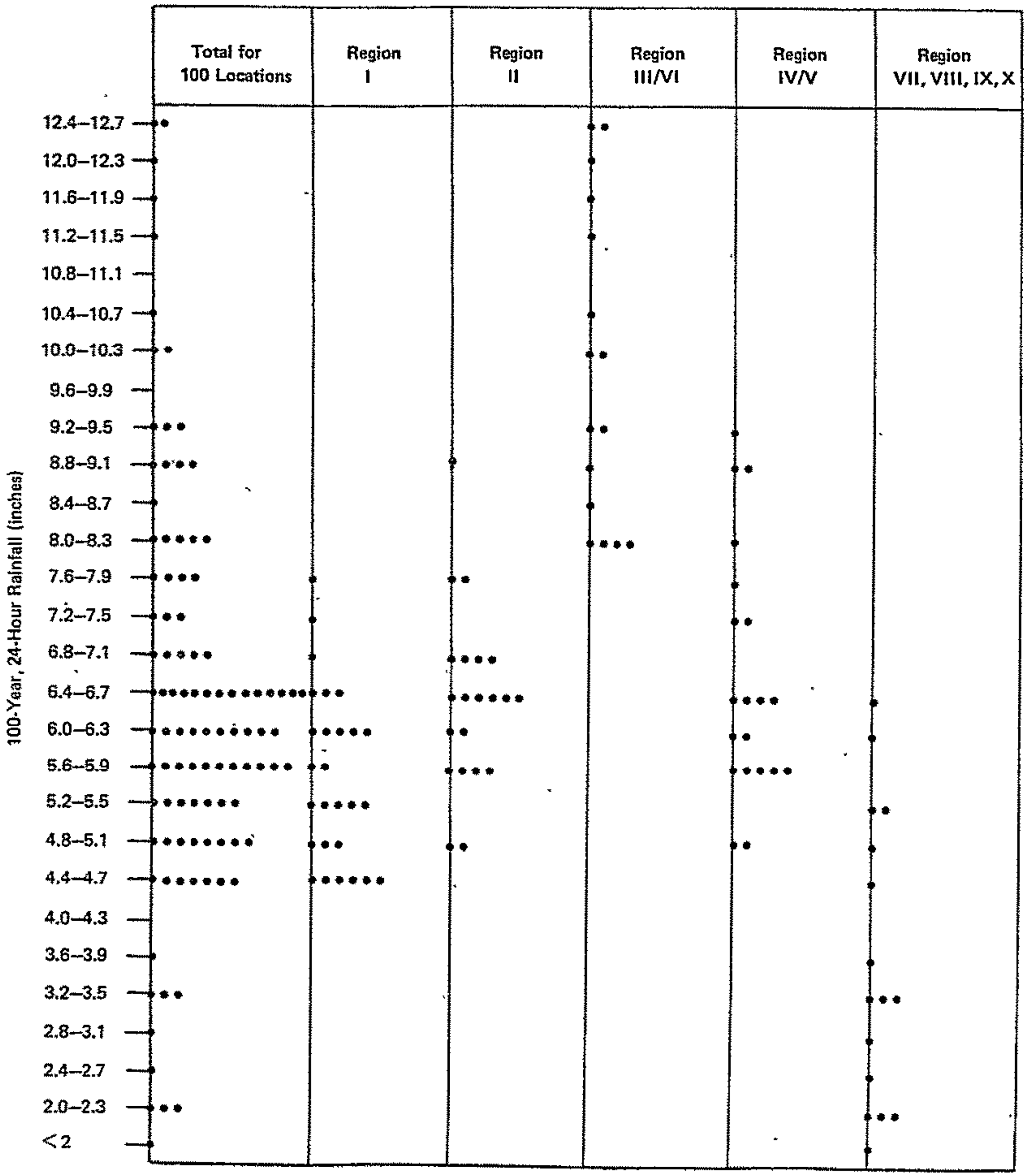

FIGURE 4.4 RAINSTORM POTENTIAL

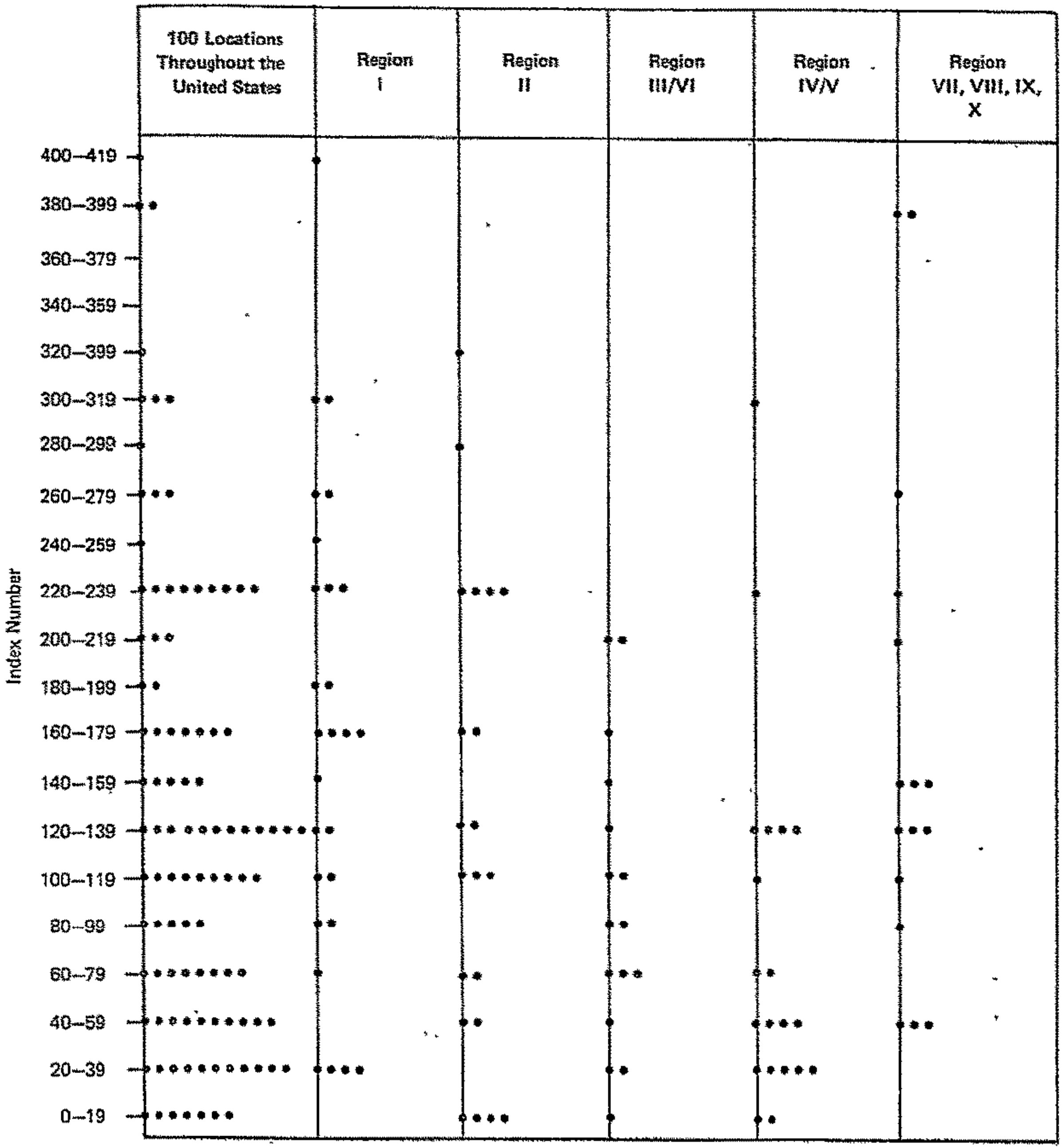

FIGURE 4.5 RAINSTORM/TERRAIN EROSION POTENTIAL

vehicular access for maintenance to all parts of the site. It is of course very likely that fragile desert ecosystems would be irrevocably changed by construction as extensive as that required for the rectenna, but such changes would be almost entirely confined within the boundaries of the site. Biota densities in such areas are generally so low, and the deserts are so extensive, that the impact of the rectenna would be quite small. It may be preferable to accept the inevitability of ecological changes due to the rectenna, attempting to design a new ecosystem adapted to it rather than trying to preserve the old. While it is important to preserve large areas of desert in their natural state, there is no reason to believe that limited and localized changes are necessarily damaging. For example, the impact of a rectenna would be less profound than that due to irrigation of a similar area of desert and conversion to farmland; and the importance of power production is in many ways, comparable to that of agriculture. It is interesting to consider the possibility of multiple uses for the rectenna structure in desert areas — for example, is it possible to design a rectenna which, at modest additional cost, would be adaptable to the creation of desert greenhouses on a large scale, to be used for recreation, for intensive agriculture, or for the production of biomass for fuels?

In the Midwest and Southeastern areas, large areas of flat land are available, but they are mostly now used intensively for agriculture. In some cases it is possible to find presently unproductive land in these regions which could be used for rectenna installations, but in general it would be necessary either to accept the cost of removing land from farming or else of devising rectennas which could be built in such a way as to permit continued agriculture beneath them. A study is needed of the mutual adaptability of rectennas and different types of crop. An elevated rectenna structure would presumably be needed to grow wheat or corn, but a sawtooth billboard rectenna at ground level might not interfere very much with many vegetable crops, so that the major cost of this multiple use would be wire mesh to protect workers from microwave radiation. An elevated rectenna would be needed for growing oranges in Florida, but in this case the waste heat from the rectenna might be of great value in preventing frost damage. Cotton would seem to be a good crop for a rectenna site, except that some alternative would be needed to the aerial spraying now extensively used.

The greatest problems with rectenna siting naturally arise in the crowded Northeast and MidAtlantic regions. From the data presented in the previous Section, it appears that, in these areas (where, according to the assumptions of the study, the greatest density of rectennas should be located), it is not only more difficult to find sites, but the ones found also exhibit more difficult terrain than in other regions, with rougher landforms and more problems with water features. This is due not only to the physical characteristics of the land, but to the fact the most of the easier sites have already been pre-empted by other intensive and incompatible uses. Many of the sites found in this study were not very satisfactory and more detailed investigation is needed to determine whether the Northeast rectenna siting problem is as challenging as it appears to be. There are of course a number of options available with respect to providing SPS power to the most populous regions of the country, and a trade-off study is needed to determine the best mix. They include:

1. Accepting the impact of rectennas, in terms of displacing people and facilities (this is of course what must be done when major hydropower facilities must be built, so there is precedent for this approach).

2. Utilizing long transmission lines (> 800 miles) to bring in power from regions (mostly west of the Mississippi) where rectenna sites are more readily available. Unless underground lines are developed, the land-use problems in obtaining right of way for such lines may be almost as difficult as those in finding local rectenna sites.
3. Building rectennas off-shore. There are interesting possibilities for multiple uses for floating rectennas, including provision close to fishing grounds of harbor and canning facilities for fishing fleets defense and Coast Guard facilities, and mariculture. Whether or not these uses could offset the additional costs of off-shore rectennas cannot be answered until at least a preliminary engineering study of off-shore rectenna systems has been carried out.
4. Building rectennas in rough terrain, in mountainous or swampy areas, or in areas now heavily forested, all of which impose additional costs.
5. Designing rectennas as desirable facilities, adapted to multiple land uses or compatible with existing uses.

One other problem should be mentioned with Northeast sites, which is that rectennas must of course be designed to cope with adverse weather conditions, including heavy snow cover and occasional freezing rain in winter. This problem is shared with many sites across the northern half of the nation. It was not possible to evaluate realistically the siting impact of these weather conditions, because there has not yet been even a preliminary study of rectenna designs to minimize sensitivity to these effects.

Although the effect was not investigated quantitatively, there is a strong impression from the site selection process that, in many cases, the difficulties of finding sites are related more strongly to the number of sites required than to the area of each. If costs are broadly construed to include societal and regulatory problems as well as expenditures, it appears that the marginal cost of increased rectenna area is less than the mean cost of that area. In other words, it may often be easier to build a rectenna of twice the area (and hence power output), or perhaps two adjacent rectennas, than to find two separated sites. As discussed in Chapter I, this phenomenon is one of those which can have a direct effect on the system design of the on-orbit SPS, and it is therefore worthy of more detailed analysis.

Finally, it is clear from the wide variety of terrain types encountered in the selection process, and from the above comments regarding the desirability of multiple land use, that a single rectenna design which can be installed anywhere is highly unlikely. Although the mobile rectenna factory could be useful in desert or perhaps prairie areas, there are so many sites which would require different construction techniques that such a factory is probably not worth developing. In practice, the commonality between rectennas should be at the billboard level: this type of rectenna design is adaptable to being erected in many different site-specific ways. The size of each billboard should be small enough to allow ease of handling during construction and maintenance (it is almost certainly better to replace billboards whenever the output drops below tolerance than to attempt to identify in the field and replace individual diode rectifiers).

4.4 DIRECTIONS FOR FUTURE WORK

The process used for site selection in this study involved many subjective elements, and the attempts at numerical site-rating schemes were primitive and unsatisfactory. It is entirely possible to develop an objective process for site comparison, based on detailed analysis of the various factors and their interrelationships. An example of such a site-impact model is the REAP system[20] for evaluating the local economic and demographic impacts of large-scale energy facilities. It would be very useful to extend this type of model to the broader range of considerations which are involved in rectenna site selection. With the addition of more detailed data sources, especially at the local level, such a development would greatly increase the credibility of site studies of the present type and provide needed data for evaluting the costs and benefits of the SPS as well as the system design.

To ensure realism in consideration of rectenna siting problems, it is recommended that that more detailed investigation be undertaken of a selected small sample of sites. Without implying that such sites are actual candidates for rectennas, mush useful information about the problems which may be encountered with rectenna installations could be obtained by exercises such as the preparation of Environmental Impact Statements for several potential locations. Local public opinion polls might also be useful in assessing the perceived costs of a rectenna installation, although there is a risk of arousing public opposition which would be quite unwarranted by a purely hypothetical study; moreover, it is not clear that present public attitudes about events which are more than a decade away can provide useful prediction.

Further work is urgently needed on the engineering design of different types of rectenna, with emphasis on their adaptability to different types of terrain and to various joint uses of the land. A preliminary study of the off-shore rectenna would be particularly useful. In all cases, it is recommended that modular rectenna designs be given highest priority.

Finally, as mentioned above, much further work is needed on the problems of siting rectennas in areas of high population density. For CONUS applications, the various options for overcoming the difficulties need analysis; but it should be noted that the list of available options may be much shorter in other parts of the world.

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