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MULTIOBJECTIVE LOCATION ANALYSIS OF REGIONAL ENERGY FACILITY SITING PROBLEMS

RICHARD L. CHURCH AND JARED L. COHON

October 1976

POLICY ANALYSIS DIVISION
NATIONAL CENTER FOR ANALYSIS OF ENERGY SYSTEMS
BROOKHAVEN NATIONAL LABORATORY
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FOREWORD

This report is one of a continuing series of policy analysis and model development studies in the area of energy facility siting prepared by the Brookhaven National Laboratory Regional Energy Studies Program, sponsored by the Division of Biomedical and Environmental Research, U.S. Energy Research and Development Administration. The intent of the research component addressed to siting model development is to prepare assessment tools appropriate to the regional scale of energy policy analysis. This contribution, prepared by consultants to the Regional Studies Program, explores the application of new multi-objective programming and location theoretic techniques to the regional siting problem.

Other reports in this series on energy facility siting include:

P. Meier, "Energy Facility Location: A Regional Viewpoint", BNL-20435, May 1975.

Energy Policy Analysis Group, et al., "A Preliminary Assessment of a Hypothetical Nuclear Energy Center in New Jersey", BNL-50465, Nov. 1975.

T. Backstrom and M. Baram, "Artificial Islands for Clustersiting of Offshore Energy Facilities: An Assessment of the Legal and Regulatory Framework", BNL-50566.

P. Meier and D. Morell, "Issues in Clustered Nuclear Siting: A Comparison of a Hypothetical Nuclear Energy Center in New Jersey with Dispersed Nuclear Siting", BNL-50561.

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The authors wish to thank Professor Charles ReVelle of the Department of Geography and Environmental Engineering, The Johns Hopkins University for his assistance in the initial discussions of the regional energy facility location problem.

I. INTRODUCTION

A. Background

In the past decade, due at least in part to the passage of the National Environmental Policy Act that emphasized the necessity for demonstrating an environmental evaluation of alternatives, utilities and their consultants have made increasing use of mathematical modelling and computer techniques in the siting decision-process. In particular, so-called site screening and overlay techniques have become widely used by the Architect-Engineer consulting firms commonly retained by electric utilities for site selection advice and environmental evaluation. Although a recent review of these models (Graf-Webster, 1975) reveal some differences in the mechanics of the process (manual map overlays as opposed to computerized systems, differences in weighting criteria, and others), all are based on the common procedure of selecting candidate areas (10's to 100's of square miles) from candidate regions (100's to 1000's of square miles); subsequently defining candidate sites (1 to 10 square miles); and finally selecting sites by some weighting of evaluation criteria to yield potential and preferred sites.

Public agencies involved in the siting process have also shown interest in the development and use of such tools. At the Federal level, two of the ERDA Laboratories have on-going research programs emphasizing computerized siting methodologies based on the screening-weighting approach; The Regional and Urban Studies Department of Oak Ridge National Laboratory has developed a computerized site screening model for both nuclear and fossil facilities using the State of Maryland as a case study (Yaffee & Miller, 1974) and the Energy and Environmental Systems Division of Argonne National Laboratory has developed a somewhat simpler model called "SITE" (Frigerio et al, 1975). And at the State Agency level, there are several examples of screening studies focussed on the identification and evaluation of power plant sites in a particular state. (New York, 1974).

To what extent such site screening and overlay methods are appropriate for regional analysis, however, remains in some question. In regional scale energy policy analysis the focus is on the analysis and resolution of rather broad trade-offs; in regional siting analysis, for example, there is typically little emphasis on particular sites, but much concern with site categories (e.g. estuarine v. inland, clustered energy centers v. dispersed siting, load center v. mine-mouth, etc.). The study of such trade-offs are not easily handled with conventional approaches.

Another important shortcoming of the site screening approach is its limited ability to address adequately the problem of cumulative impact, due mainly to its inherent focus on the individual site and the environmental impact at that particular location. Even though a particular facility may be judged to have no significant impact on a particular resource at a particular site, a more pertinent question from the regional view point concerns the cumulative impact of all facilities on that resource, not only those power facilities proposed for the short-term (which are within the focus of a site screening approach), but also all the facilities that might be proposed in the future, and including a consideration of the resource demands by other, competing uses (which are clearly beyond the capability of the site screening approach). This problem has been stated rather elegantly by Ertel, (1974) in her analysis of the controversy over the proposed diversion of

Connecticut River flood waters to Quabbin Reservoir and the Boston Water Supply System using the Northfield Pumped Storage facility

> "...the institute found no reason to question the assumption that the minimal flow reduction from this particular project would not have a "significant" impact upon the riverine ecosystem. What did appear, however, was general agreement that the cumulative effects of this diversion, of possible future diversions, of increasing needs for water supply in the Basin itself, and of other consumptive uses of water (i.e., for nuclear plant cooling purposes) would have a serious impact. That point of impact, however, cannot, on the basis of existing knowledge, be predicted. Therefore, project-by-project environmental impact prediction will never specify that "threshold point" at which the ecosystem would be seriously and irretrievably impaired. Each project will specify only the "minimal" effect of its own needs, not the cumulative effect of the many demands being placed on the river."

Yet, it is precisely this cumulative impact on a particular regional resource, over time and over all uses, that is of principal interest to the regional perspective. Thus to the regional policy analyst, the question of whether or not a particular proposed generating facility at a particular location will cause significant environmental impact is not nearly as important as the question of whether or not this facility is consistent with the optimum use of resources for power generation in the entire region. Thus, the regional perspective implies a longer temporal view than that necessary for the evaluation of a single project.

None of these arguments should be viewed as a criticism of site screening and evaluation techniques and their proponents, or indeed as a criticism of their utility. It is patent that the selection of specific sites is a very important part of the planning process, and the screening and overlay techniques now in use do represent a significant advance over methods less scientific. However, as a tool for regional policy analysis they would appear to require considerable extension.

B. Approaches to Regional Siting Analysis

The regional Energy Studies Programs at the ERDA National Laboratories, with their emphasis on regional energy policy issues, have suggested a number of alternative approaches to the development of siting models that are appropriate to the regional scale of analysis. At Oak Ridge National Laboratory a sophisticated approach based on political interaction analysis has been developed as an adjunct to their siting model, allowing resolution of regional siting issues in the context of a prediction of political feasibility (Yaffee, 1976). And at Brookhaven, emphasis has been on the development of operations research approaches that could interface with the ensemble of energy systems analsis models resident at BNL's National Center for Analysis of Energy Systems, and the regional environmental impact models at the BNL Atmospheric and Oceanographic Sciences divisions (Meier, 1975).

As an initial step in the development of such an operations research approach to regional siting policy analysis, this report presents an exploratory analysis of two areas of inquiry that appear especially promising. The first, examined in Chapter II, rests on the application of location theory, an area of inquiry that has seen a strong resurgence in the recent mathematical geography and regional economics literature as a result of its ability to address a rather large number of facility planning problems, in both the private and public sectors. The second area of inquiry, the focus of Chapter III, is multi-objective programming, a formalization of the notion that siting decision-making is an adversary process, in which a resolution of conflicting objectives is the key issue.

Multi-objective location modeling, a merger of the two areas of inquiry, may provide a useful analytical framework for regional energy planning. The Regional Energy Facility Location Model, which is based on such a merger, is presented in Chapter IV and various extensions of the basic model formulation are presented in the Appendices.

C. <u>References</u>

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II. LOCATION ANALYSIS

A. Introduction

The location-allocation problem can generally be described as the problem of finding the location of sources in some specified space so as to serve certain sinks with known locations and requirements in such a way that some objective is optimized. For example, in power plant location the problem would be that of obtaining the best combination of sites and transmission lines so as to minimize the total costs while maintaining desirable environmental standards. A generalized description of the location-allocation problem is as follows:

Given:

1. The locations of the sinks on a finite demand surface.
2. The requirements or demand level.
3. The costs of transport or delivery of service for a prespecified metric.
4. The cost associated with any potential source facilities.

Find:

1. The number of sources.
2. The locations of the sources.
3. The allocation of the sinks to the sources and amounts delivered or interaction level.
4. The capacity or total interaction level of each source.
5. The total costs or some measure of performance of the system.

Depending on the types of space and costs as well as the objective being optimized, a great variety of modelling formulations is possible.

B. Regional Science and Mathematical Programming Approaches

The subject of location analysis has undergone tremendous advancement in the past decade. Much of this interest and associated research can be attributed to the presence of the electronic computer. Most location research has been classified as belonging to one of two categories. The first is that area associated with regional science, economics, and sociology. Many modelling attempts have centered around description and prediction of migration patterns and clustering and other important patterns. Most regional science approaches can be though of as simulations of a locational problem: theories about location are incorporated into a model. A limited range of location decisions can be evaluated by testing policies with the simulation model.

The second area is essentially oriented toward mathematical programming. This category has developed from the opposite sense than the first category. Rather than trying to predict changes in patterns or understanding why a cluster or location appears, this area has concentrated on the formulation and solution of models that can be used to identify superior location alternatives. These techniques are prescriptive; they are used to support decision making. This second category which deals with the formulation and solution of decision (prescriptive) models is further categorized below.

C. Two Divergent Approaches

Basic research in mathematical programming approaches to identifying optimal location patterns has developed into the following two major areas:

1. Planar facility location models.

2. Network facility location models.

The classification of the two categories rests not on what type of facility is being located but the spatial characteristics of the solution space. The first major area has risen from the use of the euclidean plane as the potential solution space. Usually demand areas or customer areas are located on the plane as points. Potential facility sites are either allowed to be anywhere on the plane or only in special prespecified positions. Distances are usually measured with a euclidean metric, a rectilinear metric, or a function of either one. The secondary category has developed from the use of networks to represent the basic properties of the problem. Nodes of the network are usually considered demand areas and potential sites. Arcs denote the transportation routes or links between nodes. In certain problems all points on the network (i.e., nodes and arcs) are considered as potential facility sites. Thus, the essential difference between planar and network models is the definition of the area of feasible locations. Planar models may allow location anywhere within a prespecified area, while network models restrict feasible locations to a set of points that are connected by a network of arcs.

Controversy exists as to which basic approach (i.e., network or planar facility models) is superior overall. Both approaches have their advantages and disadvantages. The main appeal of the network problem is transportationally motivated: true links and costs of travel can be easily represented by the network. These spatial differences cannot easily be incorporated in planar models. On the other hand, the planar approaches seem more general, less tied to specifics, and more sensitive to the basic properties of the problem than the seemingly insignificant pecularities of a particular example. But in real applications, the optimal solution should be sensitive to the peculiarities of the specific problem at hand rather than the basic properties of a general problem. This has added lustre to the network approaches. In addition, many network problems have appeared easier to solve than similar planar problems. Furthermore, the proof of optimality of a particular network approach is usually easily developed due to the use of many integer-linear programming principles. The approaches in euclidean space have been harder to define in neat mathematical terms and have, thus, been harder to solve or the optimality of approaches has been more difficult to prove. However, as the number of nodes increases in the network problem, computational difficulty increases substantially.

Network approaches have been used in more applications than planar approaches due to the above properties. In a sense, planar problems have received their widest acclaim in theoretical circles. However, certain properties of the planar approach have made them particularly interesting in certain communications, observation, and defense oriented problems.

D. Private and Public; The Differences

Another basic area of classification in location modelling is motivated by the use that a model is designed to serve. Basically the major areas are classified as public facility location models and private facility location models (ReVelle, et al., 1970). The major difference between public facility models and private facility models rests on the identification of a realistic objective function.

The belief that mathematical location modelling can identify "optimal" location patterns rests on the basis that some realistic objective can be identified and by some measure quantified. For example, in the area of private facilities location analysis, a reasonably accurate statement of the objective of locating warehouses is to minimize manufacturing and distribution costs. Since most cost elements included in the objectives of private facility location can be reasonably estimated, the models can picture with some degree of accuracy the real location problem they are designed to solve.

Unlike private facility location analysis, the objectives of public facility location analysis are more difficult to capture and to quantify. The difficulty in defining direct measures for public facilities has resulted in a search for some surrogate measure with which the decision maker may be comfortable. Three different surrogate measures which have received attention in location models are: (1) total weighted distance or time for travel to the facilities, (2) the distance or time that the user most distant from a facility would have to travel to reach that facility, i.e., the maximal service distance, and (3) the population covered within a prespecified distance.

The development of a regional energy facilities location model also rests on the basis that some realistic objective(s) can be identified and in some way quantified. Unfortunately, a major complicating issue is that the regional energy model is not clearly publicly or privately oriented but a mixture of the two areas (i.e., there will both publicly motivated and privately motivated objectives). This means that tradeoffs between the objectives motivated by the private developers of the utilities (e.g., minimize cost of facility and distribution lines) and the objectives motivated by the public sector (e.g., keep facilities as far as possible from population centers) must be evaluated. This is a major complicating factor that makes the development of a regional energy facilities location model difficult and complex.

E. Specific Location Problems

It is beyond the scope of this brief review to discuss all possible areas in which topics of location analysis can play a role in the regional decision making for energy facility location and allocation. However, in order to hopefully show wide application of location analysis techniques as well as multiobjective analysis techniques a major portion of this paper deals with the development of a prototype model (incorporating several location and multiobjective techniques) which could prove useful in such decision making. The remaining part of this section deals with several covering location problems which have proved extremely useful in public facility location analysis. With this information part 3 of this section deals with the restructuring of a specific covering problem useful for nuclear plant location decision making.

1. Introduction to Covering Problems

Public facility location modelling has received a great deal of interest in the past five years. The main difference among many of the different approaches to public facilities location modelling is in the measure of effectiveness used. These measures are used to spell out how effective a particular location configuration is with respect to the overall purpose of the service and to the area the facilities are intended to serve. Numerous measures have been developed; the use of a particular one being dependent on the type of service provided. One example of an effectiveness measure which has been widely used is the total weighted distance or time for travel to the facilities (ReVelle, et al., 1970). The smaller the total weighted distance or time the more accessible the facilities are in general. Another example of an effectiveness measure is the distance or time that the user most distant from a facility would have to travel to reach that facility, that is, the maximal service distance (Toregas, 1971). For a given location configuration, the maximum distance which any user would have to travel to reach a facility would reflect the worst possible performance of the system. Many of the location problems incorporating the maximal service distance concept can be loosely defined as belonging to a class of "covering problems"

One covering problem which has received attention is the location-set covering problem developed by Toregas (1971), Toregas and ReVelle (1972) and Toregas, et al., (1971). This problem identifies the minimal number and the location of facilities which insures that no demand point (node) will be further than the maximal service distance from a facility. Case and White (1974) have designated this as the total cover problem.

Recognizing that in many circumstances it is not possible to provide the number of facilities to totally cover all demand within a desired maximal service distance, Church and ReVelle (1974) defined the maximal covering location problem. This problem may be stated as:

> Maximize coverage (population covered) within a desired distance S by locating a fixed number of facilities.

Church and ReVelle have presented a linear-integer programming formulation for the maximal covering problem which can be applied to either a network or a euclidean plane problem. For either case, potential facility sites are predefined and finite in number and demand points desirous of coverage are fixed and finite in number. Each demand point has a number or weight (e.g., population at that point) assigned to it which is the value associated with covering that point with a facility. A demand point is "covered" when the closest facility to that point is at a distance less than or equal to the desired maximal service distance. A demand node is "uncovered" when the closest facility to that node is at a greater distance than the desired maximal service distance. Their objective is to maximize the number served or "covered" within the desired maximal service distance by locating a fixed number of facilities. Their formulation can be used with linear programming and a branch and bound algorithm to identify optimal solutions to this type of maximal covering problem. Church (1974) has also employed several heuristics in solving this type of maximal covering problem which identify good or optimal solutions with great frequency.

Case and White (1974) have reported on a problem related to the maximal covering problem which they have designated as the partial covering problem. Whereas the total cover problem involves the determination of the minimum number and location of facilities such that all demand points are covered, the partial cover problem seeks the determination and location of a given number of facilities such that a maximum number of demand points is covered. The partial cover problem is actually a special case of the maximal covering problem where the covering weights assigned to each demand point are equal to one. Case and White have also discussed the use of a heuristic approach to the solution of the partial cover problem.

In the case of the maximal covering approach given by Church and ReVelle and the partial covering approach developed by Case and White, the potential facility sites are restricted to a finite number of prespecified points.

2. Solving the Maximal Covering Location Problem with Prespecified Facility Sites

The maximal covering location problem was formulated by Church and ReVelle (1974) in the following manner:

I. Max $Z = \sum_{i \varepsilon I} a_i y_i$

subject to

(1) $\sum_{j \varepsilon N_i} x_j \geq y_i$ for all $i \varepsilon I$

(2) $\sum_{j \varepsilon J} x_j = p$

(3) $x_j = 0,1$ for all $j \varepsilon J$

(4) $y_i = 0,1$ for all $i \varepsilon I$

where

I = denotes the set of demand points

J = denotes the set of potential facility sites

S = the distance beyond which a demand point is considered "uncovered"

$x_j = \begin{cases} 1 & \text{if a facility is allocated at site } j. \\ 0 & \text{otherwise} \end{cases}$

$N_i = \{ j \varepsilon J \mid d_{ij} \leq S \}$, the set of facility sites eligible to provide coverage to point i .

d_{ij} = the shortest distance from point i to point j.

a_i = population to be served at demand point i.

p = the number of facilities to be located

$y_i = \begin{cases} 1 & \text{if a facility is located within the coverage distance, S, of point i, i.e., is covered} \\ 0 & \text{otherwise} \end{cases}$

The objective is to maximize the number of people served or "covered" within the desired service distance. Type (1) constraints allow y_i to equal one only when one or more facilities are established at sites in the set N_i. The number of facilities allocated is restricted to equal p in constraint (2).

An equivalent form to the above problem can be structured as:

II. Min $Z = \sum_i a_i \bar{y}_i$

subject to

(5) $\sum_{j \in N_i} x_j + \bar{y}_i \geq 1$ for all $i \in I$

(6) $\sum_{j \in J} x_j = p$

(7) $x_j = 0,1$ for all $j \in J$

(8) $\bar{y}_i = 0,1$ for all $i \in I$

where

$$\bar{y}_i = 1 - y_i = \begin{cases} 1 & \text{if demand node } i \text{ \underline{not} covered by a facility within } \overline{S} \text{ distance} \\ 0 & \text{otherwise.} \end{cases}$$

The Formulations I and II are equivalent since one can be transformed mathematically into the other by a simple variable substitution. The objective of Form II can be interpreted as minimizing the number of people that will not be served within the desired maximal service distance S. Formulation II has been utilized in optimally solving the maximal covering location problem using linear programming and a branch and bound algorithm. Computational experience and further refinements of the approach are given in Church and ReVelle (1974) and Church (1974). Formulation II can also be used to solve the partial cover problem defined by Case and White by assigning $a_i = 1$ for all $i \varepsilon I$.

3. The Minimum Impact Location Problem

Parts 1 and 2 of this section have been included in order to clearly define some of the developments of covering location problems. However, until now no mention has been made about how these developments can help in energy facility planning. Although the maximal covering location problem is not directly applicable to power plant facility location, certain elements of the maximal covering problem can be used advantageously in nuclear power plant facility location. Essentially, in locating nuclear power plants one would want to (1) provide an exclusion area and (2) minimize the amount of population within a given distance of the plants. This is done in order to provide a measure of safety for long term low level exposure and for the risk of an accidential breakdown. The second objective is very interesting in that it is essentially the opposite of what the objective is in the maximal covering problem. In essence one would try minimizing the coverage by locating a number of facilities. This problem will be called the minimum impact location problem (MILP) and is essentially the opposite of the maximal covering location problem. By using information on the MCLP one can easily define the following MILP:

$$\text{Min} \quad Z = \sum_{i=1}^{n} a_i \bar{y}_i$$

subject to

$$(9) \qquad \sum_{j=1}^{n} x_j = n-p$$

$$(10) \qquad x_j - \bar{y}_i \geq 1 \qquad \text{for all } j \varepsilon N_i \text{ and all } i$$

$$(11) \qquad x_j, \bar{y}_i = 0,1 \qquad \text{for all } i \text{ and } j$$

where $N_i = \{ j \varepsilon J | d_{ij} \leq S \}$

S = shortest desired service distance

d_{ij} = shortest distance between i and j

a_i = population at point i

$\bar{y}_i = \begin{cases} 1 \text{ if demand area } i \text{ is covered by any site} \\ 0 \text{ otherwise} \end{cases}$

$x_j = \begin{cases} 1 \text{ if facility is } \underline{\text{not}} \text{ established at point } j \\ 0 \text{ otherwise} \end{cases}$

n = number of sites

p = number of facilities

The above problem locates a fixed number of facilities while minimizing the number of people within S distance of the facilities.

The above section has shown the development of covering problems and associated application in nuclear plant location. Similar problems exist in the location literature which can be applied or modified for nuclear facility location. The above example is incorporated in the development of the safety section of the RELM model given in this paper.

F. Summary

It is important to recognize that both the regional science approaches and the mathematical programming approaches to location analysis can prove valuable in regional decision making for the location of power plants and refineries. Disciplines in regional science can help analyze and predict spatial and socioeconomic impacts for a given facility location configuration. The mathematical programming approaches to locational analysis can prove equally valuable in regional decision making by using imputed information (like the socioeconomic impacts) and determining a best or optimal configuration on the basis of a stated objective and a structured constraint set. When more than one objective is considered then special approaches of multiobjective analysis must be used.

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III. MULTIOBJECTIVE ANALYSIS

A. Introduction

Multiobjective analysis represents a relatively new approach to planning and problem-solving. Its role in public investment theory was first delineated by the economist Stephen Marglin in Maass, et. al., (1962) and in Marglin (1967). The implications of multiobjective analysis for mathematical programming were first discussed by Kuhn and Tucker (1952) although their observations were generally unused until the early 1960's. In this section multiobjective analysis is explained both as a planning device and as a mathematical programming procedure; several multiobjective solution methods are categorized and reviewed; and potential application of multiobjective analysis to regional energy facility siting is discussed.

B. The Economic Rationale for Multiobjective Analysis

Multiobjective analysis has been developed and applied to real problems because it represents an important generalization of conventional single-objective analytic methods. A multiobjective problem exists whenever it is inappropriate to select a single, unambiguous measure of system performance. An acceptable single criterion for selecting one alternative over another is frequently not found in private sector problems and rarely found in public sector problems so that it can be stated with some confidence that multiobjective problems are ubiquitous and their solution, therefore, is of practical significance. The remainder of this review will concentrate on public sector problems.

Conventional approaches from neoclassical welfare economics base the evaluation of alternatives in the public sector on a single objective — the maximization of net economic efficiency benefits. The value of these benefits have a precise, theoretical meaning (gross economic efficiency benefits resulting from a good or service are defined as the area under the demand curve up to the amount of good or service provided), but in practical application measurement problems frequently arise because of inadequate or nonexistent data, the absence of markets for certain goods and services, or the inappropriateness of the criterion for measuring certain project effects. Thus, for example, the economic efficiency benefits which would result from the construction of 10,000 MW of new electrical generating capacity in the Northeast United States are difficult to estimate for all three of the reasons cited above. Data problems are prevalent in the estimation of demand curves for electricity. Markets do not exist for the cooling capacity of water so that the economic efficiency benefits (disbenefits) of cooling water use for the new capacity could not be easily estimated. Finally, it would be clearly inappropriate to place a monetary value on the safety aspects of nuclear generators (although, no doubt, some economists would attempt to do just that).

Multiobjective problems arise when project impacts cannot be conveniently put in monetary terms in that non-commensurable effects, e.g., dollars and degrees above natural water temperature, exist. Furthermore, even when all would agree on a monetary measure, the existence of many conflicting interest groups and actors in the public decision making process also promotes multi-objective analysis.

It is generally accepted that many (some would say most or all) public sector problems are multiobjective in nature and that this is due to incommensurable project impacts and the multiplicity of actors in the decision making process. It is impossible to make a general statement about the specific objectives that should be considered in public sector planning since they are (and should be) problem specific. A discussion of the major types of objectives that frequently occur in public investment planning may be of interest so that three types are discussed.

Economic efficiency continues, of course, to be a major objective of public investment — no one wants to be inefficient unless there is a good reason. The several issues which arise in measuring economic efficiency benefits are thoroughly discussed by Prest and Turvey (1965).

One of those good reasons may be a distributional or equity objective or objectives. An equitable (or to be more cynical, "politically feasible") distribution of project impacts is rapidly becoming an objective which all public planners everywhere must explicitly consider. Whether a beneficial project output such as water or electricity or an undesirable impact such as costs, displacement, pollution or inconvenience is at issue, people or groups can be expected to make a claim for inequities, where an "equitable" alternative is one in which they are better off. Cohon and Marks (1973) demonstrate one procedure for incorporating an equity objective into multiobjective river basin planning. Major et al., (1975) show another approach while Brill (1972) discusses many different mathematical formulations of an equity objective for water quality planning.

A third category of objectives is environmental quality — a popular issue of the 1960's and a formal planning requirement since the National

Environmental Policy Act (NEPA) of 1970. Environmental quality is also ubiquitous in public investment planning in the United States since any structural alternative disturbs the environment and since the objective has been institutionalized. A major difficulty with the measurement of environmental quality is its multidimensional nature: there is air, water, land and noise pollution each of which is measurable by a large set of parameters. Thus, for any particular problem there may be several environmental quality objectives, e.g., minimize dissolved oxygen deficits in streams, and minimize the difference of effluent temperature and ambient stream temperature. Miller and Byers (1973) applied multiobjective programming to a watershed design problem in which environmental quality objectives were important.

Procedures for the identification and quantification of objectives have been largely unexplored owing, perhaps, to an emphasis on the development of solution techniques rather than application. Cohon (1975) has discussed this aspect of planning in the context of experiences gained from applications.

C. Multiobjective Analysis and Mathematical Programming

Multiobjective analysis has had a significant impact on systems analysis and on one of its major sets of techniques — mathematical programming. The development of multiobjective programming (or vector optimization) techniques has brought a new dimension of reality to systems analysis that may allow it to fulfill its potential as a practical evaluative tool. Conventional models with a single objective function yield a single, "optimal" solution which prescribes a course of action for decision makers. A single solution for a multiobjective public sector problem is useless for decision makers. Instead, decision makers must be intimately concerned with the range of choice; if that range is a single alternative, then decision makers are unnecessarily constrained. Furthermore, if the implications of alternatives for all of the relevant objectives are not indicated, a single-objective approach may be actually misleading.

Several multiobjective programming methods have been presented in the literature. [See, for example, the conference proceedings: Cochrane and Zeleny (1973) and Zeleny (1976).] Before discussing these techniques a few definitions will be presented. The general multiobjective maximization problem can be stated as,

$$\max_{\bar{x} \text{ feasible}} \quad [Z_1(\bar{x}), Z_2(\bar{x}), \ldots, Z_p(\bar{x})] \tag{12}$$

where $\bar{x}$ is an n-dimensional vector of decision variables and $Z_k(\bar{x})$ is the k^{th} objective which is a function of the n decision variables. Thus, the problem is to maximize all of the p objectives simultaneously while maintaining feasibility which is defined by constraints on the decision variables. Conventional, single-objective problems differ from the problem stated in (12) only by the dimensionality of the objective function.

The central notion in multiobjective problems is that of noninferiority (efficiency, Pareto optimality or admissability are equivalent concepts in different contexts) which replaces the idea of optimality of single-objective problems. A solution is noninferior if there is no other feasible solution which yields a higher value of one objective without yielding lower values of at least one other objective. Inferior solutions, therefore, are dominated solutions in the sense that there exist feasible alternatives which are better on the basis of all objectives. These concepts are shown in Figure 1 in which point C is clearly inferior since there exist feasible solutions such as B and D that dominate C, e.g., Z_2 can be increased by moving from C to D without decreasing Z_1. Points A, B and D are noninferior since there are no feasible points which dominate them. Clearly the solutions of interest are the noninferior solutions. The collection of noninferior solutions is called the noninferior set which is shown as the cross-hatched portion of the boundary of the feasible region in objective space in Figure 1. In multiobjective problems there are tradeoffs among the objectives. In Figure 1 as one moves along the noninferior set from A to D to B, one objective increases while the other objective decreases. The amount which one objective must be sacrificed to gain some amount of another objective is the tradeoff.

The noninferior set contains fewer than all of the feasible solutions, but there is still a wide range of choice within the set. If preferences defined over the objectives are stated then one alternative from among the noninferior solutions is unambiguously superior. This solution is called the "best compromise solution", and it can be shown graphically as the point in the noninferior set at which an indifference curve is tangent to the noninferior set as shown in Figure 2.

D. Multiobjective Programming Techniques

Cohon and Marks (1975) suggested three major categories for multiobjective solutions methods: generating techniques, techniques which rely on a

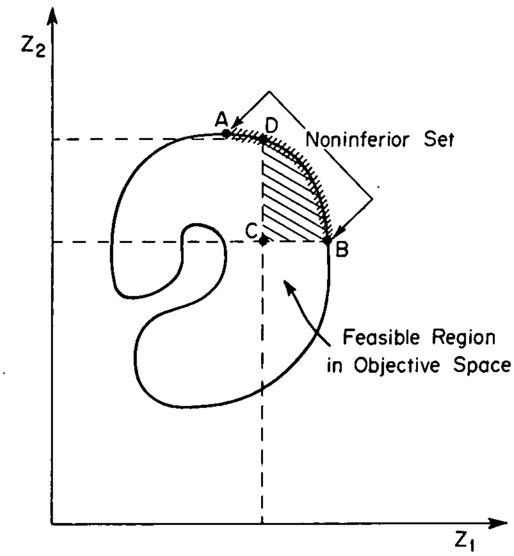

Figure 1. Definition of noninferior set.

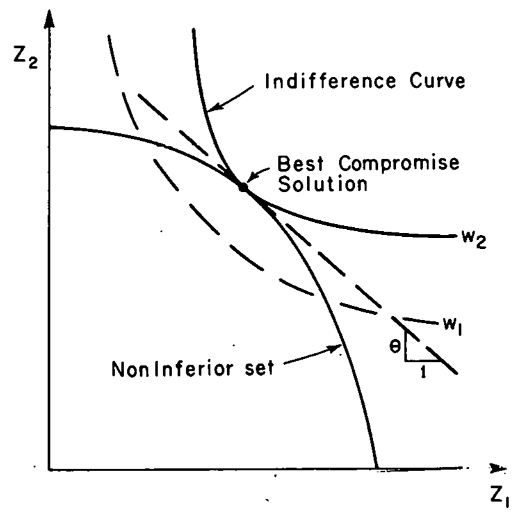

Figure 2. Definition of best compromise solution.

prior statement of preferences and techniques that develop preferences iteratively. A fourth category is discussed here, as well: multiple decision maker methods. Each of these types of methods has a role in the analysis of planning problems but these roles differ considerably so that there is some danger of using the wrong technique in certain situations. The characteristics of each of these categories is discussed in more detail below. In addition those specific methods which are currently applicable to large-scale real problems are mentioned. A review of most of the existing methods is presented in Cohon and Marks (1975).

1. Generating Techniques

Generating techniques emphasize the importance of information in the decision making process. The goal of these methods is the development of an adequate approximation of the noninferior set thereby delineating the full range of choice. Tradeoffs are shown explicitly and the onus is on decision makers to articulate their preferences in selecting an alternative from among the generated noninferior solutions. An important result of the solution process is a great deal of insight into system performance which analysts and decision makers gain.

Generating methods of significance include the weighting and constraint methods, the noninferior set estimation (NISE) method and the multiobjective simplex method. The weighting and constraint approaches proceed by converting the vector of objectives into a single-objective problem so that conventional techniques may be used. Variation of the parameters (weights or constraints) traces out an approximation of the noninferior set. The constraint method is relatively easier to use because with most existing linear programming codes parametric variation of constraints is more straightforward than is parametric analysis of the objective function. Cohon and Marks (1973, 1975) discuss both of these techniques in detail.

A technique which is a more efficient version of the weighting method is the noninferior set estimating (NISE) technique presented for two-objective problems in Cohon, et. al., (1976) and applied in Church, et. al., (1976). Computational efficiency is gained by exploiting the shape of the noninferior set. In addition, the NISE algorithm guarantees that the best available approximation is available even when the procedure is terminated prematurely.

The multiobjective simplex method is presented in Zeleny (1975). Unlike the other generating methods, the multiobjective simplex finds all noninferior solutions. It is too computationally intensive for large-scale problems, and as an approximating technique it is not as efficient as the other generating methods.

At their current stage of development generating techniques tend to be computationally burdensome for problems with four or more objectives. In addition, higher dimensional problems present difficulties in the presentation of results. The tradeoffs among two or three objectives can be conveniently and dramatically shown as in Figure 2, but four or more objectives preclude a concise, graphical presentation. To a large extent, higher dimensional problems are just simply difficult for analysts and decision makers regardless of the solution technique which is used.

2. Methods Which Rely on Prior Articulation of Preferences

Methods which rely on prior articulation of preferences prescribe quite different roles for analysts and decision makers. The emphasis of the methods in this category is on the definition of decision makers' preferences. The statement of preferences can take the form of weights on the objectives, constraints on the objectives, a multiattribute utility function, or goals and priorities for the objectives. With the statement of preferences the analyst can then proceed directly to the best compromise solution without generating an approximation of the noninferior set. Solutions "techniques" for the cases of weights and constraints are not really required since only one single-objective problem need be solved. Marglin (1967) discusses these two cases.

Multiattribute utility theory has been developed by Raiffa (1968, 1969), Keeney (1969) and others. An excellent review of the theory and its application is provided by Farquhar (1976). Geoffrion (1967) presented an algorithm for proceeding from a statement of a multiattribute utility function to the best compromise solution for two-objective problems. Goal programming (Charnes and Cooper, 1961) is perhaps the best known multiobjective technique. It proceeds by eliciting a target and a priority for each objective. A new problem is then formulated to minimize deviations (weighted by the priorities) from the targets on the objectives. A possible problem with this technique pointed out by Cohon and Marks (1975) is that some targets and priorities may lead to inferior solutions.

There are disadvantages which may be encountered in using techniques based on a prior articulation of preferences. Several difficulties may arise regarding decision makers: their identification, their accessibility and their number. Public sector problems are typified by a complex, sprawling decision process in which decision making authority may not be clearly defined. An unambiguous statement of preferences whether weights, constraints or a utility function will be difficult to define in such circumstances. Even when these difficulties are surmounted a major weakness of these methods is that decision makers are required to articulate their preferences without complete knowledge of the range of choice which is possible. The existence of a multiobjective problem necessarily implies that the objectives are of importance which must mean that the tradeoffs are significant and that decision makers should understand the tradeoffs before articulating their preferences.

3. Methods Which Rely on Iterative Articulation of Preferences

An iterative articulation of preferences is fostered by this category of techniques. Analysts and decision makers interact through a prescribed procedure with the goal of coverging on the best compromise solution. Most of the methods operate in the following manner: a noninferior solution is generated and is submitted for consideration by the decision makers after which their reactions are incorporated into the process, a new noninferior solution is generated and the process is repeated until decision makers are satisfied or other termination rules become operable.

The iterative procedure which has received the most attention is the step method developed by Benayoun, et. al., (1971). The method follows the general algorithm stated above. One curious aspect of the step method is its termination rule. If a decision maker is not satisfied after p iterations, where p is the number of objectives then the step method terminates with the conclusion that no best compromise solution exists. This is clearly a useless result since decision makers will select a course of action regardless of the conclusion from a mathematical algorithm.

Another iterative approach is the surrogate worth tradeoff method developed by Haimes and Hall (1974) and Haimes, et. al., (1975). In the preliminary stage "tradeoff curves" between all pairs of objectives are generated with the constraint method. The tradeoff curves are shown to decision makers who must react by scaling the tradeoffs. The reactions are used by the analyst to construct "surrogate worth functions" from which points of indifference for the tradeoffs are inferred. The identification of these points leads to the best compromise solution. The procedure is obviously elaborate. Its practical value is yet to be established.

Iterative and interactive procedures are subject to the same criticisms directed at the techniques in the previous category regarding the analyst's ability to elicit useful preference statements from the public decision making process. Iterative methods do improve on prior articulation techniques in that some information is presented to decision makers before value judgments are made.

4. Multiple Decision Maker Techniques

The underlying philosophy of the previous three classes was that the role of the analyst or planner is to provide information to or receive information from decision makers so that a best compromise solution could be identified. There was no attempt to predict the outcome of the decision making process. Instead, the objective was to help the decision makers in their search for good alternatives. If the political decision making process is accepted blindly or with full knowledge of what it is, then these approaches are quite reasonable. Even when there is some skepticism about the process, it is our belief that the appropriate role for the analyst is that given him by the previously discussed techniques.

Regardless of one's view of how the political decision making process <u>should</u> work, it is of interest to know how it <u>does</u> work. This is precisely the aim of the multiple decision maker techniques (although some of these methods are normative). Here, the underlying philosophy is one of prediction, i.e., given a set of alternatives and some indication of the decision makers' preferences, these methods attempt to predict the outcome of the decision process. Clearly, these approaches are not intended for use in the same manner as the previous methods. Instead, they are envisioned as models from which analysts and decision makers can learn about the decision making process.

Of the four classes of techniques, multiobjective, multiple decision maker methods are simultaneously the least developed and most complicated. The attempts at modelling the multiobjective, multiple decision maker problems have just begun. The authors who have considered the problem with varying degrees of success include Contini and Zionts (1968), Dorfman and Jacoby (1970), Haith (1971), and Russell, et. al., (1972). Only "Paretian environmental analysis" (Dorfman and Jacoby, 1970) is discussed here.

In "Paretian environmental analysis" Dorfman and Jacoby (1970) made a simplification by reducing the general multiobjective, multiple decision maker problem to a single objective, multiple decision maker problem. The single objective, multiple decision maker problem was then formulated as a weighted sum of the participants' utilities which were measured by net efficiency benefits accruing to the constituency of each participant in the decision making process. The problem is identical to the weighting method (see generating techniques), but in this case a weight is a measure of a decision maker's political influence in the decision making body. Dorfman and Jacoby varied the weights over a range of values which they felt were politically feasible. By examining the results and by using their knowledge of the political situation, the authors selected a range of outcomes which could be reasonably expected to result from the decision making process.

One of the strengths of Paretian analysis is that it does not rely on preference information from decision makers. But, recall that this is avoided by reducing all considerations to the monetary units of economic efficiency benefits. The other methods in this class mentioned above are more detailed in their representation of the decision making process. Vote-trading (logrolling), voting probabilities and coalitions are modeled.

E. Applications of Multiobjective Analysis

There have been few real-world applications of multiobjective analysis since it is a relatively new approach to problems. "Text book" applications such as those in Haimes, et. al., (1975) are of little interest: the true test of a technique is its ability to affect decisions in a real-world setting.

Applications to real problems include the analysis of river-basin planning in Cohon and Marks (1973), in which efficiency and equity objectives were considered, and in Miller and Byers (1973) and Major (1974) in which efficiency and environmental quality were the important objectives. Multiobjective analysis of fire station location in Baltimore City is being currently pursued at Johns Hopkins. Preliminary results are discussed in Schilling, et. al., (1976). The importance of this study is that multiobjective analysis and location analysis are merged for the first time, extending the work of Church and ReVelle (1974). There have been no applications of multiobjective analysis to energy problems.

F. Multiobjective Analysis and Regional Energy Facility Siting

Although there have been no applications of multiobjective analysis to energy planning problems, this is surely not a result of the nature of the problem. Energy problems are most definitely multiobjective. National planning, e.g., for pricing policies or new exploration must confront at least the following objectives: inflationary impacts, national security (energy independence), environmental quality and regional and class distribution.

Regional energy planning and, in particular, regional energy facility siting are multiobjective problems as well. Facility siting is subject to at least the following objectives: cost implications for utilities and consumers, environmental quality, risk to populations from nuclear facilities and equity. The objectives are discussed in detail in the next section in which a regional energy facility location model is presented.

The decision making process(es) to which regional energy planning must respond is obviously complex. For this reason, a strong recommendation for the use of generating techniques can be made. Particularly during preliminary planning the goal of analysis should be insight which can best be gained by exploring the noninferior set and the tradeoffs which exist among objectives. The results of such analysis can be very useful.

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IV. A REGIONAL ENERGY FACILITY LOCATION MODEL

A. Introduction

The regional energy facility siting problem is a very complex one for several reasons. First, there are many objectives which one would like to optimize simultaneously in selecting plant locations, making it conceptually difficult from the perspective of the analyst as well as the decision maker. The second complexity is the size of the problem, i.e., the land area included in the region and the additional generating capacity which must be located are both large. The region's size and the level of detail at which it is analyzed are important determinants of model size and computational burden.

Thirdly, the dependence of system costs (one of the planning objectives) on transmission distance as well as plant size and location results in analytical complexity. The transmission line — generating plant relationship has the effect of creating an enormous number of location alternatives. After locating a generating facility, which is itself a difficult problem in the present context, one then must continue to search for the best transmission route.

A fourth complexity arises from the economic forces at work in the problem. Our basic consideration in the analysis of additional generating capacity is the development of sources which can supply electrical energy sufficient for regional needs. While this objective is undoubtedly perceived by all, quasi-public utilities must also be concerned with the maintenance of a rate of return which is high enough to attract required capital. The rate of return on investments in generating capacity is a function of revenue from energy sales and the costs of new facilities which are functions of consumption, price, plant location and transmission line routing. Furthermore, consumption is a function of price so that, in the end, all of these quantities which are affected by siting decisions interact. These interactions should be taken into account in regional energy planning.

A regional energy facility location model (RELM) is presented in this section. The model merges multiobjective and location analyses discussed in Sections II and III. RELM captures a good deal of the regional energy planning problem defined above, but there are certain aspects that are not included. The model selects locations, sizes and types of power plants while taking into account capacity requirements, population safety, environmental quality and natural resource requirements, the equity of capacity distribution among political jurisdictions or subregions, plant, transmission and infrastructure costs and water transfer costs. The economic consequences of demand for energy are not included, and the transmission problem is not captured in its entirety. It is suggested, therefore, that RELM be viewed as only a part of a larger planning methodology.

One possible planning methodology in which RELM could be employed is shown in Figure 3. The methodology begins by inputting new generating capacity requirements (derived from projected regional energy demand and gross reliability) and a fuel mix into RELM. With this information and the data discussed in the description of the model below, RELM generates a spatial configuration of generating facilities. The model is multiobjective so that the configuration is noninferior and it is found by using one of the generating techniques discussed in Section III.

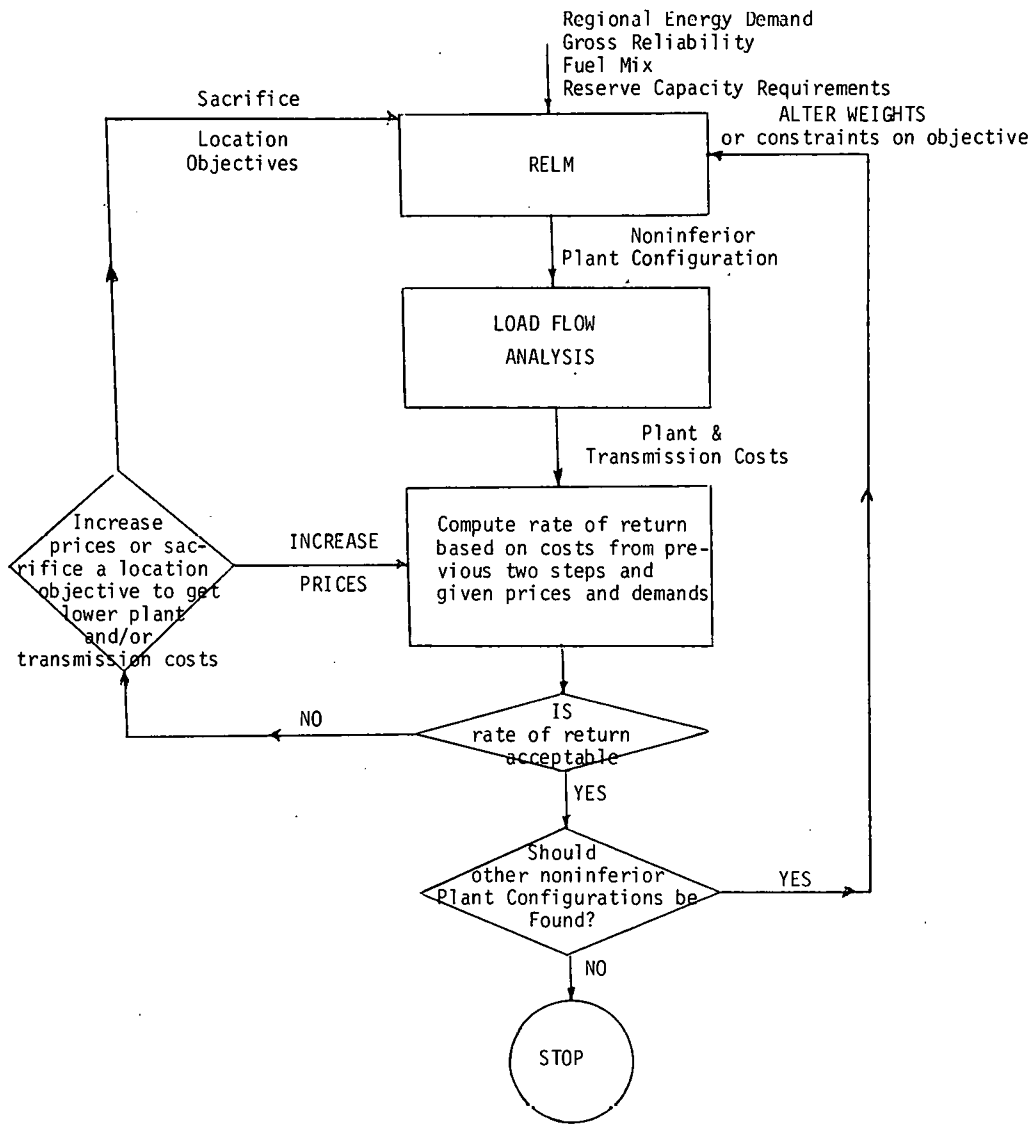

Figure 3. A planning methodology which uses relm.

It is assumed in RELM that plants assign to the closest load center. Since this will not be true, in general, the configuration from RELM is subjected to a load flow analysis to determine transmission losses and routes and so that more reliable transmission cost estimates can be made. The transmission costs from this step and the facility costs from the solution of RELM are used in conjunction with projected prices and demands for energy to compute a rate of return for investment in new capacity. If the rate of return is not sufficiently high then either: prices are increased until the rate of return is acceptable or some prespecified ceiling on prices is reached; or, location objectives are sacrificed in order to generate a new configuration which allows for lower facility and/or transmission costs. An example may be the generation of a "less safe" or "less equitable" configuration to achieve lower costs. The effect would be to tradeoff location objectives against rate of return and inflationary impact. When the rate of return is acceptable then, if desired, a new noninferior solution is generated by altering the weights or constraints and solving RELM again.

One aspect of the siting problem which is not captured by the proposed methodology is the aesthetic impact of transmission lines. This could, perhaps, be incorporated by using a procedure to determine an estimate of the visual impact of lines after they have been routed by the load flow model.

The goal of the proposed methodology is the development of interesting and useful alternatives for regional energy planning. The generation of several noninferior alternatives and extensive sensitivity analyses on input such as demands and fuel mix would be expected to provide a great deal of insight into reasonable planning possibilities within a region, the degree to which objectives conflict, and the sensitivity of potential solutions to the validity of assumptions about prevailing regional conditions. Keep in mind, however, that the regional scale of the analysis does not allow RELM or the proposed methodology to identify specific facility locations. Rather, "gross" locations such as at the county or multi-county level are found. The identification of specific locations would require further, detailed analysis.

The energy facility location model is the central element of the methodology. It is a multiobjective location model which has the following form:

Objectives:

Minimize Facility Costs
Minimize Water Transfers
Maximize Equity of Plant Distribution
Minimize Population Safety Impact

Subject to the Constraints:

Minimum Capacity and Concentration Constraints
Fuel Mix Constraint
Water Quantity Requirements
Water Requirements for Heat Dissipation
Air Pollution Constraints
Constraints Required for Formulation of the Objectives Above.

In the remainder of this section each of these components of the model is discussed in detail after which some of the issues relative to implementation of the model are presented. A summary of the formulation and a list of the symbols used are included in appendices at the end of the section.

The version of RELM presented in this section assumes a fuel mix; fuel availability is not modelled. Another version for coal-fired energy facilities, RELMC (RELM for Coal), is presented in Appendix D. RELMC takes into account coal availability and the transportation requirements for moving the coal to conversion facilities (power and gasification plants).

B. Minimum Capacity; Concentration Requirements

There are two types of generating capacity constraints in RELM: minimum new generating capacity required to meet demands; and maximum allowable concentration at any site. Both of these constraints are discussed in this section.

The theoretically correct approach to determining capacity additions to an existing supply system is grounded in neoclassical economics. The optimal capacity addition should take into account consumers surplus and revenue from increased consumption of electricity and the costs of constructing and operating new capacity. These effects are not included in the model, however, due to the complexities related to estimation of consumption and prices. A methodology was proposed in Section A for incorporating these economic considerations.

The approach taken here is to specify new capacity for the region *a priori*. This capacity requirement is denoted as D, and it represents the total capacity addition, measured in MW, which is required to meet electricity demands in the region. The capacity requirement is

$$\sum_{j} \sum_{k} S_{jk} \geq D \qquad (13)$$

where S_{jk} represents the number of units of a prespecified amount of new capacity of type k located at site j. The type index k may refer to fuel type, e.g., nuclear or fossil, cooling technology, e.g., once-through or cooling tower and to any other plant characteristic which is considered important. It should be pointed out that many different assumptions or scenarios for demand may be tested by parametrically varying D.

Another set of constraints relates a 0,1 integer variable, F_j, for each site to the capacity variables in a way which controls the degree of concentration at a site,

$$S_{jk} - Q_{jk}F_j \leq 0 \qquad \forall_{jk} \tag{14}$$

where F_j equals one if a plant is located at j and zero otherwise and Q_{jk} is the maximum number of units of type k which may be located at j. Q_{jk} may be the same at all sites, i.e., $Q_k = Q_{jk}$ for all j would represent a policy of no installations of a given type larger than a prespecified limit. Alternatively, Q_{jk} may vary from site to site to reflect geographical or design considerations.

It is interesting to note that capacity could be considered an objective. Parametric variation of Q_{jk} in (14) would trace out the tradeoff between capacity concentration and objectives such as the minimization of water transfers. Whether or not it is appropriate to investigate such tradeoffs will depend on the context within which the model is used.

C. Fuel Mix Constraints

For various reasons, one may want to require a prespecified mix among the types of capacity. In particular, one may want to constrain the solution so that a certain fraction of the new capacity use a certain fuel. Such constraints may be motivated by fuel availability or the desire to be independent from foreign sources. Such constraints would tend to be region specific to reflect the relative scarcity of some fuels in a region.

Call τ_N the set of all types of new capacity k that are powered by nuclear energy and α_N the maximum fraction all new capacity that may be nuclear. Then we can require that no more than α_N of new capacity in the region may be nuclear by the constraint,

$$\sum_j \sum_{k\varepsilon\tau_N} S_{jk} \leq \alpha_N \sum_j \sum_k S_{jk} \tag{15}$$

Similarly, a minimum fossil fuel capacity requirement is,

$$\sum_j \sum_{k\varepsilon\tau_F} S_{jk} \geq \alpha_F \sum_j \sum_k S_{jk} \tag{16}$$

where τ_F is the set of all fossil-fueled plants and α_F is the minimum fraction of new plants which must be fossil-fueled in the region.

A further distinction may be made among the capacity types. One may like to require that of all new fossil-fueled plants, at least α_C of them should be coal-fired. Defining τ_C as the set of all types that are coal-fired, the following constraint would be included,

$$\sum_j \sum_{k\varepsilon\tau_C} S_{jk} \geq \alpha_C \sum_j \sum_{k\varepsilon\tau_F} S_{jk} \tag{17}$$

Other fuel-mix constraints of this form can be included by defining appropriate new parameters analagous to the α's and τ's above.

D. Environmental Quality and Natural Resource Constraints

Power plants impact the environment in many different ways. In this section we will concentrate on four environmental quality and resource use aspects of the problem: land impacts, water use, heat discharges into water, and air quality. It should be kept in mind that although these considerations can be captured in the model, their representation is relatively simplistic so that more detailed analyses will probably be required.

1. Land Impacts

A power plant (not including transmission lines) impacts land and its use by disrupting or precluding other potential land uses, by altering the landscape, and by altering soil composition due to plant construction and to emissions of various types. None of these impacts are taken into account explicitly in RELM. They are considered, however, in the definition of J, the set of feasible facility locations.

All of the land impacts mentioned above tend to be localized in that they occur within the scale of our smallest planning unit of a county. Thus, land impacts are best taken into account early in the analysis when potential plant locations are assembled. Those counties in which the known land impacts would be unacceptable (because of political opposition, special soil characteristics, zoning, local topography or the lack of sufficient space for a plant) should be excluded from the set J. In effect land impact is treated here as a strict constraint resulting in the infeasibility of a location if any of the various land impacts are unacceptable.

2. Environmental Quality - Air Constraints

There are essentially two types of gaseous emissions from power plants. The first type is associated with the production of power, e.g., combustion products, fly ash, or radioactive emissions.* The second type is associated with the type of cooling process, e.g., water vapor, warmer air, etc. Both types of emissions can be considered undesirable if the magnitude of emissions is relatively large. For example, it could happen that due to local meteorological conditions, any increase in water vapor could bring on troublesome fogging. This would necessitate a certain type of cooling process, or stated in another way, this dictates that a certain process could not be used. A simple method for insuring that a particular technology is not used would be to use the following type of constraint

$S_{jk} = 0$ for those sites j where technology k would be incompatible with meteorological or other conditions (18)

A more realistic approach would be to limit the capacities of units established on the basis of meteorological conditions. For example:

$$S_{jk} \leq \bar{C}_{jk} \qquad (19)$$

where $\bar{C}_{jk}$ = the maximum allowable number of units due to meteorological or other prevailing conditions.

It is also possible to incorporate a more substantial approach within RELM to maintain air quality standards. For example, the elements of Teller's fuel substitution model† can be included in RELM to model interactive meteorological effects. This is done in the following way:

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* However, it is assumed here that radioactive emissions are to be controlled and do not present any real locational problems other than the objectives of maintaining a free zone and minimizing the population within a certain distance of the plant which are discussed below.

† Teller, A., "The Use of Linear Programming to Estimate the Cost of Some Alternative Air Pollution Abatement Policies", Proceedings of the IBM Scientific Computing Symposium on Water and Air Resource Management, IBM, White Plains, New York, 1968, pp. 345-353.

$$\sum_k \sum_j \Gamma^m_{jn} E_{mk} S_{jk} \leq \varepsilon_{mn} \qquad \forall_{m,n} \tag{20}$$

where ε_{mn} = standard for air pollutant m at monitoring station n.

E_{mk} = emission level of pollutant m, technology k.

Γ^m_{jn} = net transfer of pollutant m from site j to monitoring station n.

S_{jk} = size of capacity established at site j using technology k.

This latter approach, perhaps, could be classified at a level of detail greater than what is actually called for in the Regional Energy Location Model. Whether to include this representation or the more simple approaches depends on the analytical context.

3. Water Availability Including Low Flow Augmentation

Power plants need water for cooling which is taken into account in the model by the water availability constraints. A representation of two river basins is shown in Figure 4. There are three power plants shown (although there could be any arbitrary number) each of which has water diverted to it from the stream. The quantity of this diversion at site j is

$$\text{Diversion at site } j = \sum_k W_k S_{jk} \tag{21}$$

where W_k is the cooling water flow required per period (say a year) by a unit of prespecified size of type k (fuel type, cooling option, etc.) and S_{jk} is the number of units of type k to be installed at site j. Note that if water requirements are site specific then the water use coefficients should be

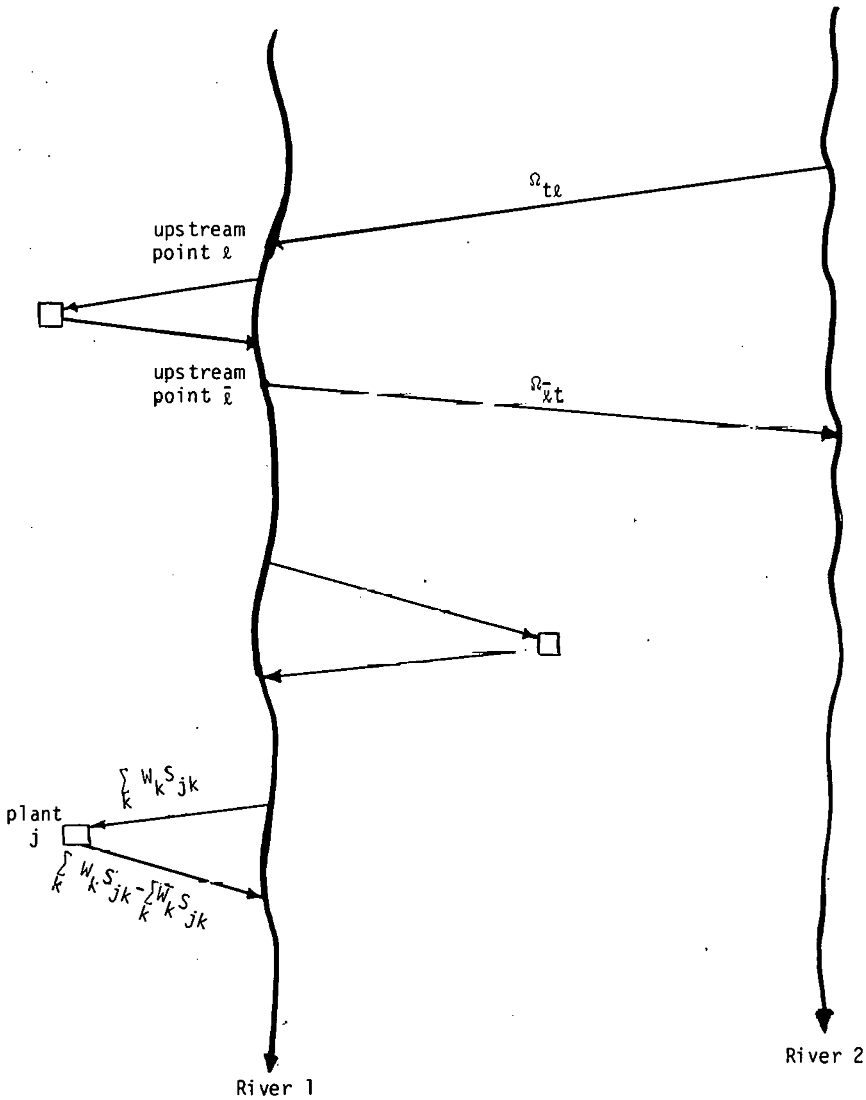

Figure 4. Schematic representation for water use formulation.

further subscripted, i.e., W_{jk}.

The consumptive use at a plant, i.e., the difference between water diverted and water returned to the stream, is denoted by $\overline{W}_k$ which is again for a unit of prespecified size of type k. Assuming linearity, the total consumptive use at site j is

$$\text{Consumptive use at site } j = \sum_k \overline{W}_k \, S_{jk} \tag{22}$$

and the total water returned from site j is

$$\text{Return flow from } j = \sum_k W_k \, S_{jk} - \sum_k \overline{W}_k \, S_{jk} = \sum_k (W_k - \overline{W}_k) \, S_{jk} \tag{23}$$

as shown in Figure 4.

The purpose of the water requirement constraints is to ensure sufficient water for power plant operations. This can be accomplished by imposing continuity at each site from which water is diverted from the stream for cooling purposes. For site j we would write,

$$\text{Water Diverted} \leq \text{Water Available}$$

which can be represented mathematically as,

$$\sum_k W_k \, S_{jk} \leq A_j - \text{Water lost upstream} + \text{water added upstream} \tag{24}$$

where A_j is the safe yield at site j assuming no upstream development beyond what currently exists.

The inequality in (24) can be further developed by considering Figure 4. The sources of upstream water losses are all of the upstream power plants and the potential interbasin transfers (exports) between upstream points ℓ and t, denoted $\Omega_{\ell t}$. The source for a water addition (imports) is the interbasin transfer in the opposite direction, $\Omega_{t\ell}$. Incorporating these flows into (24) gives,

$$\sum_k W_k S_{jk} \leq A_j - \sum_{\ell \in U_j} \sum_k \overline{W}_k S_{\ell k} + \sum_t \sum_{\ell \in U_j} \Omega_{t\ell} - \sum_{\ell \in V_j} \sum_t \Omega_{\ell t} \qquad (25)$$

where U_j is the set of all power plant and import sites upstream of site j, and V_j is the set of all export sites upstream of j.

As mentioned before A_j represents the water available assuming no development in the stream other than what currently exists. A_j may be measured as the α percent safe yield or that flow in the stream which, based on past records, would be equalled or exceeded α percent of the time where α is prespecified. The choice of α for the determination of A_j would depend on the analytical point of view.

Another consideration relative to water use is total consumptive use in a river basin in addition to consumption at each site. Total consumptive use constructed for a particular basin could be written as:

$$\sum_{j \in U_j^*} \sum_k \bar{W}_k S_{jk} \leq \alpha_{j^*} \qquad \text{for all } j^* \qquad (26)$$

where j^* is the farthest downstream point in any defined basin; U_j^* is the set of all sites in the basin upstream of j^*, and α_{j^*} is the total amount of allowable consumptive use in the basin with farthest downstream point j^*.

α_{j*} may be a fraction of the amount of a seven consecutive day low flow occurring once in ten years.

If the above constraints are important, then it seems that a particularly important alternative in regional development would be to analyze the benefits due to better facility placement as opposed to costs of developing low flow augmentation facilities. This alternative could add a completely new dimension to RELM. Basically, there could be a reservoir development and operating model which could be developed for each basin. Then an interacting element could be developed which would check to see if major improvements in objective values could be accomplished by flow augmentation and at what costs these improvements in objective values are obtained. The link between RELM and such a reservoir development model is the value of α_{j*} which is a function of reservoir development.

4. Thermal Discharges

Power plants generate waste heat which is released in discharges of heated cooling water. Since the discharged water is warmer than the receiving water body, a temperature rise of the latter is experienced. The purpose of the thermal discharge constraints is to insure that temperature rise standards of receiving water bodies can be met.

The maximum permissible temperature rise in °F at site j (allowing for variations in standards from state to state) will be denoted as $T_{j,max}$. The maximum allowable heat discharge from plant j in BTU/hour, $H_{j,max}$, is related to $T_{j,max}$ by

$$H_{j,max} = 3600 \; T_{j,max} \; \rho \; C_p \bar{A}_j \qquad (27)$$

were ρ is the density of water in lb/ft^3, C_p is the specific heat of water in BTU/lb - °F, $\bar{A}_j$ is the flow at site j in ft^3/sec. Equation (27) can be rewritten as,

$$H_{j,max} = \Psi_j \bar{A}_j \tag{28}$$

where

$$\Psi_j = 3600\ T_{j,max}\ \rho\ C_p \tag{29}$$

The maximum allowable heat input to the stream represents an upper bound on the heat discharge from power plants on controlled water bodies. Taking into account all of the power plants which discharge at j or at points upstream of j (neglecting dispersion) leads to the constraint,

$$\sum_k H_{jk} S_{jk} + \sum_{\ell \varepsilon U_j} \theta_{\ell j} \sum_k H_{\ell k} S_{\ell k} \leq H_{j,max} \tag{30}$$

where H_{jk} is the average heat load discharged in BTU per unit plant size of type k (including cooling option) at site j, $\theta_{\ell j}$ is an attenuation coefficient which represents the decay of thermal impact of heat discharged from an upstream point ℓ to point j, and all other symbols are as defined before. In effect (30) requires that the heat load discharged at j and the heat load remaining from upstream discharges not exceed the maximum permissible heat load in the water body at point j.

Substituting the relationship in (28) into (30) yields,

$$\sum_k H_{jk} S_{jk} + \sum_{\ell \varepsilon U_j} \theta_{\ell j} \sum_k H_{\ell k} S_{\ell k} \leq \Psi_j \bar{A}_j \qquad \forall_j \tag{31}$$

where,

$$\overline{A}_j = A_j - \sum_{\ell \varepsilon U_j} \sum_k \overline{W}_k S_{\ell k} - \sum_k \overline{W}_k S_{jk} + \sum_t \sum_{\ell \varepsilon U_j} \Omega_{t\ell} - \sum_{\ell \varepsilon V_j} \sum_t \Omega_{\ell t} \qquad (32)$$

which follows from (25).

It should be noted that the specific form of the water requirement and thermal impact constraints may take on different forms depending on the physical configuration under consideration. For example, more than one generating site may withdraw or discharge at the same point in the stream. Particular variations such as this can easily be considered by altering the appropriate terms in the constraints. It should also be pointed out that the heat constraints could easily be made seasonal if the temperature rise standards vary from one season to the next. Finally, note that A_j, the safe yield, is used here. This seems reasonable since one is concerned with, in this case, events of relatively common frequency. Any appropriate value of A_j could, of course, be included.

E. Facility and Infrastructure Costs; Selection of Unit Plant Size

The costs for new capacity arise from capital expenditures and operating and maintenance costs for all of the necessary equipment and structures related to generation, transmission and cooling and from infrastructure costs. These costs are nonlinear for a given plant, and they vary with plant type. For the purposes of a regional planning model the plant cost representation in Figure 5 should be sufficient. It is assumed that costs are composed of fixed costs, β_j, for site preparation and linear variable costs, α_{jk}, which are a function of plant type. The fact that fixed costs may themselves be a function of

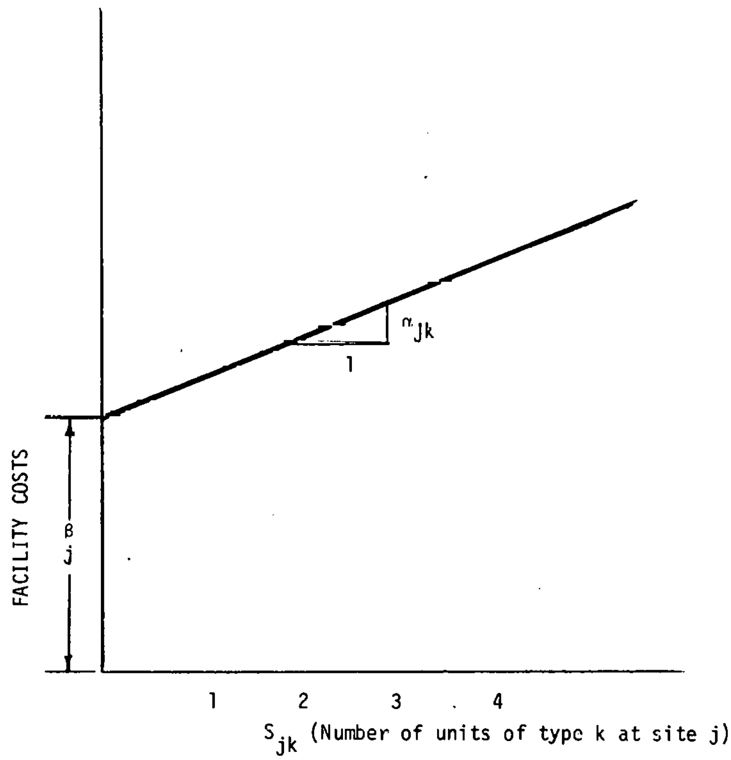

Figure 5. Facility cost function.

plant size and type is not captured by this function. Total plant costs at site j, C_j, are thus,

$$C_j = \beta_j F_j + \sum_k \alpha_{jk} S_{jk} \qquad \forall_j \tag{33}$$

and total system costs, C, are,

$$C = \sum_j C_j = \sum_j [\beta_j F_j + \sum_k \alpha_{jk} S_{jk}] \tag{34}$$

Water use facilities such as transfers and reservoirs should also enter into the cost function. These elements should be included as the application of the model requires.

The linearity of the variable costs in Figure 5 is not unreasonable since the cost function is defined for the <u>number</u> of units of a fixed size. The selection of unit size will affect the accuracy of the cost approximation, and unit size should, therefore, vary with plant type. For example, all plants which burn a fossil fuel may have a unit size of, say, 800 MW while nuclear facilities may be sized in 1000 MW units. The actual unit plant sizes should be chosen so as to gain as much accuracy as possible in the cost estimation.

The fixed cost portion of the cost function, β_j, reflects the economies of scale and the importance of infrastructure in energy facilities. If fixed costs are not significant then the term $\beta_j F_j$ may be omitted.

Transmission of energy results in another cost factor. A reliable transmission cost estimate requires a load flow analysis as indicate in Figure 3. It is possible, however, to include a good representation of the transmission problem within RELM itself. The necessary additions to the model are presented in Appendix C. A more simple, and less realistic, approach is presented here. It is based on the assumption that energy facilities will be tied into an existing transmission grid at the nearest load center to the facility. This assumption is unrealistic when energy centers or concentrated areas of capacity are contemplated. However, the simple approach does promote a wider distribution of facilities, and in so doing, the iterative methodology presented in Figure 3 would be expected to converge more quickly to a solution which yields a satisfactory rate of return.

Define α_j as the transmission cost or distance from facility site j to its closest load center. This parameter is incorporated in (34) to give,

$$C = \sum_j [(\beta_j + \alpha_j) F_j + \sum_k \alpha_{jk} S_{jk}] \qquad (35)$$

Notice that transmission costs do not vary with capacity. It is also worth reiterating that a RELM solution will generally underestimate transmission costs. The load flow analysis is still an important part of the methodology.

F. Water Transfers as an Objective

The interbasin transfer of water is a controversial alternative regardless of the reasons for the transfer. The minimization of interbasin transfers to provide cooling water may be important, therefore, to enhance the feasibility of sizing alternatives. The statement of this objective is quite straightforward,

$$\text{Min} \quad \sum_{t} \sum_{\ell} \Omega_{t\ell} \tag{36}$$

where $\Omega_{t\ell}$ is as defined previously.

It would be expected that interesting tradeoffs among transfers and low flow augmentation and the degree of capacity concentration could be generated. It should also be pointed out that it is quite appropriate to include a separate objective for water transfers when these alternatives also enter into the cost objective. This is not double-counting!

G. Population Safety Impact

Questions have been raised with respect to the safety of nuclear power plants. Unfortunately, there is no easy way to identify the risks of long term low level radiation exposure. In addition, the impact of a significant uncontrolled breakdown is known, but the risk of such an occurrence is hard to quantify. It appears that the security of transported materials and the risk of an extortion inspired attack on a facility or transported materials looms as a serious, hard to control unknown. Security procedures proposed to protect the public are a function of the quantity transported, how materials are transported, and the security precautions in personnel hiring; but they are not a function of facility location. Facility placement affects only those safety issues related to long term low level exposure or accidental breakdown.

The currently accepted approach to minimizing the impact of nuclear reactors, based on the individual dose guidelines of 10 CFR 100, is to provide an exclusion area immediately around a facility and to minimize the number of people within an area of certain radius around the plant. The exclusion area aspect is dealt with in RELM during the site selection process while other criteria related to the larger impact area are explicitly considered.

Two alternative formulations are presented below. The first minimizes the number of people within a prespecified distance of the plant. The second approach maximizes the distance from a facility to population centers. Note, that neither approach takes into account the population distribution (although the second formulation may do this implicitly) or meteorological conditions. These could perhaps be incorporated with further model development.

1. Minimizing Population or Exposure Within a Given Distance of the Facility Sites.

There are essentially two ways of viewing the risk associated with living within a given distance of a nuclear facility. The first is that the more facilities established within that distance, the larger the risk, and the second is that the major risk or impact is associated with the mere presence of one or more plants within that given distance. For the first case, it seems appropriate to consider the following objective:

$$\text{Min} \quad \sum_i \sum_{j \varepsilon IA_i} F_j P_i \tag{37}$$

where P_i is the population within the area represented by point i, F_j is a 0,1 variable defined above and IA_i is the set of potential facility locations which may impact point i.

This objective has units of plant-people. A plant-person is one person living within a given distance of a nuclear power plant. If that person lives within a given distance of two plants, then his impact is counted twice and equal to two plant-people. The objective is to minimize the total impact in plant-people as a surrogate approach to maximizing safety.

The above approach does not capture the potential dependence of risk to populations on the capacity of plants located within the impact area. However, this can be included in the above approach by using:

$$\text{Min} \quad \sum_i \sum_k \sum_{j \varepsilon IA_i} S_{jk} P_i \tag{38}$$

This objective is measured in units of capacity — people (e.g., 1000 MW - people). A capacity-person is one person living within a prespecified distance of an established unit of capacity. This objective also has the advantage of allowing a distinction to be made between nuclear and fossil-fuel plants. One would want to exclude all S_{jk} for which k is related to fossil plants or to define a different impact area.

For the second case where a person is impacted by the mere presence of one or more facilities but not as a function of how many facilities, one can consider the following approach:

$$\text{Min} \qquad \sum_i P_i C_i \tag{39}$$

subject to the additional constraint,

$$- F_j + C_i \geq 0 \text{ for all } i \text{ and all } j \varepsilon IA_i \tag{40}$$

The variable C_i is equal to one only if one or more facilities are placed within a given distance of area i. Thus, the objective function measures the total population within a fixed distance of one or more nuclear power plants. Minimizing this function is another surrogate approach to maximizing safety. For this formulation, the constraint in (14) would require adjustment to relate the 0,1 variable F_j to nuclear plant types only. It is worth pointing out, however, that fossil plants are clearly obnoxious facilities so that <u>not</u> adjusting (14) to confine the safety objective to nuclear facilities only may be appropriate.

2. Maximizing the Distance of the Nuclear Power Facilities from Population Centers as a Surrogate Approach for Maximizing Safety

This approach can be accomplished by the following objective and constraints:

$$\text{Min} \qquad \sum_{i \varepsilon I^*} \sum_j d_{ij} Y_{ij} \tag{41}$$

subject to the additional constraint,

$$- F_r + \sum_{j\varepsilon\Gamma_{ri}} Y_{ij} \geq 0 \quad \text{for } i\varepsilon I^* \text{ and } r = 1,2,\ldots, \bar{r}_i \qquad (42)$$

where

$$Y_{ij} = \begin{cases} 1 \text{ if the closest facility to i is j} \\ 0 \text{ otherwise} \end{cases}$$

a_{ij} = $M-d_{ij}$

Γ_{ri} = the set of r closest sites to i.

M = largest interpoint distance

d_{ij} = shortest distance from point i to point j

$\bar{r}_i$ = total number of sites j within S distance of i

Essentially, the objective measures the negative value of the average distance of population centers to their closest nuclear plants. By minimizing this quantity, one actually maximizes the positive value of the average distance of population centers to their respective closest nuclear facility. The constraints are included to define the values of the variables Y_{ij} for a particular facility configuration.

H. Distribution of New Capacity

Without some type of constraint limiting the use of each particular geographical or political area, it is possible that a large fraction of the generating capacity could be assigned to one particular area in the region. This would occur if there is an unusually large water supply, close to but with no significant impact on load centers, no appreciable problem with heat dissipation, or no major environmental or aesthetic difficulty. It could also occur if any one area would prove to be a generally better area (i.e., fewer impacts than other areas). Such a configuration if it indeed does occur, would most likely generate strong objections from the "targeted" area and possibly lead to strong criticisms of the overall approach for locating generating capacity.

The criticism generated by such a possibility could be along several arguments of which we give three:

1. "Why can't other areas make sacrifices and suffer the negative impacts of a nearby facility?"
2. "This is not equitable, we are being taken advantage of .... You are dumping generating capacity on us."
3. "We don't need all that power. Let's only build what we need for the needs of our immediate area."

Whether these arguments are considered valid or not they must be addressed by the decision making process and they should also be addressed, therefore, by the analytical process. One approach which might be used to address these arguments would be to require that each geographical area house at least a fraction of the capacity needed for their area. This approach could be accomplished mathematically in the following manner:

Let

GA_g = $i \varepsilon I$ and $j \varepsilon J$ such that i and j belong to geographical area g

D = total generating capacity to be developed.

P_i = population of impact area i.

S_{jk} = amount of generating capacity at site j using technology k.

Min G_g = minimum acceptable fraction of needed capacity established in immediate area of g. e.g., 75 percent.

$$\underbrace{\frac{\sum_{i \in GA_g} P_i}{\sum_i P_i} (D) (\mathrm{Min}\ G_g)}_{\text{minimum acceptable capacity in area}} - \underbrace{\sum_{j \in GA_g} \sum_k S_{jk}}_{\text{established capacity}} \leq 0 \qquad \text{for all } g \tag{43}$$

The above relationship requires that established capacity in area g be at least as large as that fraction of total demand generated by the area multiplied by some minimum supply fraction, Min G_g.

Even if each area is required to serve a certain fraction of their needs, it could also happen that a particular area could be called upon to serve considerably more than their needs. This could be mitigated by incorporating the following constraint:

$$\frac{\sum_{i \in GA_g} P_i}{\sum_i P_i} (D) (\mathrm{Max}\ G_g) - \sum_{j \in GA_g} \sum_k S_{jk} \geq 0 \qquad \text{for all } g \tag{44}$$

where Max G_g is the maximum allowable fraction of needed capacity established in the immediate area of g, e.g., 150 percent.

Another possibility worth consideration is a constraint limiting the amount of capacity established in a particular area to be less than a percentage of the region's total capacity. For example:

$$(D) \overline{(\mathrm{Max}\ G_g)} - \sum_{j \in GA_g} \sum_k S_{jk} \geq 0 \qquad \text{for all } g \tag{45}$$

where $\overline{\mathrm{Max}\ G_g}$ = largest percentage of total developed capacity allocated to a particular area of g.

Note that all of the above representations enter as constraints in the model. Tradeoffs between the capacity distribution objective and other objectives could be generated by varying the minimum or maximum functions, (Min G_g), (Max G_g) and $\overline{(\text{Max } G_g)}$. An alternative approach to equitably distributing plant capacity is to minimize the range of the distribution directly,

$$\text{Min } Z = y_{max} - y_{min} \tag{46}$$

subject to the additional constraints

$$(\text{Max } G'_g) \leq y_{max} \qquad \text{for all g} \tag{47}$$

$$(\text{Min } G'_g) \geq y_{min} \qquad \text{for all g} \tag{48}$$

$$- D \frac{\sum_{i \varepsilon GA_g} P_i}{\sum_i P_i} (\text{Max } G'_g) + \sum_{j \varepsilon GA_g} \sum_k S_{jk} \leq 0 \qquad \text{for all g} \tag{49}$$

$$D \frac{\sum_{i \varepsilon GA_g} P_i}{\sum_i P_i} (\text{Min } G'_g) - \sum_{j \varepsilon GA_g} \sum_k S_{jk} \leq 0 \qquad \text{for all g} \tag{50}$$

where y_{max} = the largest fractional generating excess for any area

y_{min} = the largest fractional generating deficit for any area

Max G'_g = the fraction of generating capacity established in area g, which is in excess of the area's needs.

Min G'_g = the fraction of generating capacity which needs to be imported from other geographical areas to area g.

By using the objective in (46) one would be minimizing the range of each areas fractional deviation of capacity from their needs. Note that Max G'_g and Min G'_g are now decision variables. While the above formulation minimizes the range of fractional supply, one can also minimize the maximum fractional supply (Min y_{max}) or maximize the minimum fractional supply (Max y_{min}).

Another possibility would be to minimize the sum of the deviations of each areas new capacity from their needs. This can be done in the following manner:

$$\text{Min} \sum_g y_g + z_g \tag{51}$$

subject to the additional constraint,

$$D \frac{\sum_{i \varepsilon GA_g} P_i}{\sum_i P_i} - \sum_{j \varepsilon GA_g} \sum_k S_{jk} = y_g - z_g \qquad \text{for all } g \tag{52}$$

It is important to note that this objective is presented in terms of capacity excess or deficit whereas, the previous approaches are couched in terms of <u>fractional</u> capacity excess or deficit. A further possibility could be to either minimize the maximum excess or minimize the maximum deficit. This can be done as follows:

$$\text{Min} \quad (\text{Max } E) \tag{53}$$

subject to the additional constraint

$$- D \frac{\sum_{i \varepsilon GA_g} P_i}{\sum_i P_i} + \sum_{j \varepsilon GA_g} \sum_k S_{jk} \leq (\text{Max } E) \qquad \text{for all } g \tag{54}$$

where (Max E) is the largest excess in generating capacity over all geographical areas.

$$\text{Min (Max D)} \tag{55}$$

subject to the additional constraint

$$D \frac{\sum_{i \varepsilon GA_g} P_i}{\sum_i P_i} - \sum_{j \varepsilon GA_g} \sum_k S_{jk} \leq \text{(Max D)} \qquad \text{for all } g \tag{56}$$

where (Max D) is the largest deficit in generating capacity over all geographical areas.

In the distribution of power plants another major criticism may be voiced if in solving a particular siting problem an area's new capacity is to be 100 percent nuclear when on the average, nuclear will comprise a much smaller percentage of newly established generating capacity. A basic criticism could be along this argument:

> Why is our area selected for 100 percent nuclear? Because of safety issues, why should be have so much nuclear capacity when other areas are benefiting from increased safety due to a larger fraction of fossil plant capacity?

One way to attempt to increase fairness in light of this problem would be to modify the previous approaches in this section. For example, if it was established that for each geographical area a minimum acceptable fraction of the total newly developed capacity is to be nuclear, we could write

$$\underbrace{\frac{\sum_{i\varepsilon GA_g} P_i}{\sum_i P_i} D\, \alpha_{ng}}_{\text{minimum acceptable nuclear capacity}} - \underbrace{\sum_{j\varepsilon GA_g} \sum_{k\varepsilon\tau_n} S_{jk}}_{\text{established nuclear capacity}} \leq 0 \qquad (57)$$

α_{ng} = minimum acceptable fraction of nuclear capacity in geographical area g.

τ_n = the set of technology k which is nuclear oriented.

Notice that this constraint is of similar form to that of the first constraint mentioned in this section. Each and every constraint or technique discussed in this section can be modified in the above manner to provide equitable distribution of generation types over differing geographical areas. Similar distinctions can be made with respect to developed coal or oil capacity in a particular geographical area. This is appealing since there could be significantly different costs associated with coal or oil supplies, and one would not want to burden one area with an abnormally high average generation cost .

I. Implementation and Use of RELM

There is frequently a gap between the theoretical statement of a model and its implementation for the analysis of real-world problems. At this stage of RELM's development, this gap exists and one would expect it to be significant. A great deal of preliminary analysis will be required to develop the inputs required by the model. The elements which are required are discussed (hypothetically) below. Computational requirements are also considered.

1. Site and Analysis Area Selection

RELM is based on a discrete representation of a geographical area. "Sites" in the model are actually points in space which may represent any land area which may range in size from a few square miles to several counties. The selection of the area which a point is to represent should be based on computational and analytical considerations. A useful rule would be to select points to represent the largest contiguous area possible which will still capture all of the important aspects of the problem, i.e., the area should be approximately homogeneous with respect to population density, land use, environmental attributes and existing infrastructure. One implication of this rule is that the area represented may vary from point to point, e.g., small for urbanized areas and relatively large in rural areas.

Site selection is also an initial screening process. Only those areas which are feasible facility locations should be included. Considerations such as land use and safety exclusion zones will disqualify some areas. Note, however, that spatial attributes such as population must be adequately captured so that location impacts are realistically reflected by the model. This requirement may result in the inclusion of infeasible locations as "demand points" in the model at which facilities may not be placed.

The total area or region to which RELM may be applied is related to the site selection process. Computational requirements of RELM are a function of the number of discrete points which are included in the model. Thus, as the area of analysis increases, the area represented by a single point must also increase to maintain computational efficiency. A specific potential application of the model is to an area covered by a single energy pool.

This scale of analysis would appear to be quite reasonable in terms of the area represented by a point and the number of points to be modeled. For example, the PJM power pool includes slightly more than 100 counties. The selection of counties as the analytical unit would not cause an inordinately large computational burden, nor would this scale smooth out important spatially varying attributes.

2. Data Requirements

The data requirements for RELM are not extensive, but each piece of data may imply a significant amount of analysis for its derivation. This difficulty is not necessarily a characteristic of RELM, but it is generic to complex problems.

The first major requirement is the development of a discrete representation of the analysis area. This aspect and the site screening process are discussed above.

Data on capital and operating costs of generating facilities and infrastructure costs for all sites and technological alternatives are required. In addition, water transfer and reservoir costs (if low flow augmentation is considered) must be derived. This data would probably be the easiest to obtain.

Distances for impact areas of nuclear facilities must be supplied in order to state the safety objectives. There is some uncertainty regarding the appropriate value for this distance so that sensitivity analysis will be particularly important here.

Upper bounds on capacity concentration and fuel-mix requirements must be derived. These are essentially policy issues which, again, may require a significant amount of experimentation.

Water requirements, consumptive use and heat generation by fuel and cooling option must be derived. These data may require some effort, but one would expect little analytical difficulty. A more nebulous task, however, is the estimation of heat and air pollution attenuation coefficients, maximum allowable heat loads, and air quality standards. Sensitivity analyses should be emphasized here in an attempt to deal with the uncertainty surrounding these numbers.

There is a host of numbers which must be estimated for use in the methodology but not directly in RELM. Energy demand, reserve capacity requirements, load factors and gross reliability are required to derive required new capacity which is a parameter of RELM. Prices and transmission costs are required to compute rate of return which must then be compared to required rate of return, another input. The rate of return computation is expected to involve the most uncertainty.

There are undoubtedly other data requirements which would become apparent only when implementation is attempted. The data required is extensive, but regional energy planning demands this complexity.

3. Computational Requirements

RELM has been formulated as a linear integer programming problem of considerable size. It is expected to be relatively computationally intensive, but we would claim that the analytical benefit gained would exceed the costs of operation.

The solution costs of RELM are a function of the number of constraints and integer variables included in the formulation. A problem with, say, 100 discrete points (on the order of a county-level analysis of the PJM pool) and five total technological options (fuel and cooling combinations), would have approximately 800-1300 constraints and 100-200 integer, 0,1 variables depending on the specific form of the safety and distribution objectives employed. This is a large problem, but certainly not beyond the capability of existing linear and integer programming packages such as IBM's Mathematical Programming System Extended (MPSX).

A substantial saving could be realized if the fixed-cost portion of facility costs were ignored and the safety objectives which require 0,1 integer variables were not used. In this case the formulation would result in a linear programming problem with close to 800 constraints. This is definitely not an inordinately large problem. It would probably cost on the order of $50 for a single solution on a computer with rates consistent with academic computing facilities. Of course, the sacrifice of realism associated with the elimination of integer variables must be carefully examined.

APPENDIX A. — SUMMARY OF THE RELM FORMULATION

Objectives

1. Minimize Total Facility Costs

$$\sum_j [(\beta_j + \alpha_j)F_j + \sum_k \alpha_{jk} S_{jk}]$$

2. Minimize Water Transfers

$$\sum_\ell \sum_t \Omega_{\ell t}$$

3. Minimize Population Impact

a) Minimize $\sum_i \sum_{j \varepsilon IA_i} F_j P_i$, or

b) Minimize $\sum_i P_i C_i$

S.T. $- F_j + C_i \geq 0$ for all i and all $j \varepsilon IA_i$, or

c) Minimize $\sum_{i \varepsilon I^*} \sum_j a_{ij} y_{ij}$

S.T. $- F_r + \sum_{j \varepsilon \Gamma_{ri}} y_{ij} \geq 0$ for $i \varepsilon I^*$ and $r = 1,2, \ldots, r_i$

4. Distribution of Capacity

a) $- (\text{Max } G_g') \dfrac{Dx \sum_{i \varepsilon GA_g} P_i}{\sum_i P_i} + \sum_{j \varepsilon GA_g} \sum_k S_{jk} \leq 0$ for all $g \varepsilon G$

and

$$(\text{Min } G'_g) \frac{Dx \sum_{i \varepsilon GA_g} P_i}{\sum_i P_i} - \sum_{j \varepsilon GA_g} \sum_k S_{jk} \leq 0 \text{ , or}$$

b) Minimize $y_{max} - y_{min}$

where $\text{Max } G'_g \leq y_{max}$

$\text{Min } G'_g \geq y_{min}$, or

c) Minimize deviations from proportional capacity

$$\text{Min } \sum_g y_g + z_g$$

$$\frac{Dx \sum_{i \varepsilon GA_g} P_i}{\sum_i P_i} - \sum_{j \varepsilon GA_g} \sum_k S_{jk} = y_g - z_g \text{ , or}$$

d) Minimize $(\text{Max } G'_g)$

Constraints:

1. Minimum Capacity and Concentration

$$S_{jk} \leq Q_{jk} F_j \qquad \forall_{j,k}$$

or could be written as:

$$\sum_k S_{jk} \leq Q_j F_j \qquad \forall_j$$

where Q_j = maximum allowable generating capacity at site area j.

$$\sum_j \sum_k S_{jk} \geq D$$

2. Fuel-Mix Constraints

e.g., fossil-fuel plants comprise at least α_F of all new capacity

$$\sum_j \sum_{k \epsilon \tau_F} S_{jk} \geq \alpha_F \sum_j \sum_k S_{jk}$$

3. Water Requirements (quantity)

$$\sum_k W_k S_{jk} \leq A_j - \sum_{\ell \epsilon U_j} \sum_k \overline{W}_k S_{\ell k} + \sum_t \sum_{\ell \epsilon U_j} \Omega_{t\ell} - \sum_{\ell \epsilon V_j} \sum_t \Omega_{\ell t} \qquad \forall_j$$

4. Water Requirements (heat dissipation)

$$\sum_k H_{jk} S_{jk} \leq \Psi_j \overline{A}_j - \sum_{\ell \epsilon U_j} \Theta_{j\ell} \sum_k S_{\ell k} H_{\ell k} \qquad \forall_j$$

5. Air Pollution Constraints

$$\sum_k \sum_j \Gamma^m_{jn} E_{mk} S_{jk} \leq \varepsilon_{m_n} \qquad \forall_{m,n} \quad , \text{ or}$$

$$\sum_{j \epsilon GA_g} E_{mk} S_{jk} \leq \varepsilon_m$$

APPENDIX B. — NOTATION USED IN RELM

J denotes set of potential facility areas.

I denotes set of impact areas and demand centers.

K denotes type of technology implemented at a particular site.

G denotes the set of geographical areas.

L denotes the set of stream points and reservoir water source points.

T denotes the set of potential water transfer source sites.

N denotes the set of air pollution monitoring sites or requirement grid.

M denotes the type of pollutant measured.

S_{jk} = the size in units of capacity established at site j using technology k.

F_j = 1 if site area j is to be used for facility placement.
0 otherwise

Q_{jk} = largest allowable capacity of type k at site j.

W_k = average amount of water needed for type k per unit of installed capacity.

A_j = total upstream or site availability of water for site j.

V_j = t point t is upstream of j.

$\Omega_{t\ell}$ = amount of water transferred from sites t to site ℓ.

$\overline{W}_k$ = average amount of consumed water for type k per unit of installed capacity.

H_{jk} = waste heat (BTU/500 MW) discharged by plant j of type k.

Ψ_j = $3600\ T_{j,max}\ \rho C_p$

$\overline{A}_\ell$ = amount of upstream water coming into ℓ.

$\Theta_{\ell j}$ = attenuation coefficient for heat discharged at immediately upstream monitoring points of j.

D = new capacity requirement for the region measured in terms of units (e.g., 500 MW).

α_j = transmission cost from site j to nearest load center.

U_{j*} = 1 and j points j and 1 are upstream of j*

$\sum_m$ = standard for pollutant m at monitoring station n.

E_{mk} = emission level of pollutant m, technology k.

Γ^m_{jn} = net transfer of pollutant m from site j to station n.

GA_g = j or i/j or i is in geographical area g.

X_j = t/transfer site t is "upstream" of j.

P_i = population at impact area i.

IA_i = j/site j impacts area i.

C_i = 1 if area is impacted
0 otherwise

I* = $i \varepsilon I/P_i \geq P^*$, definition of significantly populated area.

p* = minimum amount of population necessary to classify an area as a major population center.

y_{ij} = 1 if j is the closest site to impact area i.
0 otherwise

Γ_{ri} = the set of r closest sites to i.

$\bar{r}_i$ = total number of sites j within s distance of i

τ_c = set of technology k types associated with coal burning facilities.

τ_F = set of technology types k associated with fossil fuel burning facilities.

α_c = smallest allowable fraction of fossil capacity that must be of a coal burning type.

β_c = fraction of total capacity that is a minimum limit for coal capacity.

α_{ng} = minimum acceptable fraction of nuclear capacity to be established in geographical area g.

τ_n = set of technology types k associated with nuclear facilities.

α_{j*} = total amount of consumptive use allowed in basin j*.

APPENDIX C. — ADDITIONS TO RELM TO INCLUDE AN EXPLICIT REPRESENTATION OF ENERGY TRANSMISSION

If all things are exactly the same for two power plant sites except for their positions relative to the demand area they would serve*, it would seem reasonable to pick that site which is the closest to the demand area due to resultant lower transmission costs and smaller transmission line losses. In order to build this quality into the model, it is necessary to determine which power plants will serve which load centers.

This can be approached in one of the two following ways:

1) Include within RELM a fixed charged transportation model with transshipment nodes which will minimize the total cost of transmission subject to meeting demands at each load center. This approach is discussed below.
2) Assume that each power plant serves its closest load center. This approach was discussed in Section IV-E of the main body of the report.

The first approach is based on the addition of a transshipment problem to the RELM matrix. The transshipment problem with fixed charges determines the optimal cost configuration of transmission lines and the amount of energy delivered between plants, cities, and transfer points**. It would then be easy to include the transshipment constraint set and objective within

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* This includes water availability, environmental impact and facility costs.

** Transmission line losses are neglected so even this more complicated approach is not a substitute for the load flow analysis. The approach is more realistic than the simple approach offered in Section IV-E.

the RELM model to give RELM a transmission line and cost estimating capability along with the ability to determine how each load center receives its energy. On the next few pages, a simple transshipment model is defined which can be incorporated into RELM.

We will define three types of points:

power plants — ship energy to either transfer centers or sinks (city or load center).

transfer center — an intermediate point which can receive energy from plants and/or energy shipped from a city.

cities (sink) — receive energy from plants and transfer points and can ship energy to another city or transfer point.

The following symbols will be used. Note that this notation is not consistent with the RELM notation in Appendix B.

f_{ji} = fixed cost of establishing transmission link between facility site j and demand area i.

f_{jk} = fixed cost of establishing transmission link between facility site j and transfer point k.

f_{ki} = fixed cost of establishing transmission link between transfer site k and demand area i.

f_{iz} = fixed cost of establishing transmission link between city i and city z ($i \neq z$).

$$y_{ji} = \begin{cases} 1 \text{ if link } j\ i \text{ is used} \\ 0 \text{ if link } j\ i \text{ is not used} \end{cases}$$

$$y_{jk} = \begin{cases} 1 \text{ if link } j\ k \text{ is used} \\ 0 \text{ if link } j\ k \text{ is not used} \end{cases}$$

$$y_{ki} = \begin{cases} 1 \text{ if link } k\ i \text{ is used} \\ 0 \text{ if link } k\ i \text{ is not used} \end{cases}$$

$$y_{iz} = \begin{cases} 1 \text{ if link } i\ z \text{ is used} \\ 0 \text{ if link } i\ z \text{ is not used} \end{cases}$$

t_{ji} = amount of power shipped from plant j to city i.

t_{jk} = " " " " " " j to transfer point k.

t_{iz} = " " " " " " city i to city z.

t_{ik} = " " " " " " city i to transfer point k.

t_{ki} = " " " " " " transfer point k to city i.

C_{ji}, C_{jk}, C_{iz}, C_{ik}, C_{ki} costs of shipping along various links.

$$\text{Minimize} \quad \sum_i \sum_j C_{ji} t_{ji} + f_{ji} y_{ji} \;+\; \sum_j \sum_k C_{jk} t_{jk} + f_{jk} y_{jk} \;+\; \sum_i \sum_{\substack{j \varepsilon I \\ i \neq Z}} C_{iz} t_{iz} + f_{iz} y_{iz} \qquad \text{(C-1)}$$

transmission costs for shipping power from power plants to cities — transmission costs for shipping power from power plants to transfer points — intercity transmission costs

$$+ \sum_i \sum_k (C_{ik} t_{ik} + C_{ki} t_{ki} + f_{ik} y_{ik} + f_{ki} y_{ki})$$

transmission costs for shipping power from cities to transfer points or transfer points to cities

The first summation gives the total cost for transmitting energy from power plants to cities. The second sum is for power plant-transfer point links; the third is for intercity transmission; and, the last summation is for transfer point-city transmissions in either direction. These cost terms can be treated as a separate objective or this can be added to the facility cost objective of equation (34).

There are four sets of constraints. Demand at each sink must be satisfied:

$$\sum_j t_{ji} + \sum_k t_{ki} - \sum_{\substack{z \in I \\ z \neq i}} t_{iz} - \sum_k t_{ik} \geq D_i \quad \text{for all } i \qquad \text{(C-2)}$$

Incoming energy from plants	Incoming energy from transfer points	Outgoing energy to other cities	Outgoing energy to other transfer points	Demand for energy at i

The amount shipped from a power plant cannot exceed the quantity generated:

$$\sum_i t_{ji} + \sum_k t_{jk} \leq \sum_k S_{jk} \quad \text{for all } j \qquad \text{(C-3)}$$

Outgoing energy to cities from j	Outgoing energy to transfer points from j	Energy Production capacity at j

Continuity at transfer points must be maintained:

$$\sum_j t_{jk} + \sum_i t_{ik} - \sum t_{ki} = 0 \quad \text{for all } k \qquad \text{(C-4)}$$

Incoming energy from plants to transfer k	Incoming energy from cities to transfer k	Outgoing energy to cities

The 0,1 integer variables, y_{ji}, y_{jk}, y_{ki}, y_{iz} must be related to flows in the corresponding links. These constraints also represent link capacity constraints.

$$t_{ji} \leq Cap_{ji} Y_{ji} \qquad \text{all } j, i \qquad (C-5)$$

$$t_{jk} \leq Cap_{jk} Y_{jk} \qquad \text{all } j, k \qquad (C-6)$$

$$t_{ki} \leq Cap_{ki} Y_{ki} \qquad \text{all } k, i \qquad (C-7)$$

$$t_{iz} \leq Cap_{iz} Y_{iz} \qquad \text{all } i, z \qquad (C-8)$$

where Cap_{ji}, ..., Cap_{iz} are the capacities of the corresponding links. Actually, the capacity parameters can be specified as an arbitrarily large number if it is desirable to represent transmission lines as uncapacitated.

APPENDIX D. — A REGIONAL ENERGY FACILITY LOCATION MODEL FOR COAL (RELMC)

Since coal is an important energy source in the northeast United States, a modified version of RELM, called RELMC, is presented for the analysis of coal-fired facility location. RELMC draws on the RELM model presented in the main body of the report, although there are some modifications and additions. In those cases where a RELM objective or constraint is used, the reader is simply referred to the appropriate section of the report.

The objectives for RELMC are similar to those of RELM. The minimization of interbasin water transfers (Section IV-F), and the distribution of new power plant and gasification capacity (Section IV-H) are unchanged. The safety objectives of Section IV-G can be discarded, however, it may be useful to include them in order to capture the undesirability of locating coal utilization facilities near population centers.

Costs still represent an important objective (Section IV-E) although new factors must be considered. These factors include:

- transportation of coal from source to facility by pipeline (as a slurry), truck, or rail
- transmission of gas (from coal gasification) as well as energy from coal-fired steam electric plants
- costs for conversion facilities such as gasification plants and steam-electric plants
- costs for cooling facilities.

In addition, there are all of those factors that affect all energy facilities such as water supply and distribution and infrastructure costs. A new mathematical formulation is not presented here. These factors can be incorporated into the mathematical forms offered in Section IV-E.

The air pollution constraints (Section IV-D-2), and the thermal discharge constraints (Section IV-D-4) are unchanged. The water availability constraints (Section IV-D-3) can be used in their form in RELM although other sources, such as well supplies, may be incorporated by simply adding a new term to equation (25).

The new constraints relate to facility capacities and demands taking into account the need to ship the fuel (coal) from its source. Four types of facilities are considered: sources (deep or surface mines), slurry facilities that are not located at a source, coal gasification plants, and power plants. The symbols which are used are listed below. This notation is not intended to be consistent with the RELM notation in Appendix B.

<u>Additional Notation for RELMC</u>

J denotes set of potential facility areas

K denotes set of coal source sites

B_K BTU's/ton of coal from source K

t_{ki} tons of coal shipped from source k to slurry facility i

t^1_{kj} is the tons of coal shipped from source k to site j which will be utilized for gasification

t^2_{kj} tons of coal shipped from source k to site j which will be utilized for steam-electric generation

$$F^1_j = \begin{cases} 1 \text{ if gasification plant is built} \\ 0\text{, otherwise} \end{cases}$$

E^1_{dry} = efficiency of gasification from dry coal

E^1_{wet} = efficiency of gasification from slurried coal

Q_j^1 = capacity at site j for coal gasification

Q_j^2 = " " " " " electricity generation

X_{jd}^1 = BTU's of gas shipped to demand area α.

D_d^1 = demand for BTU's of gas at area d (D_j^{gas})

X_{jd}^2 = BTU's of electricity shipped to demand area d from plant j

D_d^2 = demand for BTU's of electricity at area d ($D_d^{elect.}$)

P_{ij}^1 = tons of coal piped from slurry site i to coal gasification facility j

P_{ij}^1 = tons of coal piped from source k to coal gasification facility j

P_{ij}^2 = tons of coal piped from slurry facility i to power plant j

P_{kj}^2 = tons of coal piped from source k to power plant j.

Capacity limitations at site j for coal gasification:

$$\sum_k (t_{kj}^1 B_k) \quad + \quad \sum (P_{ij}^1 B_i) + \sum_k P_{kj}^1 B_k) \quad \leq \quad Q_j^1 F_j^1 \qquad \text{all } j \tag{D-1}$$

Incoming BTU by truck or rail to site j to be used for coal gasification	Incoming BTU's from pipeline slurry to be used for coal gasification

Definition of total coal gas generated:

$$E_{dry}^1 \sum_k (t_{kj}^1 B_k) + E_{wet}^1 [\sum_i (P_{ij}^1 B_i) + \sum_k P_{kj}^1 B_k] = \sum_d x_{jd}^1 \qquad \text{all } j \tag{D-2}$$

BTU's of coal gas generated from truck and rail services	BTU's of coal gas generated from pipeline sources

Coal gas supplied must exceed gas demand at each demand point

$$\sum_j x^1_{jd} \geq D^{gas}_d \qquad \text{all } d \qquad \text{(D-3)}$$

Capacity limitation of power plants

$$\sum_k (t^2_{kj} B_k) + [\sum_i P^2_{ij} B_i + \sum_k P^1_{kj} B_k] \leq Q^2_j F^2_j \qquad \text{all } j \qquad \text{(D-4)}$$

Incoming BTU's by truck and rail to be used for electric generation

Incoming BTU's from pipeline slurry to be used for electric generation

Definition of total electricity generated

$$E^2_{dry} \sum_k (t_{kj} B_k) + E^2_{wet} [\sum_i P^2_{ij} B_i + \sum_k P^2_{kj} B_k] = \sum_d x^2_{jd} \qquad \text{all } j \qquad \text{(D-5)}$$

BTU's of electricity generated from truck and rail sources

BTU's of electricity generated from pipeline sources

$$\sum_j x^2_{jd} \geq D^{elect.}_d \qquad \text{all } d \qquad \text{(D-6)}$$

Coal shipments cannot exceed supply

$$\sum_j (t^1_{kj} + t^2_{kj} + P^1_{kj} + P^2_{kj}) + \sum_i t_{ki} \leq \text{Coal}_k \qquad \text{all } k \qquad \text{(D-7)}$$

Direct shipment from source via truck or rail and pipeline to energy facility

Direct shipment to pipeline slurry facility

Continuity at intermediate slurry facilities

$$\sum_k t_{ki} = \sum_j P^1_{ij} + \sum_j P^2_{ij} \qquad \text{all } i \qquad \text{(D-8)}$$

tons of coal incoming from sources	tons slurried to plants	tons slurried to steam plants

THE BROOKHAVEN NATIONAL LABORATORY REGIONAL ENERGY STUDIES PROGRAM

The Brookhaven National Laboratory Regional Energy Studies Program is part of a national effort supported by the U.S. Energy Research and Development Administration (ERDA) to create an energy assessment capability which is sensitive to regional conditions, perceptions, and impacts. Within ERDA, this program is supported by the Division of Technology Overview and includes, in addition to a concern for health and environmental impacts of energy systems, analysis of the complex trade-offs between economics, environmental quality, technical considerations, national security, social impacts, and institutional questions. The Brookhaven Program focuses on the Northeast including the New England states, New York, Pennsylvania, New Jersey, Maryland, Delaware, and the District of Columbia. The content of the program is determined through an identification of the major energy planning issues of the region in consultation with state and regional agencies. A major component of the program in 1976 was the Northeast Energy Perspectives Study which examined the implications of alternative energy supply-demand possibilities for the region. In 1977 a major component is the northeast portion of the National Coal Utilization Assessment carried out in collaboration with several other laboratories in other regions of the United States.