A SYSTEM FOR THE ECONOMIC ANALYSIS
OF BALANCED ENERGY CONVERSION
AND STORAGE SYSTEMS

By

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A SYSTEM FOR THE ECONOMIC ANALYSIS OF BALANCED ENERGY CONVERSION AND STORAGE SYSTEMS

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PREFACE

A dissertation is not the product of a single person. Such an effort requires help and guidance from many individuals. I wish to acknowledge the kindnesses of many persons here at Oklahoma State University, even if not mentioned.

I should like to acknowledge the interest of Dr. William L. Hughes, Head, School of Electrical Engineering, in this area of energy storage research. In turn, I wish to acknowledge those companies whose financial support made possible this research effort. These companies are: Public Service Company of Oklahoma, Oklahoma Gas and Electric Company, Arkansas Power and Light Company, Kansas Gas and Electric Company, St. Joseph Light and Power Company, and Empire District Electric Company. It is a source of personal satisfaction that this research is a result of free-enterprise support. Special mention is due a number of persons at Oklahoma Gas and Electric Company who further assisted this research by supplying various data and information.

I wish to thank Dr. J. Leroy Folks for his understanding help and early services on my committee. I wish also to mention my appreciation to Dr. Wolter J. Fabrycky for his initial introduction to this research area, and for his many kindnesses at the start of my program. I want to thank Dr. Dale D. Grosvenor not just for his services on my committee, but also for the assistance by him and his staff during the many research hours in the Computer Center.

Dr. Kenneth A. McCollom's many efforts on my behalf are gratefully acknowledged. As administrator of the Energy Storage Research project, his inter-disciplinary discussions helped much to focus this research towards fruitful goals. Moreover, it was his personal enthusiasm about the broad goals of energy storage which challenged my full interest in this research area.

I wish to express my appreciation to all of the faculty of the School of Industrial Engineering and Management for their valuable contributions and helpful efforts. Prof. H. G. Thuesen knows, I am certain, of my appreciation for his many wise counsels and friendly invitations for a cup of coffee. I wish to thank Dr. Paul E. Torgersen for his services on my committee, and for his kind assistance in graduate program problems.

A school can be measured by the number of subjects it teaches, or by its teaching of students. Much of my preparation and realized growth for a career in engineering education results from the teaching influences of two people in the School of Industrial Engineering and Management. The successful accomplishments of my doctoral program are largely due to their understanding and motivation over these past years. I think that Prof. Wilson J. Bentley, Head, School of Industrial Engineering and Management, will understand when I say that he does more than teach the "Barnard-Lohmann" text; he demonstrates the principles by his own actions. I wish to thank him also for personal counsel concerning my teaching objectives.

I owe much to Dr. James E. Shamblin for his penetrating-to-the-problem-root technical advice during periods when research snags were frequent. However, my major appreciation is for his unflagging patience and always heartening encouragement throughout the course of this dissertation.

To these two people I acknowledge my gratitude and a debt that is not possible to repay by tangible means. I hope to repay part of this obligation in coming years by following their example of teaching—students.

Far from last in importance, I wish to acknowledge a son's debt to his parents. Without their loyalty and steadfast support during these many past years I could not have achieved this personal goal for a career in engineering education. In addition I thank my father for his consulting advice, as a Professional Engineer, in some problem areas.

However, my deepest appreciation is for their inculcation of many personal values whereby this teaching goal is not measured by its cost but by its worthwhileness. This dissertation is gratefully dedicated to my parents.

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NOMENCLATURE

Terminology

Capacity = a maximum kilowatt or kilowatt-hour value

Component = one type, or composite-type, of equipment for an energy storage function

Conversion = the production of electrical power from an energy source; that equipment

Demand = the need for electricity at the point of consumption

Energy = kilowatt-hours

Energy Demand Curve = the plot of kilowatt demand for a period of time

Peak(s) = the higher-level kilowatt values of the energy demand curve

Power = kilowatts

Requirement = the kilowatt or kilowatt-hour specification of equipment rating

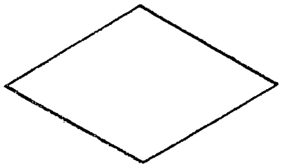
Research User = that person who uses this dissertation's simulation system as an analysis technique in his energy system or storage equipment research

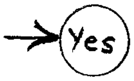
Storage Procedure = the operating rules for how much and when to store energy

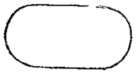
Storage Technology = the selected equipment for a whole in-hold-out cycle of the storage of energy; also "energy storage system (or sub-system)"

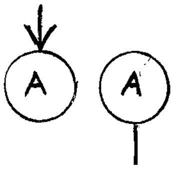
(Energy Conversion and Storage) System = the feasible combination of conversion equipment and storage equipment into one energy system

Derivation Logic Symbols

 = decision, or choice

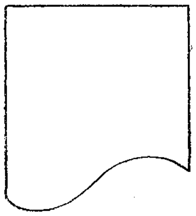


= decision path, or branch; also , if with decision symbol

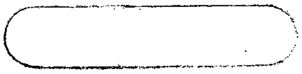


= connectors

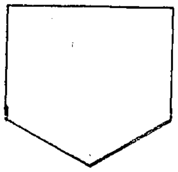
 = punched card: read-in data; punch output

 = write output

 = call sub-routine

 = counting test, do loop, or sub-program logic sequence

 = computation

 = loop (to)

⬠ = loop point

▽ = start, or end of program

▷ = entry to, or return from sub-routine

"DMDTBL(HR)" = subscript identification of matrix array (computer table) position

`*` = multiply

/ = divide

CHAPTER I

INTRODUCTION AND REFERENCE LITERATURE

Engineering, an "older" definition, is defined as "the application of science ... to produce ... for the welfare and benefit of mankind". The general goal of this research investigation is to meet the latter part of the above definition. The hope is that this goal will be achieved by a research contribution to mankind's quest for energy.

The preceding contribution is planned by research accomplishments towards the following specific goal. The specific goal of this dissertation is the economic analysis of conceptual models of energy storage systems. For this analysis a simulation system is developed to examine the economic feasibility of energy conversion systems coupled with storage technologies on the basis of an annual energy demand.

The subsidiary system simulation models require the capabilities for examination of varying energy storage technologies, and for examination of power generation and storage systems which utilize unconventional energy sources. For the design and selection of energy systems the simulation results need to present information about both the costs and capacity requirements of the associated equipment. A successful accomplishment of this goal will result in an improved state-of-the-art for analysis of energy storage technologies, and will advance the current knowledge about the feasibility of energy conversion and storage systems.

Scope of Problem

One of the primary foundations for the economic growth of today's nations is the production of energy—heavily manifested in electricity. The rate and need for energy has been growing faster than the population. Since 1900 in the United States, the generation of electrical energy has been doubling every ten years [1].

When the existing and potential energy needs are considered in terms of energy <u>sources</u>, the problem of energy supply assumes a new magnitude of importance. If this country is to maintain its standard-of-living and economic growth much less the problems of worldwide growth in living standards, then the production of energy <u>and</u> sources of energy can be viewed as a current, fundamental problem.

In the near future considerations will have to be given to more efficient forms of utilizing existing energy supplies, to new sources of energy, and to advanced technologies of converting energy to electrical form. Without research in all the aspects of this area, beginning soon, the results to society could be severe for two key reasons: first, long-time research efforts will be required for solutions to the complex engineering problems; second, our society of high population density could not exist without energy in the usable forms as required today.

Environment of the Problem

Gaucher [2], and others, report that by the year 2100 the present major sources of energy, including fission, will be unable to supply the total energy requirements. Even with new energy sources, their utilization can require the development of new energy conversion facilities. An example of new energy source utilization is evident today in the increasing construction of nuclear power plants instead of building more conventional, steam-turbine generation, plants in some regions. Based on existing literature, this problem area and its significance is not yet widely recognized by the general population. This may be largely because the general population does not envision problems a century ahead, or it has the belief that "something will be invented in time". Today oil companies and electrical utilities are starting to consider a longer "time horizon" than just a decade. It is this recognition that has caused part of the impetus to prognosticate and to evaluate sources of energy on a longer range basis than before, and to support some research in this area. Yet, Sporn's [3] viewpoint of this progress is not overly optimistic. He relates:

> Looking ahead to the end of this century, growth in electrical energy generation in the United States to a level of 6000 billion kWh is

> clearly indicated. The implications of sixfold expansion over present levels in electrical energy are: capital resource requirements amounting to perhaps $300 billion; a build-up in annual primary energy needs to a level of 1600 billion tons of bituminous coal equivalent; and the numerous complex technological problems created in designing, building and operating the generation, transmission and distribution facilities of the yet not fully grasped much larger power systems that will necessarily evolve. These constitute an almost impossible to overemphasize challenge.
>
> But they are also sobering prospects. Contemplating them one cannot help wonder whether the electric power industry, including both its manufacturing and utility segments, is alert enough to visualize not only all these problems involved in creating these systems but whether it has the vision to see all the difficulties which that act of creation will pose in so short a time.

Relevant to the magnitude of this problem is Schultz's [4] comment:

> During the past decade and a half it has been the national policy of the United States to support strongly research and advanced study in those area of electrical engineering deemed critical in our defense and space efforts, notably electronics, communications, and control. As a result, research in these areas has grown while comparable growth has not occurred in the field of power. . . . And various analyses seem to indicate that a relatively small research effort is being made in the power field, small at least in comparison with the size of the industry and obvious needs evidenced by its forecast growth.

These next comments of Schultz [4] indicate some of the conservativeness in research efforts by those industries directly concerned with power generation:

> Equipment and appliance oriented manufacturers are evidently increasingly reluctant to undertake open-ended investigations for the utilities industry unless they can foresee a relatively immediate market application. . . . The time is now past when the electric utilities can rely

> on the well-developed techniques of an earlier day to promote the knowledge and skills that will be required to implement the future.

Still, many advances are being made in the electrical industry. Developments in power transmission are notable. Improvements in operating costs have advanced considerably in nuclear power generation. In some areas nuclear plants with fuel subsidies are becoming competitive with conventional generation.

Behind these advances are the longer-range history and current status in power generation. Conventional conversion plants (steam turbine-generator plants) are nearly engineering-optimal in design and efficiency of energy source conversion as individual units. A considerable body of literature exists on these plant designs. An area of active research is caused by "power peaking" energy requirements. The problem is one where the average yearly generation capacity requirements are often on the order of fifty per cent of peak-demand capacity requirements with concomitant losses in efficiency and plant investment cost. The literature indicates a number of attacks on these problems—special purpose gas turbines, pumped hydro storage, diversity exchange of power, and long-range transmission for different time zones. Yet, many of these studies are of the immediate range of solution to the general problems, and based more on current technology for immediate problem solutions.

Storage of Energy

Underlying the problems of energy supply, the storage of energy is the age-old quest of man. Earliest man wished that he could use winter's winds to pump water in summer and to grind grain in the fall; he wished to store summer's heat for the winter. But the sources of energy were often not available at time of need. Availability of energy and its demand were generally independent of each other. As civilization developed and populations grew, greater demands for energy arose. The energy of coal and oil, which had been stored slowly by nature, became the world's major fuels.

As discussed, the problems of the future on a worldwide basis require consideration of "unconventional" sources of energy, if the demand for power is to be met. In addition, technological advances in these areas can also prove of value to the conventional generation problems of reduced plant investment and increased fuel efficiency.

The fundamental problem is to make the generation of energy independent of the demand for energy. This is accomplished by the storage of energy. Engineering economy studies of these systems for foreseen technologies can direct research efforts towards fruitful results.

Current Research Studies in Pumped Storage

Conventional conversion systems can be visualized as a two-block model: a conversion block which generates at essentially the same rate as the demand function block. This relationship is portrayed in Figure 1, where "blocks" are entities of detail having logical wholeness in system interrelationships.

However, when energy conversion utilizes an uncontrolled energy input (or when combined with conventional generation) then a three-block model is necessary to overcome the inequalities over time of input and output energy rates. The first block can be visualized as directly supplying demand, or the storage sub-system, or both (see Figure 3). The second block, storage, in turn holds supplied energy during some time periods, and sometimes supplies energy to the demand block. The third block, demand, obtains its energy from either generation, or storage, or both.

One such typical system under active research is the "electrolysis-fuel cell" storage sub-system of a complete energy conversion with storage system. Energy generation input is received by the electrolysis component, which breaks water into hydrogen and oxygen. The hydrogen, in turn, is stored in some container which acts as the time-equalizer of input and output energy rates. When stored energy demand occurs, this hydrogen with oxygen or air is released to a fuel cell as the fuel for "combustion" by which electricity is a direct product. This electricity can be sent through an inverter to provide an alternating current energy supply.

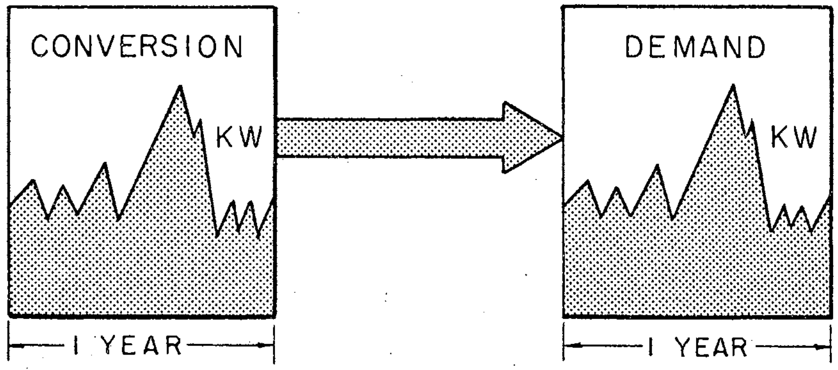


Figure 1. Two-Block Logic Model of Conventional Energy Conversion

The closest existing parallel of conventional forms of generation to an energy storage system is hydroelectric generation. The purpose of the dam is to equalize the difference in time-rates of input and demand output. Unfortunately, enough hydroelectricity is not available to meet more than a small fraction of the needs for energy.

However, dams with nil or small watershed supply have been built which purely act as an energy storage subsystem. These systems are called "pumped storage". There are a number of power companies utilizing an integrated combination of hydroelectricity, steam-turbine generation, and "pumped storage" to gain some overall system economies in fuel costs and capital investment. However, economic analyses of these combination systems for storage subsystems in terms of "pure" storage are prejudiced since the effects of watershed flow are mixed with the aspects of storage.

One of the nations's largest such combined systems is the Smith Mountain Pumped Storage Hydro Project [5]. The "stored energy", a combination of approximately a 1000 square mile watershed plus the water pumped into the reservoir during off-hours, is utilized to meet peaking loads for high demand output hours in combination with conventional generation. This is a good example of engineering utilizing natural advantages to improve efficiency. Though it is not a pure storage system, its information is relevant. Cost decisions for all equipment loading operations are based on the utility industry practices of incremental heat rates. Choice of unit is the straight-forward comparison of incremental steam fuel costs versus the cost of hydro power. It should be noted that at best this storage furnishes only a small per cent of peak load, and that the pumping capacity is about one-fourth of the pumped storage generating capacity. This hydro-generation cost is in the upper ranges of mills per kilowatt-hour when compared to the conventional generation units in this system [5]. When demand is at lowest generation power levels, water is pumped into the reservoir. At such times the conventional generation cost for pumping is lowest because: (1) the most efficient equipment is used, and (2) the fuel conversion efficiency is increased by an improved running load percentage. A major advantage of pumped storage is its ability to reach full load generation in about two minutes. This rapid start-up capability offers a significant advantage to emergency loading problems, especially when independent of power failure. A desirable factor of feasibility for any energy storage block is the capability of rapidly reaching full load independent of any external power supply.

A large system in Canada composed of steam, nuclear, and hydroelectric plants utilizes some pumped-storage energy [6]. In this article an analysis model is presented which adjusts hydro and thermal outputs by an iterative process until "further revisions would not cover the expense of extra computations". Total production costs are minimized with regard to availability of energy sources. Pumped storage is planned in terms similar to the previously described generation system. Again, it should be noted that this procedure is based on the predicted requirements "for weekly or daily economic dispatch" [6].

The most recent example of a "pure" (i.e. no watershed) pumped storage system is in New Jersey [7]. Its costs and unit efficiencies are based on combined pump-turbine generator units. The economic trade-off relationships are described as:

> The reversible turbine-generator units are used this way: At night and other times when the customer use of electricity is low, surplus electric power from other generating stations is used to pump the water from the lower to the upper reservoir. During the day as the use of electricity reaches its peak, the water is allowed to run downhill passing through the generating station where it operates the reversible turbine-generator as a turbine to rotate the generator to produce electricity. Thus the pumped-storage station becomes a peaking unit, and results in steady, more efficient operation of other stations.

The two-role unit efficiencies are of interest. With the hydraulic head varying between 650 to 750 feet the turbine generator efficiency varies up to 89.2 per cent. The unit, when acting as a pump, runs over the range of the head at 90 per cent efficiency. Here is another example where engineering design made useful advantage of an available site capability for economic improvement.

Though not the first pumped storage sub-system in the United States, the Taum Sauk project in Missouri is widely known [8]. It is one of the first such installations of major size. This development was based on the new designs of combined unit pump-turbine generators, for which its capitalization economies made feasible such systems where site conditions were desirable. Some economic relationships in this study are pertinent to trade-off investigations. These are [8]:

> The fact that some three kilowatt-hours of pumping are required to store enough water to produce two kilowatt-hours of on peak generation poses an almost insurmountable economic problem in the minds of many. These people fail to put in focus the fact that the night-time pumping is at low cost, whereas the energy delivered on peak displaces energy which frequently would cost twice as much as the energy used for pumping, and sometimes even more. However, the more important reason this 3 to 2 ratio is not controlling, is that these plants are held as ready reserve most of the hours that they are backing up the system and actually cut peaks a comparatively few hours a year. In the overall economic equation of such a project, the cost of the energy lost in the pumping is relatively small. In many cases this could easily be less than half, and maybe as little as one-third, of the savings on manpower costs alone as compared to a thermal plant.

Here is a case then where pumped storage is used for emergency and not on a year-round basis. Use of storage on a daily or weekly basis is "not ordinarily part of the economic justification of a peaking project" [8]. It happens at this site that the acre-feet capacity is a fraction of the Smith Mountain project. There is also the power system consideration of the mix of generation units. A system with a high percentage of older, inefficient steam-turbine generation equipment and low base loads has higher incremental fuel costs at peak loading for comparative economies. The rate of change of incremental heat rate curves for major generation equipment is significant to the costs of pumping. The capacity rating of the most efficient generation units relative to the daily low demand loads also affects the possibilities for economic load factor gains by pumping.

Unfortunately, as in many of these studies of storage, detailed after-the-fact total cost information is not too readily available. Especially, in the sense that natural advantages of site, rainfall, et cetera, are separably accounted so that only generalized extensions can be made. However, the Taum Sauk project indicates that economies are possible for their peaking load problems of as much as forty per cent change in summer demand load between days (only partially supplied by pumped storage). Based on improved load factors for conventional equipment and longer amortization periods of some storage-block components, this report estimates that for a good site the unit cost per firm kilowatt is as much as forty per cent less than the cost of conventional hydroelectric generation [8].

Current Research Studies in Nuclear Generation

The projections of the increased proportion of electrical energy from fission fuels vary, but one estimate value is about ten per cent by year 2200 [2]. Another description clarifies the utility industry viewpoint of economic factors as [8]:

> The relatively low incremental cost of energy expected from atomic plants as their technology becomes perfected, together with the desirability of high load factor operation of such equipment, will almost surely make hydroelectric generation by means of pumped hydro storage a very usual adjunct to the power systems of the future.

Defining "pumped hydro storage" as any economical storage system emphasizes the potential role of storage. This is especially relevant when it is considered that good storage sites are not always available nationally and that limited acre-feet capacity prevents long-time storage cycles.

Rochman [9] further clarifies the need for storage in nuclear conversion systems. Plant economy-of-scale indications are that of diminishing returns above 500 to 1000 megawatts capacity. Additionally, total annual cost per kilowatt-hour increases out of proportion to a drop in load factor. Rochman's projections indicate that a thirty-eight per cent reduction in energy output results in only a thirteen per cent decrease in annual costs. Thus, a vital need for some economic storage technology exists, if the high nuclear investment costs are not to raise energy costs. General estimates for nuclear plant first costs are 200 dollars per installed kilowatt which is more than twice the first cost of conventional plants. Moreover, if relatively constant running loads are to be realized, the implication of long-cycle time storage is significant to this research investigation.

Stubbart and Zambotti [10] recognize this problem in conceptual design comments about a nuclear conversion system. They suggest a generation output capacity of sixty per cent of peak demand with the power balance met by pumped storage. The nuclear generation supplies the base load and the "bulkier" area of the peak load. It is expected that the larger portion of the demand fluctuations are supplied by the pumped storage. The same reference describes, qualitatively, the characteristics of the two plant sub-systems. For nuclear and pumped storage, respectively, the comparative factors are: capital cost: high, low; operating cost: high, low; maintenance cost: high, low; fuel cost: low, high; load factor: high, very low [10]. The complementing qualities are obvious. Pumped storage is demonstrated as feasible with good site conditions. Load factor of pumped storage is restrained by the acre-feet storage capacity.

Unconventional Energy Sources

High potential sources of non-fossil "fuels" appear to be tidal, wind, and solar energy. Projections about generation are often nebulous for all three energy sources; their theoretical potential is large. The use of these energy sources is held back by high cost or inefficient conversion technologies. However, with practical methods of conversion the above energy sources could help meet the future demands for energy.

Underlying the most widespread possibility of utilizing these energy sources is the inherent requirement for storage. The load factor availability of these sources is random, and the availability of energy is independent of demand needs. It is this erratic and irregular output of energy that especially affects wind generator development even though its design state-of-the-art is well advanced (viz. aerodynamics).

English design and costing studies in the wind energy compendium by Golding [11] indicate kilowatt-hour costs as low as three mills (circa 1950). These costs are for above average condition power duration and velocity frequency curves. There are widespread regions in the world in this potential cost area. The load factor (i.e. time-availability of generation) is much higher for wind and solar sources than it is for tidal, unless tidal is combined with river flow as in France on the Rance River [12].

The potential growth of these generation systems is retarded by their own limited levels of applied research. It is considered, however, that much of the impetus for their development is held back by lack of a suitable storage block technology.

Summary of Current Research Studies

The usefulness of energy storage is evident for conventional plants. Generation operating economies are possible from better load factors, and, hence, lessened fuel requirements. Reduced investment in plant generation capacity is possible for low utilization, peak load periods of the year.

The fullest utilization of unconventional energy sources require energy storage as a basic condition. Here the system difficulty is a lack of suitable storage technologies with universal applicability to the most advantageous locations for the generation of uncontrolled input.

Pumped storage is a feasible system today because of its fairly high efficiencies and moderate capital costs. However, successful adoptions are limited to a relatively few acceptable sites. It should be noted that most of the pumped storage applications are those where pumped storage is severely limited in amount of storage "holding" capacity. Because of this limited acre-feet capacity, the pumped storage supplies only a fractional amount of generation capacity or total energy. The pumped storage system is often used primarily for emergency peaking.

System Model Research Concept

Throughout most of the literature references several major factors are notable. Most of the power systems, as existing equipment systems, use pumped storage as an alternative generation method (with advantageous sites) versus a new cost conventional generation capacity of low utilization. Pumped storage is often used as a limited emergency reserve; in this situation, a more prevalent equipment is the gas turbine. (The gas turbine is not constrained by acre-feet capacity limitations but is limited by high-consumption fuel costs.) Integral with these above conditions, all studies deal with the dispatching of facilities for time periods of a week or even just hours of a day.

Thus, it is important to note that these reference studies essentially have no total system effect on original design of plant generation capacities. Their primary economies are those of alternate generation equipment based on fuel efficiency conversion improvements and, or, time-limited emergency generation where site advantages exist. Because of the limited capacity and short-range dispatching, the size of plant can be affected only at the most peak period of the year, if then, depending on the existing conventional equipment. This yearly demand peak can be just a few hours of the full year.

This limit to changes in plant capacity is a result of the very simple and direct relationship existing between energy storage and plant generation investment. Use of energy storage <u>cannot</u> reduce plant generation capacity for that whole range of the demand curve which is <u>below</u> the peak demand point of power generation capacity. Local time-period storage in this non-applicable range does not save capital costs. Energy storage can substitute for conventional generation equipment in some periods to gain fuel economies as an alternate generator choice, but investment is still made in that conventional equipment necessary for those portions of the year at higher demand loading. Only if this short-time storage is used at maximum yearly peak demand, can economies result from both fuel efficiencies and plant investment in conventional generation equipment. Relevant to the described studies, this applicable demand curve period for the joint savings effect is on the order of less than a day to perhaps several days on an intermittent usage basis.

Thus, the capabilities of the current literature models are observed as inadequate for general studies of energy storage and unspecified storage technologies. Probably because of pumped-storage "volume" limitations, these studies are also limited to energy storage with only a periodic potential for possible operating economies from fuel conversion, or as a few-hour-per-year alternative to a new conventional generator or peaking gas turbine.

The fullest realization of the economic potential of energy storage systems integrated into a <u>total design balance</u> with conventional generation is not considered. It is the adoption of a total energy conversion with storage system concept that enables the maximum potential of possible savings from fuel conversion efficiency <u>and</u> conventional plant investment. In such a case yearly peak demand is supplied by the <u>sum</u> of generation from energy storage capacity and conventional generation capacity.

Such an investigation is feasible only when the demand requirements are studied for an <u>annual</u> time cycle. One reference, by Bruckner and Fabrycky [13], describes the first quantification of a preliminary model with these considerations. In this study the term "gross savings" is used to define those savings occurring from the trade-off of fuel economies and conventional plant investment as a result of energy storage over the whole year.

Undoubtedly, a major cause for the small research efforts by utility companies in total conversion with storage systems is caused by the lack of suitable storage technologies. Nevertheless, any developments of analytical models which study energy storage should not be bound just by present day, feasible technologies. Such total system models should be designed to explore potentially advantageous, future technologies in terms of the annual cycle of demand.

Introductory Remarks

Since the nature of this research involves several disciplines, a minimum of specialized terminology is used. In order to prevent interdisciplinary misinterpretation of terms commonly used throughout this dissertation, the research user can refer to the Nomenclature listing of general terminology.

Chapter II develops the simulation objectives and the design criteria of the supporting models. Chapter III presents the overall, operational relationship of the models for energy system studies. Chapter IV discusses the modification of the demand curve variable; this chapter includes the derivation, interpretation, and results of the demand curve model. Chapter V derives the three system simulation models and defines the storage procedures. Chapter VI discusses the interpretation of the computer output, and the application to design of power plants with energy storage. Chapter VII presents the results from actual simulation studies, and establishes the analysis methods for optimization. Chapter VIII describes the research conclusions and limitations; this chapter also outlines some directions for future research.

The next six chapters are each ended with a "Remarks on System Development" section. This special section serves as a summary, in the nature of an evaluation, of each stage in the development of this dissertation. The purpose is to help coordinate the diverse-discipline sectors of this research for a general perspective of the simulation system.

CHAPTER II

THE SYSTEM SIMULATION LOGIC MODELS

The fundamental block-logic models are presented in this chapter. The three system simulation models for generation systems with balanced energy storage are named: controlled input generation under a cyclical storage procedure, controlled input generation under a daily storage procedure, and uncontrolled input generation model. The structures of these logic models are developed as the bases for the model derivations in coming chapters. As requisites to this model development, the models' design objectives and criteria are established. Before this outline of objectives, some general precepts of simulation model-building are first reviewed in the following section.

Simulation Models

A model is considered to be a representation of a real system. A simulation model is defined in terms of the parameters of the actual system. Those constant or variable factors which have the major influences on the operation of the real system are included as the parameters of the model for decision-making effectiveness. Simulation is the operation of that model, instead of the physical system, in order to study the real system under a large range of parameter values. The result is a more thorough understanding of the real system under various operating conditions which would be prohibitive in cost to determine otherwise from manipulation of the real system. Evaluation of such results is used to predict, or to control, the design parameters of a given system for least costs, or maximum output.

Mathematical simulation models denote the usage of a mathematical expression to describe a whole system under study. The term "system simulation" generally denotes the usage of a model which is structurally composed of logical operation blocks that are interrelated in sequence and processing of information so that a real system is also described. In a system simulation some of the logical manipulation blocks are in themselves mathematical expressions. There is no definite hierarchical order between mathematical and system simulation. However, in practice, a system simulation model is a more complex representation of a real system which is a too complex system for mathematical expression. Often, an inherent advantage of system simulation is its capability of determining information about a larger number of parameters which enables greater understanding of the real system's operation.

Purpose and Criteria of Model Design

The purpose of simulation is keyed to the phrase "beforehand prediction". Simulated prediction before construction of a real system prevents waste in unused equipment, construction of uneconomic alternatives, and human resources in research and design work of low potential value. Moreover, simulation accomplishes these results at less cost than trial-and-error changes in a real system. By simulation, management can plan its needs for capital, equipment, and human resources. Engineers can become more effective with specific knowledge of research and design requirements.

The quality of any model is gauged by how well it logically parallels a real system in operation. Immediately adjunct, such a model needs economic operation if its usefulness is not restricted. These design objectives of model quality and economy are often in opposition. Further, the quality of a model also depends upon the amount of useful information it develops for description of the real system.

It is desirable that all of the variable, significant parameters under the control of the manager or designer are incorporated in the model as input variables. In terms of model design the model is made less useful as more variable parameters are specified as "constants". This coverage of the parameters makes possible the manipulation of the model over a large range of conditions for examination of the effects on the total system.

It is further desirable that for a given set of independent input variables a maximum amount of information is obtained about the dependent variables, or design parameters. Without sufficient information in this area it is not possible to specify adequately the construction of the real system. This availability of parameter information is a general advantage of system simulation.

For a simulation model it is further necessary to develop an "effectiveness function" of the system from which an optimum value can be derived. Without this relationship, the manager cannot make a decision about the best system design. Without this relationship the designer cannot determine the values of the system design parameters for the best system. Typically, in the commercial world the effectiveness measure is total system cost. Engineering economy analysis clarifies this as the least system cost in comparison to alternatives of equal functional capability. The quality of the simulation model is dependent upon this effectiveness function. A model can successfully evaluate a real system with tolerable accuracy in input or output parameters. But, without adequate inclusion of and a logical relationship between the significant parameters, the "pro and con" exchange of parameter values versus cost is biased. It is this trade-off examination of the cost of a parameter versus received value that enables the selection of the best system among the simulated alternatives.

Purpose and Objectives of the Simulation Models

The background and goals of this research investigation are described in the preceding chapter. The purpose of the system simulation models is accomplishment of the basic goals by quantitative evaluation of balanced energy conversion with storage systems for their physical characteristics and cost effectiveness on a basis of annual energy demand.

There are a number of groups concerned with the objectives of simulation studies. Managers require cost information for decision-making uses in facilities expansion, capitalization, and comparisons of alternatives. 2 Plant designers require the capacity specifications of storage equipment and conversion equipment before estimating and purchasing. Research and development engineers require similar information on a feasibility basis in order to determine research directions of high potential. ④ An industrial engineer concerned with economic development needs energy cost per unit of uncontrolled input systems in order to examine foreign capital needs of energy applications in underdeveloped nations.

The objectives of these simulation models are best defined by the various types of questions about energy systems for which users wish information. Typical decision-making questions from different viewpoints are:

1. What is the economic limit to use of storage versus the physical limit?
2. What is the effect on the minimum cost point of the total system by an increase in efficiency of a fuel cell component?
3. How much leeway in storage cost investment exists from no fuel cost in an unconventional energy

source application?

4. What are the effects on plant specifications and cost of operation, if the shape of the demand curve is affected by a new, industrial customer?

5. What are the uppermost cost limits for a new storage technology if it is to be economical?

6. How much fuel and fuel cost can be saved by generating at a uniform load for a given demand curve?

7. What storage components offer the best potential yield in savings by additional research or operating control efforts?

8. What are the design capacity specifications for an electrolysis unit for a given demand curve and efficiency level?

9. What are the number and size of wind generators required to meet an energy need for some underdeveloped area?

10. What is the size of the reservoir needed for pumped-storage water at a given feet of head and conversion plant generation capacity?

11. What is the marginal cost value if a high-cost and high-performance component substitutes for a standard component in the system?

12. What would be the effect on system costs of running at a constant load and supplying the demand balance by diversity exchange?

Design Criteria of the Simulation Models

The establishment of model design criteria is necessary if the desired objectives of the simulation system are to be achieved. However, any individual criterion in the final result of a finished model reflects a value judgment, since any criterion requires an evaluation of its worth when there is an opposing criterion. In most cases this results in a model design compromise in order to realize the most significant aspects of all criteria. In terms of the following criteria, it is obvious that the most restraining criterion is the low cost of a single simulation study.

The most general criterion for model design formulation is the quality of the effectiveness function, or optimization model. Throughout this research the optimization decision is based on least cost of the energy conversion with storage system in comparison to an existing system cost. A hypothetical portrayal of this economic exchange is the economic trade-off optimization model of Figure 2. This graph demonstrates also the research concept of the balanced, total exchange of storage with conversion on an annual basis.

The second criterion is not insignificant since upon it depends the practical usefulness of the simulation models. In order to study a range of conditions, the simulation models are used repetitively. Accordingly, it is very desirable that the design of the model require only a short computer processing time.

If a model is used for plant design purposes, it is necessary that actual plant demand curves are acceptable as input data. A simplified functional treatment of the demand curve does not give explicit design specifications. The usefulness of the model for analysis of different characteristics of demand curves and concomitant energy storage results requires individual curve input. Therefore,

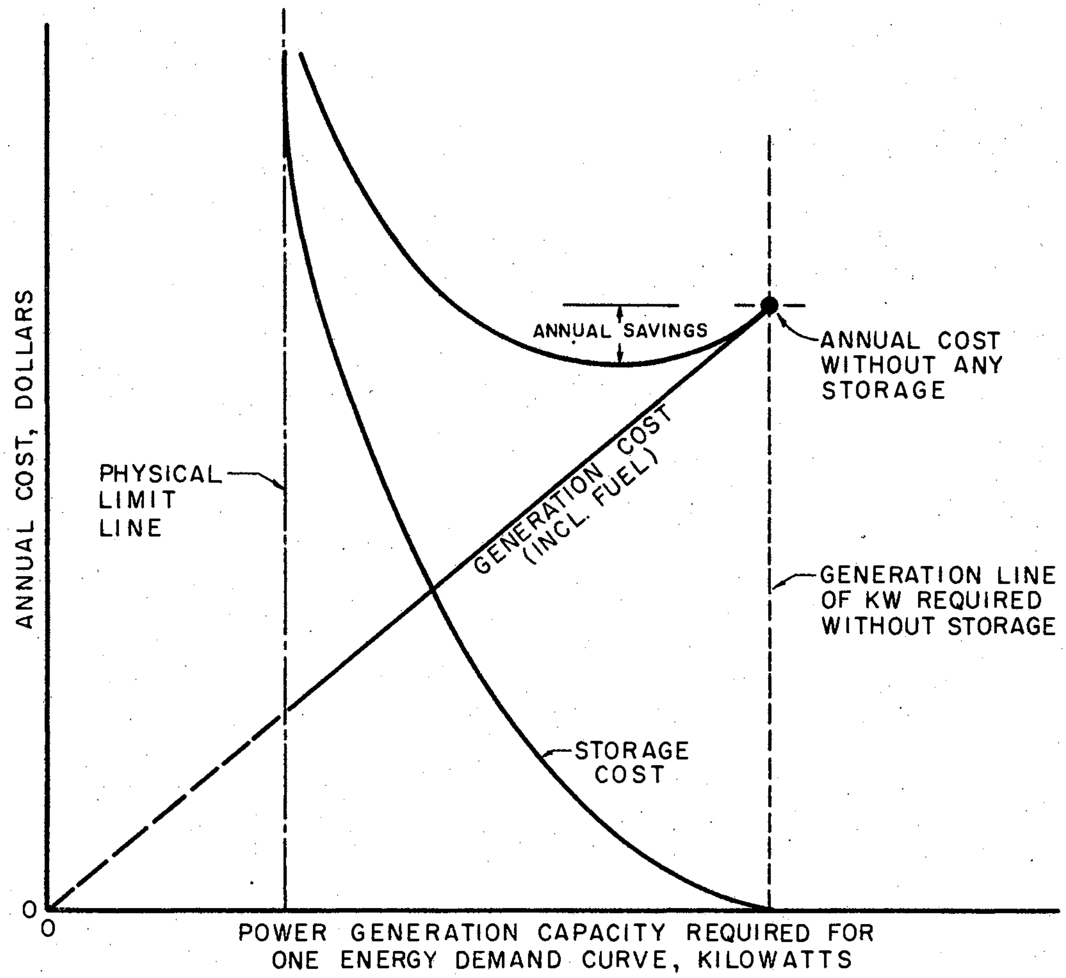


Figure 2. Economic Trade-Off Optimization Model of Energy Conversion with Storage Systems for Annual Demand

the model needs the capability of processing empirical demand curve information from any company.

If a model is used for research purposes in storage technologies, the model's definition of a storage block needs a general purpose design. Therefore, the model logic requires a capability of simulating any general conversion-storage-demand sequence of storage operation.

To support the effectiveness function, cost evaluations must be made. These evaluations must include cost extensions for all significant cost parameters otherwise trade-off optimization is biased towards one direction. Therefore, the model requires a computational package for the extension of storage component costs and other costs.

There are different lives and first costs for most of the various equipment components. At the same time the locations of the applications have different owners. Therefore, it is desirable that costs are based on engineering economy practices for qualified comparisons between alternative systems.

The model users need detailed information about specific components. Therefore, the storage block requires a detailed breakdown of processes rather than an overall storage block computation.

Similarly, the system effects from individual component changes in efficiency are desirable information for design purposes. Therefore, computational treatment of individual component efficiencies and their compound effect is a model structure requirement.

Within the storage block, itself, there is an economical trade-off of equipment costs such that different plant operating practices have different system costs for the same storage technology. Therefore, it is necessary that the model structure incorporate different storage procedures so that for a given storage technology the least system cost is possible.

Further, it is necessary that the model can realistically study an existing plant for energy storage applications. This requires the capability of computational treatment for a given mix of conventional generation equipment at their actual rated loads and operating efficiencies. Therefore, if design of a power plant system is an objective, it is necessary that the model design have the capability of optimization for empirically specified power plant facilities.

Even though the most important criterion of model design is its accuracy of real system portrayal, the model's usefulness depends upon its interpretability of the computational results. Therefore, the computer output must have a dimensional form practicable for engineering design users.

Usefulness of a model is also dependent on the ease and flexibility of preparation for a computer run. Therefore, a model design is desirable which requires little specialized knowledge or complexity for setup preparation.

Structure of Models

Figure 3 shows the original logic-block system simulation model which was used in the developmental test stages of this research. The block graphs demonstrate the concept of total balance of energy storage and conversion equipment over an annual demand period. The first block indicates the physical limit of reducing generation equipment while maintaining energy supply to the third block, demand curve. The central block represents the total operation of storage. An energy conversion system without any storage is similar to the transmission of energy exclusively between the first and last blocks. In this case, in practical terms, the conversion block function is identical to the demand block function.

Following the development of this concept test model, an evaluation of this model vis-a-vis the design criteria was made. While some criteria were adequately met by this model, the logic blocks were generally too large to establish detailed information or to have sufficient flexibility. The original model proved to be of too limited scope for the study of energy conversion with storage systems. The computer model analyzed only simple changes in storage component efficiencies with little detailed breakdown for multiple storage components. The associated demand curve, in effect, was fixed to the parameters of the curve's original state. Of interest, the running time on a small-

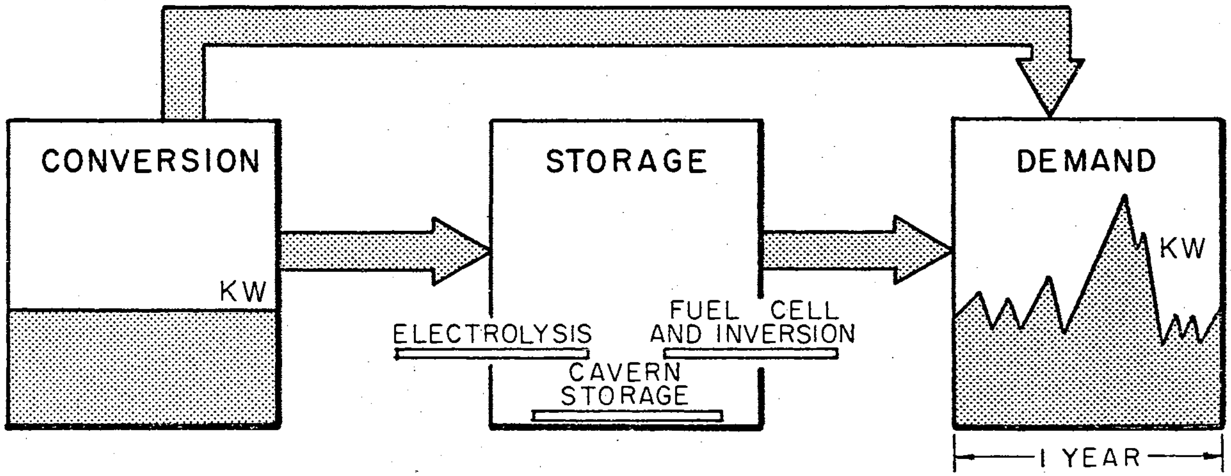


Figure 3. Original Three-Block Logic Development Model for Controlled Input Generation with Balanced Energy Storage

scale digital computer was 9.28 hours for less than hourly demand curve values for a one year time duration. However, this model served usefully as a stage in research development of the final system simulation models.

Controlled Input System Simulation Models

There are actually two models portrayed by Figure 4. The figure represents the controlled input simulation model for either the "cyclical" or "daily" storage procedure. A reason for separate models is the criterion of computer processing time. The models are similar except for storage logics. Noticeable is the detailed breakdown of the storage block into multi-components. In this manner each component is treated individually for its parameter values. In these two models the power generation conversion block represents controllable generation, viz. power fluctuation is under the power plant control on an immediate time basis. The units of measurement for each component are defined; the units are fixed. The conversion and demand blocks are also in kilowatt units. For purposes of general application, the model simulates any storage technology provided that the process is linear in sequence; any storage technology of the form which receives electric power-converts electric power to a form required by storage-holds energy over time-converts potential energy to electrical power at the point of demand is capable of study by this model. That is to say, the units of computation are kilowatts and kilowatt-hours, and storage technologies

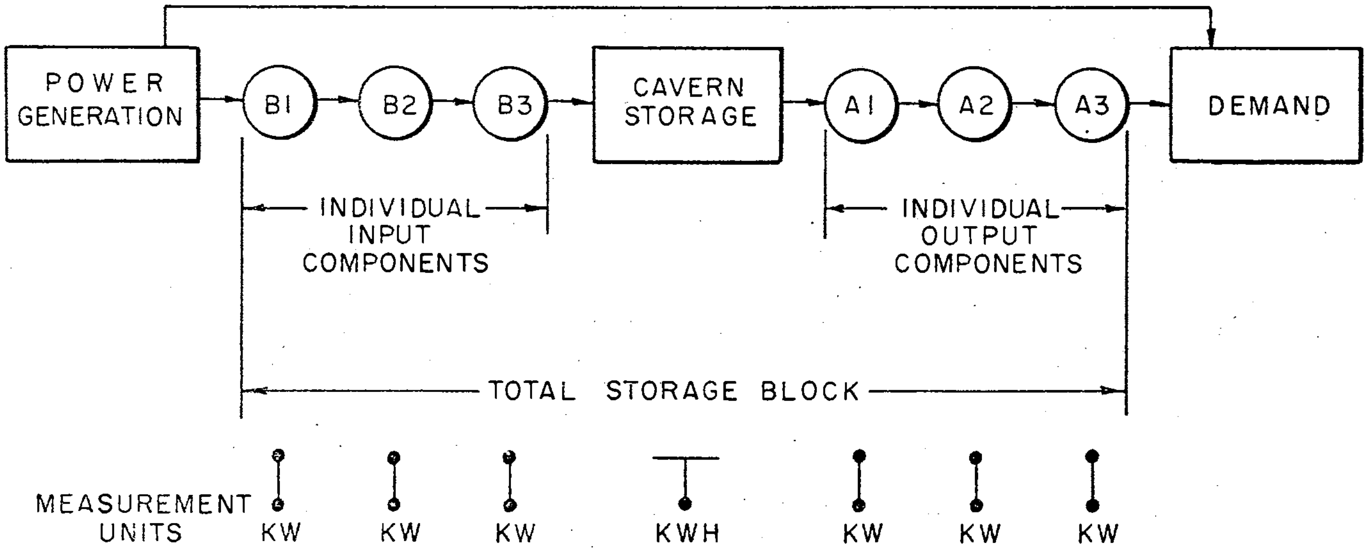


Figure 4. The System Simulation Block Logic Model for Controlled Input Generation with Balanced Energy Storage

with units so adjusted are acceptable. For more components than are available, the extra components are combined as one. The computational output reflects the "single" component parameter values. For less components, an extra component is made a "dummy" by setting a zero cost and one hundred per cent efficiency. With reference to the figure, generated power is continually supplied to the demand block (unless a zero demand value). Other generated power is supplied to the storage block at times dependent upon the storage logic. Power is received, supplied, or no activity (except hold) by the storage block, but not simultaneously because of the nature of the process. Potential energy is held in "cavern" storage and is released as required to balance demand requirements. "Cavern storage" represents the energy-holding method of any storage technology.

Uncontrolled Input System Simulation Model

Figure 5 represents the logic-block relationships for the uncontrolled input model. The storage block breakdown of components is the same as the controlled model. There is only one storage procedure for this model; it is essentially a "daily" storage procedure. A "cyclical" storage procedure offers no economic advantages to this model. The demand block in this model is identical to the controlled model. However, in this model the generation block represents the uncontrolled generation of power from any unconventional energy source. Measurement units are

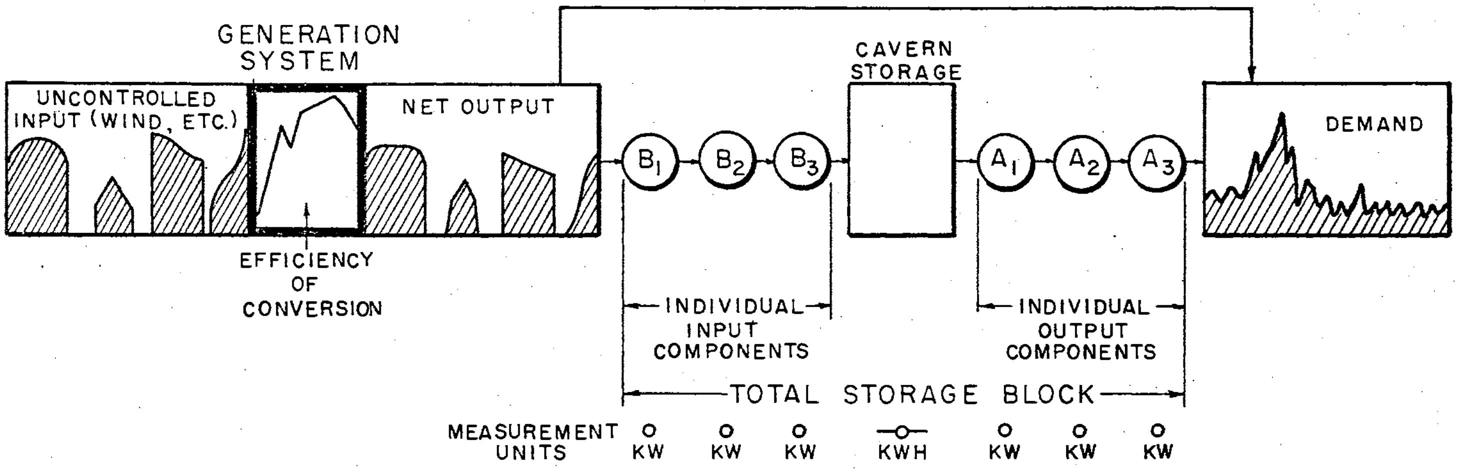


Figure 5. The System Simulation Block Logic Model for Uncontrolled Input Generation with Balanced Energy Storage

identical to the previous model. Acceptable storage technologies have the same requirements as the controlled input model.

The flow of power between the blocks is the difference between the models. An unconventional energy source is not controllable by the power plant—the plant receives power only when it is externally available. Therefore, uncontrolled input systems necessitate a storage block for feasible support of a demand function. The "efficiency of conversion" is analogous to fuel conversion efficiency of a conventional generator. In this model it represents the efficiency of the generator in conversion of the unconventional energy source. The purpose is the conversion of the theoretical potential of the energy source to the net useful electrical energy. The power density graphs inside the conversion block emphasize the fluctuations and zero-power levels of an unconventional energy source.

Power flows directly to the demand block. At the same time, whenever surplus power is available, the full surplus enters the storage block. Whenever generated power is less than demand requirements, the demand balance is supplied by the storage block. In general, the input-hold-output sequence of the storage block is much more active during the whole year than it is for controlled generation.

There is an unique application of this model. The uncontrolled model can be used to study controlled generation where the yearly function of controlled generation is defined on an a priori basis. This application is relevant to economic studies for diversity exchange of power. Also any demand curve can be horizontally segmented for the year and each segment studied by one of the three simulation models.

Input and Output Parameters

To meet the design criteria, it is desirable to incorporate in the models, as variables, all the significant, variable parameters. Generally, the user is concerned with changes in one or more of these input parameters over a range of conditions. There are three input parameters of major significance to the user. They are the demand curve, the efficiency values of each storage component, and the annual costs per unit capacity of storage and generation equipment.

Other general parameters required by the computer models are the efficiency of fuel conversion in one per cent intervals and cost per kilowatt-hour of fuel (not applicable to the uncontrolled model). Details of computer setup preparation are described in the Appendix.

The key objectives for all models are the design specifications and the determination of least system costs. These, of course, are the results of incorporating the input information for determination of its interrelated effects onto the total power system operation from model simulation. By levels of conversion block capacity, the equipment capacity requirements and system costs are available from the model's output.

Other information about fuel cost, energy requirements, and a number of parameters unique to each model are also available. Detailed interpretation of the models' computer outputs and their applications to research and design are discussed in the next chapters.

Demand Curve

The demand curve serves a dual usage. It is a major, variable input parameter. The demand curve also defines the energy needs which the system must satisfy—the "benchmark" of physical feasibility. In essence, the simulation models vary operational requirements in order to satisfy the "fixed" demand curve. Kilowatts and kilowatt-hours are the computational units of the models. Therefore, the resolution of accuracy for these different dimensions makes it desirable to have frequent measurements of the demand curve values. The controlled models can treat up to one demand point per hour for maximum accuracy. Computer core limitations for the uncontrolled input model limit the demand points to one point per two hours. Test studies indicate that as few as four demand points per day give fairly reliable results with less demand curve information required. Less than this tends to lose daily demand variation effect.

All of the models operate under a steady-state environment and are deterministically computed. Hence, the generation block cannot evaluate transient lag effects—all equipment performs at computed power loading without time lag. However, there is no restriction in study of time periods less than a year for special purposes (parameter curve program is an exception). For example, the study of one day defined by 8760 points of demand is technically possible. This flexibility assists specialized research studies such as rates of change over short time intervals for some component. By increasing the time interval between demand points, the models can study demand over periods greater than a year. In any special application, the output units of measurement require accordingly adjusted user-interpretation.

Computer Operation

A large-scale digital electronic computer is used for the model simulation. An appropriate unit is the Oklahoma State University Computer Center's "IBM 7040" computer. The effective core capacity for the user is about 25,000 words of which the majority is required. The computer program language is Fortran IV. There are no requirements in the models for external tape storage. Such requirements for increased precision of the demand curve are prohibitive in computer running time. Depending upon which model is run, the computer times range from 0.15 to 0.60 hours for 8760 demand points. Details are described in the Appendix.

Remarks on System Development

Chapter II portrays the logical structure of the simulation models. The descriptions of the models indicate their relationships to an inventory process in which energy is the "raw material" under study. In addition, specific objectives and the general development criteria clarify the direction for the research design of the simulation models. In terms of explicitly relevant criteria, some detailed design resultants now exist for the models.

However, the general picture of Chapter II serves primarily as an introduction to the in-depth derivations of the models which the coming chapters consider. Furthermore, even though the simulation models are the major research development, they do form part of a whole analytical system. A discussion of this "segmentation", for purposes of efficiency criteria, is the next chapter.

In the remaining chapters, the terms "electrolysis" and "input components" are used synonomously. "Fuel cell" and "output components" are also interchangeable. "Cavern storage" in a fuel cell storage technology is the storage of hydrogen in a sealed cavern. For some other storage technology "cavern storage" represents the time-holding of potential energy in some form. By use of these terms, the actual energy system studies in coming chapters are more easily related to the presented logic models.

CHAPTER III

THE OPERATIONAL SYSTEM

The operational approach to the analysis of energy generation systems with balanced storage is segmented into four computer program models. In this chapter the position of the computer models is explained in terms of their interrelationships and analytical roles. The cause for this division of the operational system is discussed in the following section.

Development of the Operational System Design

Following the developmental phase of the original test model, the research objectives broadened to include more requirements. These requirements included the study of efficiency effects of a half-dozen storage components onto energy systems with storage. The treatment of all of these components became desirable. The effects from parameter changes of the demand curve data became another requirement. The simulated method for storage of energy in a power plant operation also was enlarged to cover other storage algorithms. In addition, these expanded requirements necessitated the study of their combination effects on an energy system. After some of these model design requirements were developed on an individual basis, an overall analysis system structure became necessary for efficient application to research studies.

Such a system design considers the objectives of economy and simplicity of operation for the research user. The application to potential research studies of parameter variations in detailed depth indicates the need for separate computer programs. By the use of separate programs, an individual simulation study needs only the handling and preparation efforts of the relevant computer model. At the same time the costs for computer operation are at a minimum since just the area of specific concern to the user is simulated. Most important, by this arrangement computer time requirements are eliminated for those portions of an overall research study where computational results are redundant.

Operational System Design

Figure 6 portrays the flow design of the operational system. Of first interest is that there are four individual models each with their respective computer program. The initiating model is the parameter-curve program. This model analyzes the original demand curve and, when so specified, generates a new, modified demand curve analysis with a corresponding punched card deck in suitable format. The preceding analyses define the parameters of the demand curves.

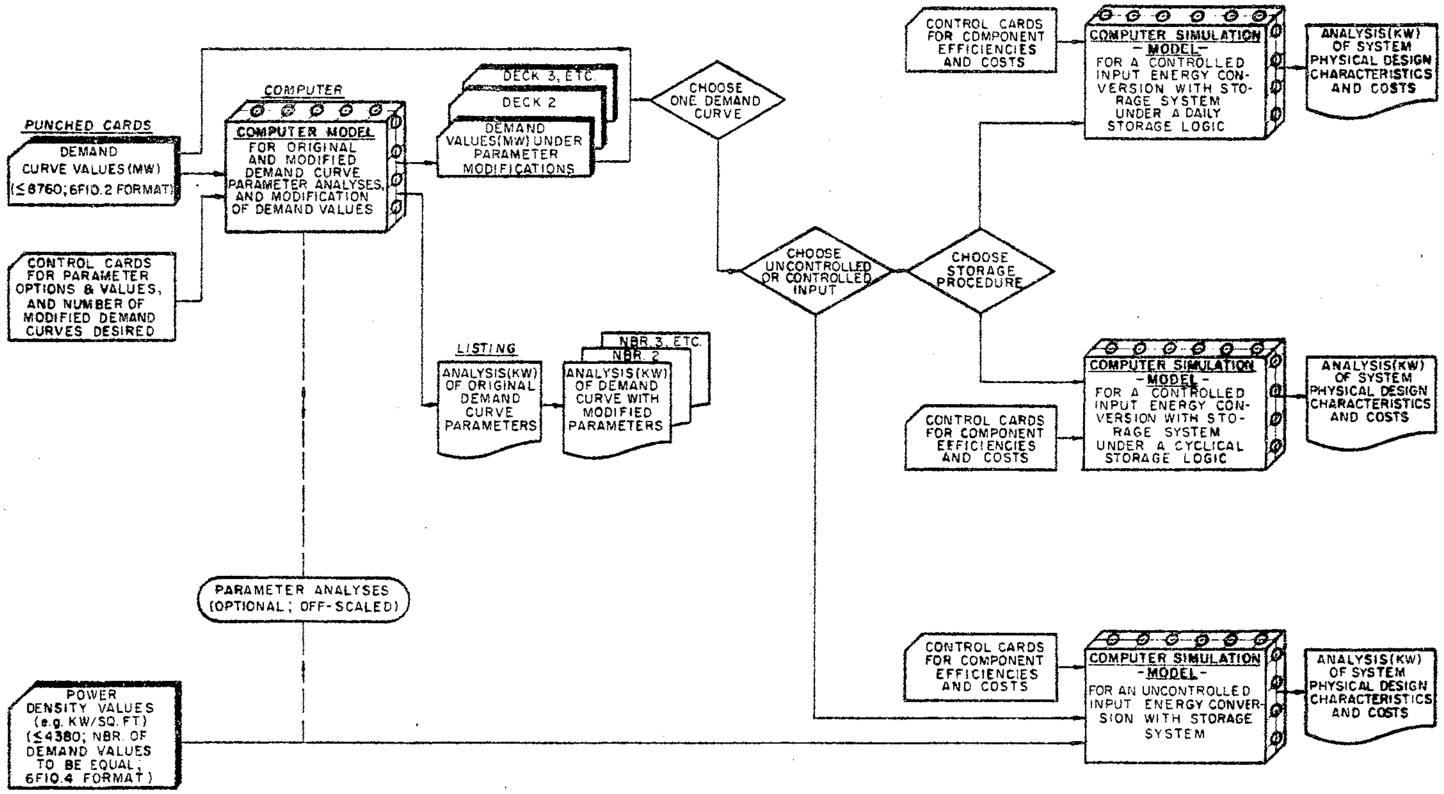


Figure 6. Operational System Design

Repetition of this process ultimately develops a library of demand curves with specific demand curve parameters. More important, this library is repeatedly usable for any subsequent research studies. This is so whether or not these studies are for the same storage technology or storage procedures. Therefore, substantial reductions in computer-time costs for demand curve generation are realizable.

As the figure portrays, the original set of demand curve values can bypass the parameter-curve model for direct input to simulation studies where a demand curve parameter analysis is not necessary (or where the parameter analysis is already available from the library).

After preparation of the demand curve data, the user selects the simulation model which is pertinent to his area of investigation. Or, with the same demand curve deck simulation studies are possible in turn under all three system simulation logics. This multiple usage of the demand data reduces preparation requirements.

The additional requirements are the preparation of control cards for the simulation models. Each of the computer programs needs only a few control cards respective to their own operation plus the general input variables. There is even a high degree of commonality of the control cards between programs. Preparation of these control cards require minimal calculation-decision efforts by the user. The uncontrolled input model needs an extra data input of the power density values.

Operational Restrictions

There are several operational system restrictions of an universal nature implied by the flow chart. They concern the user who refers directly to Figure 6 for general layout planning of a series of research studies.

The maximum capacity of the program is 8760 demand curve values, i.e. one demand point per hour of the year. This unit-time interval is a variable; larger time intervals are allowable. For all three simulation models, the demand curve punched decks must keep a chronological sequence order (earliest time point is first). All parameter-curve generated demand decks have a numerical sequence field for chronological ordering.

The uncontrolled input model requires an additional, major input of the power density values. The number of these values should equal the number of demand curve values. The power density card deck must maintain an identical order of chronological sequence with the demand curve sequence. When the number of demand curve values exceed one value per two hours, a reduction in the number of demand values is required before use of the uncontrolled model. One demand point per two hours is the maximum capacity of the uncontrolled input model. The use of every other demand point is the correct method when a demand deck exists with 8760 values. Specific details about computer setup preparation are in the Appendix.

Remarks on System Development

The operational system design is both practical and simple in application. The research user's preparation efforts are only a few decisions over and above the area of research concern. Given that a suitable demand curve is available, little time or cost is necessary for a simulation model computer run. Moreover, the operational system design actively supports realization of the design criteria.

CHAPTER IV

DEMAND CURVE MODEL

The concern of this chapter is the model for the modification of the demand curve and the analysis of the demand curve parameters. Figure 6 shows the position of the demand curve in support of the simulation models. The demand curve is both a major input variable and a subject for separate investigation; the demand curve model is a general computer program. Because of the demand curve's unique position in the operational system, this chapter covers the complete study of the demand curve model. The analysis parameters, model derivation, and computer results are then available in total perspective for reference in subsequent chapters.

Purpose of Demand Curve Model

The desired nature of the demand curve data is empirical information from electrical utility companies. Nevertheless, even for a single power company its demand curve is subject to changes in demand values over time. The simulation models can use any demand curve for its analysis of energy conversion with storage requirements. Yet, this is impractical for any large scale development of many typical shapes of demand which at the same time reflect an equal scale of power plant with storage for design studies of a system at a particular location.

The deduction is that the demand curve data serves a dual role. Demand values are the basic requirement for "fixed" input data in support of the simulation model analyses. At the same time, the demand curve "shape" is a basic consideration as a major, variable input parameter as well as the storage component efficiencies and equipment costs.

Therefore, the development of a supporting computer program model is necessary to the operational system design. By this vehicle, the just described considerations are achievable. Planned usage of "PCURVE", parameter-curve model's computer program, enables the research user to utilize the demand curve of a particular company or region without requiring a cross-reference to a multitude of demand curves from many companies and regions. This is directly accomplished by modifying certain parameters of the existing demand curve to reflect the reasonably expected variations in demand curve shape of the power company under study.

The approach of demand curve modification offers the advantages of keeping the design study at the same size scale of plant and with the same individually detailed characteristics of the local demand curve (except for those parameters undergoing change). This same approach allows the controlled movement of the demand curve's shape over wide ranges which is not possible simply from a gathering of many so-called similar demand curves. Further, the effects on energy system optimization are examinable for changes in individual demand curve parameters. This evaluation of demand parameter effects is not possible solely by comparison of a number of demand curves from similar-sized plants over many regions.

More economy in research studies is an important reason for the parameter analysis of new and modified demand curves. A new demand curve is defined in terms of its parameters, and thereby is cross-referenced in "shape" to one or more existing demand curves in the library. In such a situation, existing equivalent cost and design studies are reviewed for information about near optimal conditions for the new power plant study.

Demand Curve Parameters

The general nature of the demand curve was described in past chapters. For the determination of realistic parameters, discussions were held with power plant engineers, and examinations were made of detailed hourly values. In the examination of hourly demand values for a year the daily variation was observed as evident across the whole year. Significant patterns in weekly variation were also noted. Partly because months were not uniform in duration, no underlying monthly pattern was observed. Seasonal variations were obviously indicated except that between companies or regions no single pattern was noted as universally common. The height of the demand curve was seen as an obvious consideration and one particularly relevant to energy storage requirements. Along with height the volume, or bulk, of energy required at the higher generation capacities was considered. Further, the time duration of this seasonal peaking occurrence was noted.

For a number of demand curve examinations, the above curve parameters are similar in significance even though any given demand curve varies considerably according to its customer makeup or region. However, at the same time demand curve parameters require consideration in terms of what affects the design of energy conversion systems with storage.

The savings and costs of a storage sub-system are significantly affected by the amount of energy required for storage for a reduction in power generation capacity. Methods of storage are additionally affected by the oscillation of demand requirements over short and long periods of time.

The last area of consideration for the determination of practical parameters of demand curve definition is the ability for independent control of the parameters. As described, the shape of the demand curve is a major variable in the analyses of energy conversion with storage. Efficient usage of library demand curve card decks makes desirable the control of single parameters (or their combinations) over ranges of change in order to obtain new curves with planned characteristics for expected variations.

The results of this evaluation are the establishment of a group of parameters both realistically practical for definition and suitable for the other considerations. The selected operator parameters are the variations of day, week, peakedness, and bulkedness. There are also some additional resultant parameters which aid in definition of the demand curve. These operator parameters are universally common between companies or regions and have the most stable interpretation regardless of individual differences.

Definition of Operator Parameters

A customary measure by power plants is the percentage variation in required plant generation. This measure acts often as a guideline for cost estimation and generator loading predictions. Typically, the specification of this measure is on a monthly basis for an average day, as the "average load factor for January". Load factor is the percentage obtained by the ratio of minimum daily power generation over maximum daily power generation for a given day or an average day. A pertinent comment is that the least amount of variation (i.e. no variation) equals 100.0 per cent; maximum variation is 0.0 per cent. Figure 7 clarifies the interpretation of variation percentages.

Assuming hourly value demand curve points, the definition of daily variation for the parameter-curve model follows the customary definition of load factor.

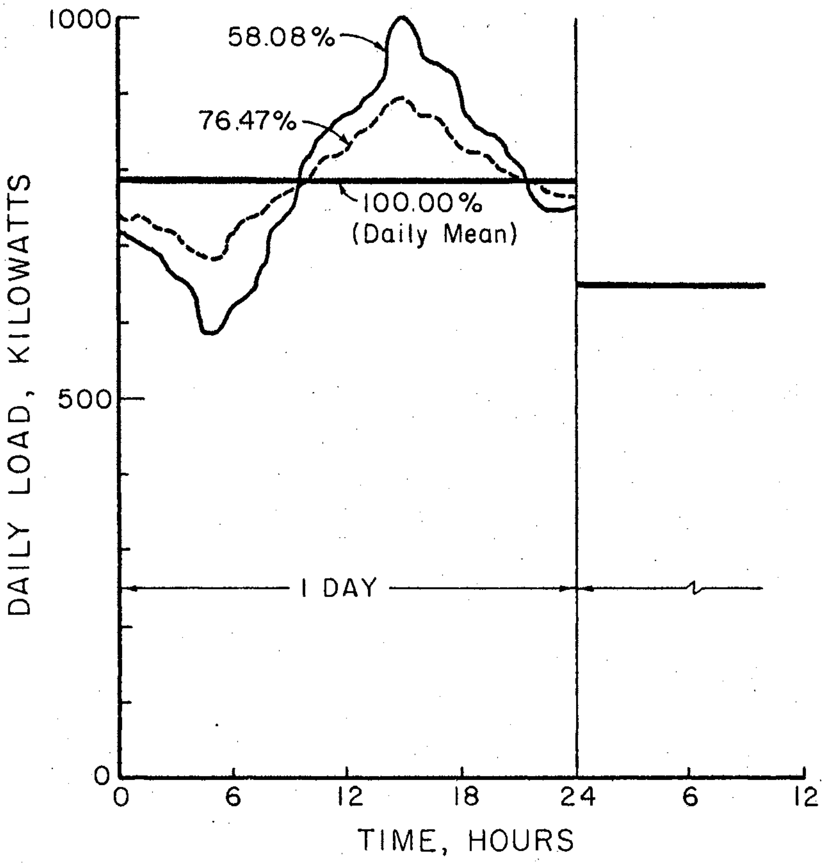


Figure 7. Demonstration of Plant Generation Daily Load Factor and the Corresponding Percentage Measures of the Daily Variation Parameter

Daily variation percentage equals the ratio of the day's minimum hourly kilowatt value over the maximum hourly kilowatt demand value as averaged for the year.

As discussed, weekly variation is of concern to power plants and represents a significant pattern underlying the demand curve. However, if independence between daily and weekly variation is maintained for analysis purposes, then measurement is not possible by the maximum and minimum hourly values of the week. The usefulness of this independence in evaluation of the effects of a demand curve variable onto the storage sub-system overweighs the value of what is possibly a more "customary" definition. Therefore, the ratio of the week's minimum daily mean over the maximum kilowatt daily mean for the same week defines the percentage of weekly variation.

Bulkedness and peakedness are less easily defined. Both of these parameters are recognized easily by power plant engineers, but no customary definitions are established. The only relevant definitions are yearly mean kilowatts and the ratio of highest to lowest kilowatt demand values for the year. At the same time for the purpose of studying energy storage systems some definitions are needed which support the analyses of these two characteristics.

Bulkedness is described as how much "weight" of energy there is in the yearly "hump" of the demand curve. Peakedness is described as how much elongated "pointedness" there is in this yearly "hump". Figures 8, 9, and 10 visibly

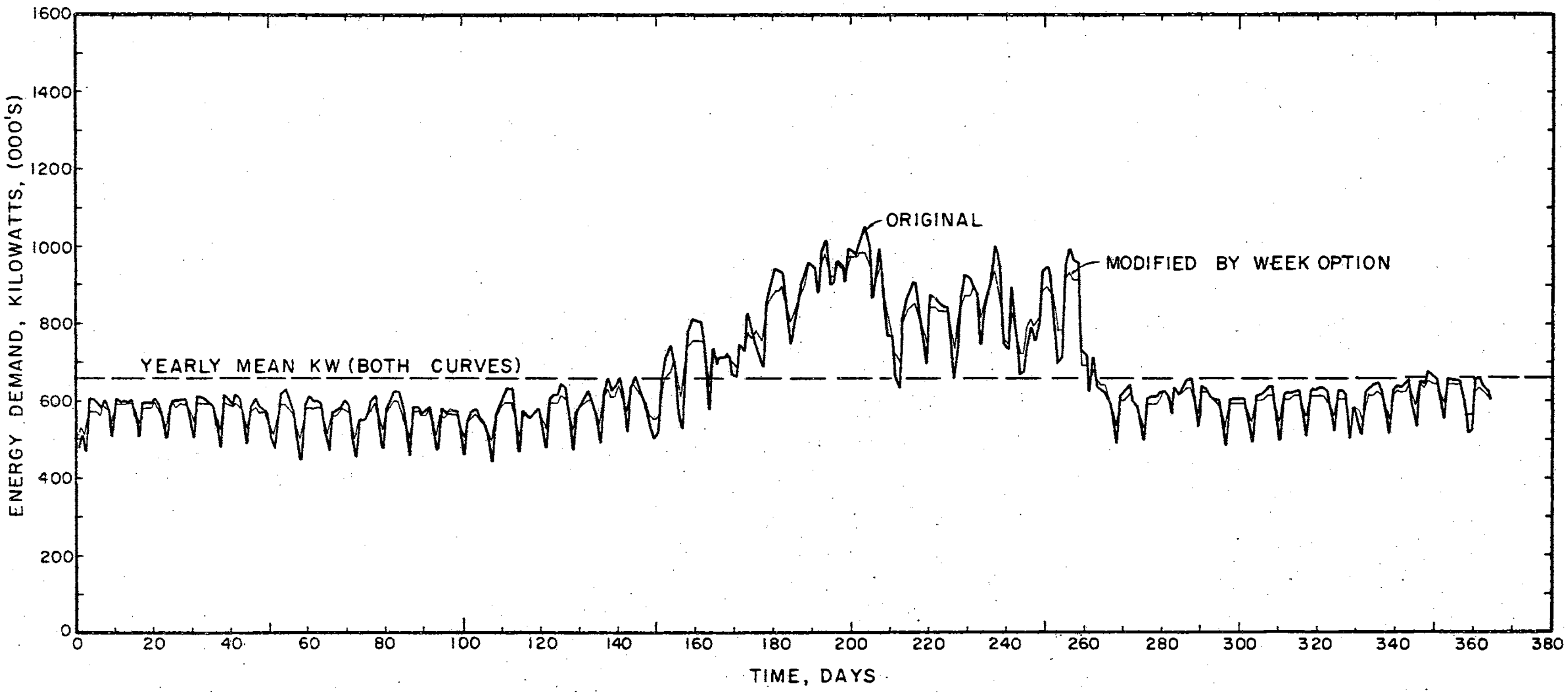


Figure 8. Annual Energy Demand Curve Plot of Daily Mean Values
The heavy line plots the original energy demand curve data.
The light line plots the modification of the original demand curve by a fifty per cent value for the week parameter option.

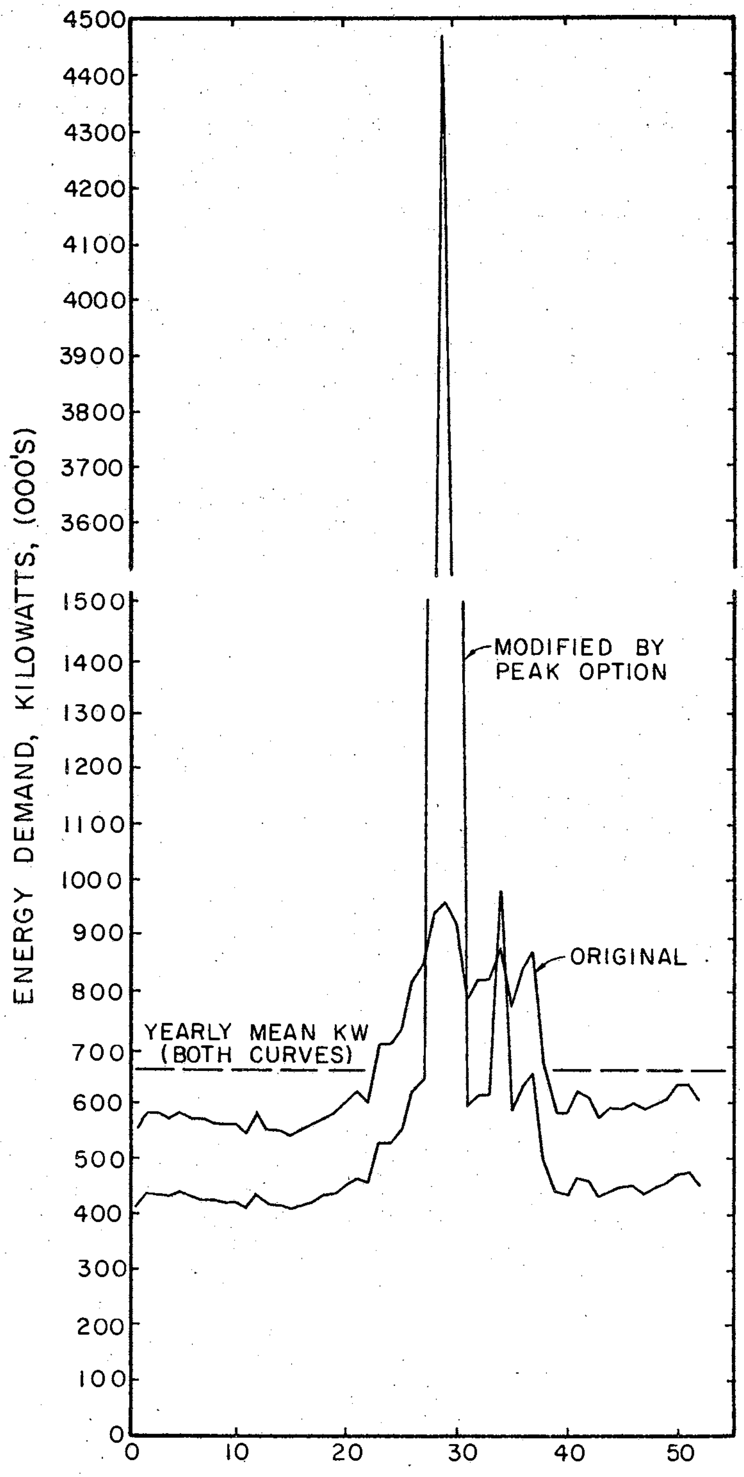


Figure 9. Annual Energy Demand Curve Plot of Weekly Mean Values Modification is by a three-week value for the peakedness parameter option.

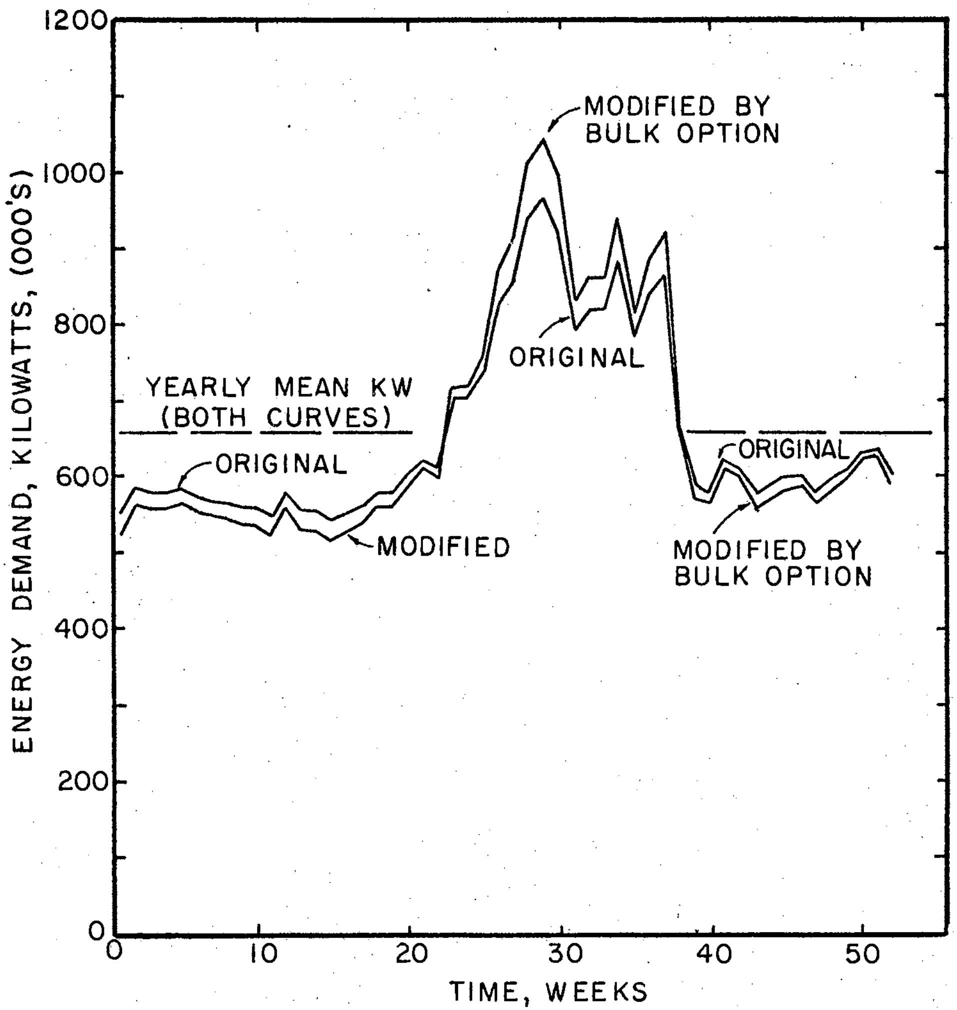


Figure 10. Annual Energy Demand Curve Plot of Weekly Mean Values
Modification is by a 125 per cent value for the bulkedness parameter option.

demonstrate these qualities. Obviously, there is a certain interrelationship between these two characteristics. A demand curve can have a high degree of bulkedness and a low or high value of peakedness depending upon what width of the year the bulk-energy is spread.

At the same time the definitions are desired which recognize the problems of demand curve modifications such that the variation is most useful to analysis of energy storage systems. Definitions are required that are explicitly communicable and, as much as possible, independent of other parameters. Two separate definitions are determined for peakedness and bulkedness.

Bulkedness is defined as the ratio of the yearly kilowatt-hour demand greater than the yearly mean kilowatt value over the total kilowatt-hour requirements for the year. Peakedness is defined as the number of demand values greater than the yearly mean kilowatt value over the total number of demand values.

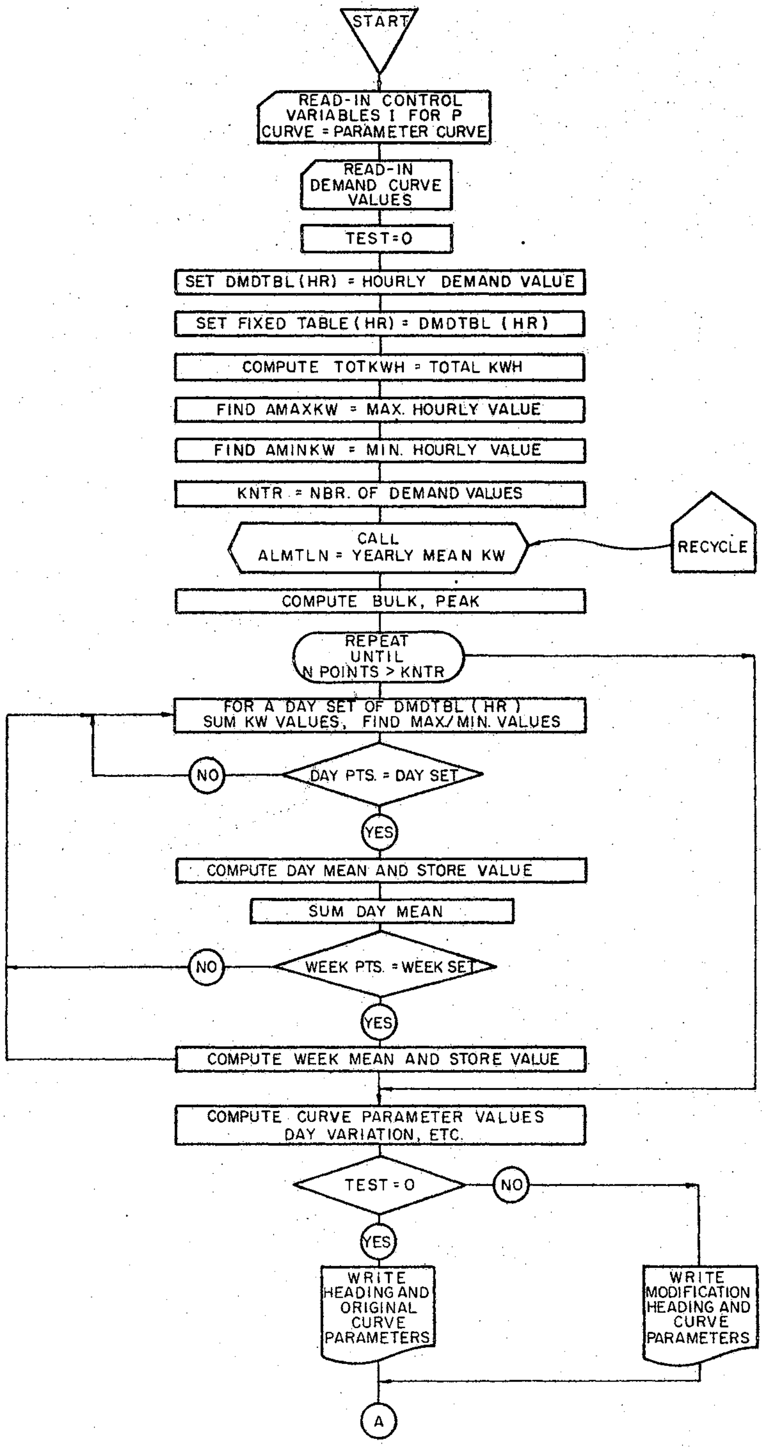
It is noted that all four of these resultant parameters are computed on the basis of hourly demand values (assuming 8760 demand values are available). The operator parameters are not so computed except for daily variation. The day operator is computationally modified in sets of twenty-four hourly demand values. The week operator is computationally modified in sets of a week's demand values by sub-sets of a day. Bulkedness and peakedness are computationally modified in sets of a week's demand points by weekly means and over the year. Other curve-defining parameters are computed for the original curve and for the modified curve; they are computed on the basis of hourly demand values since they are not operator parameters. They are defined later in this chapter.

Also of significant note, the day and week parameters are kilowatt-percentage oriented. Bulkedness is kilowatt-hour-percentage oriented. Peakedness, however, is time-percentage oriented. The effects of this orientation are considered in a later section.

Design of Program Model

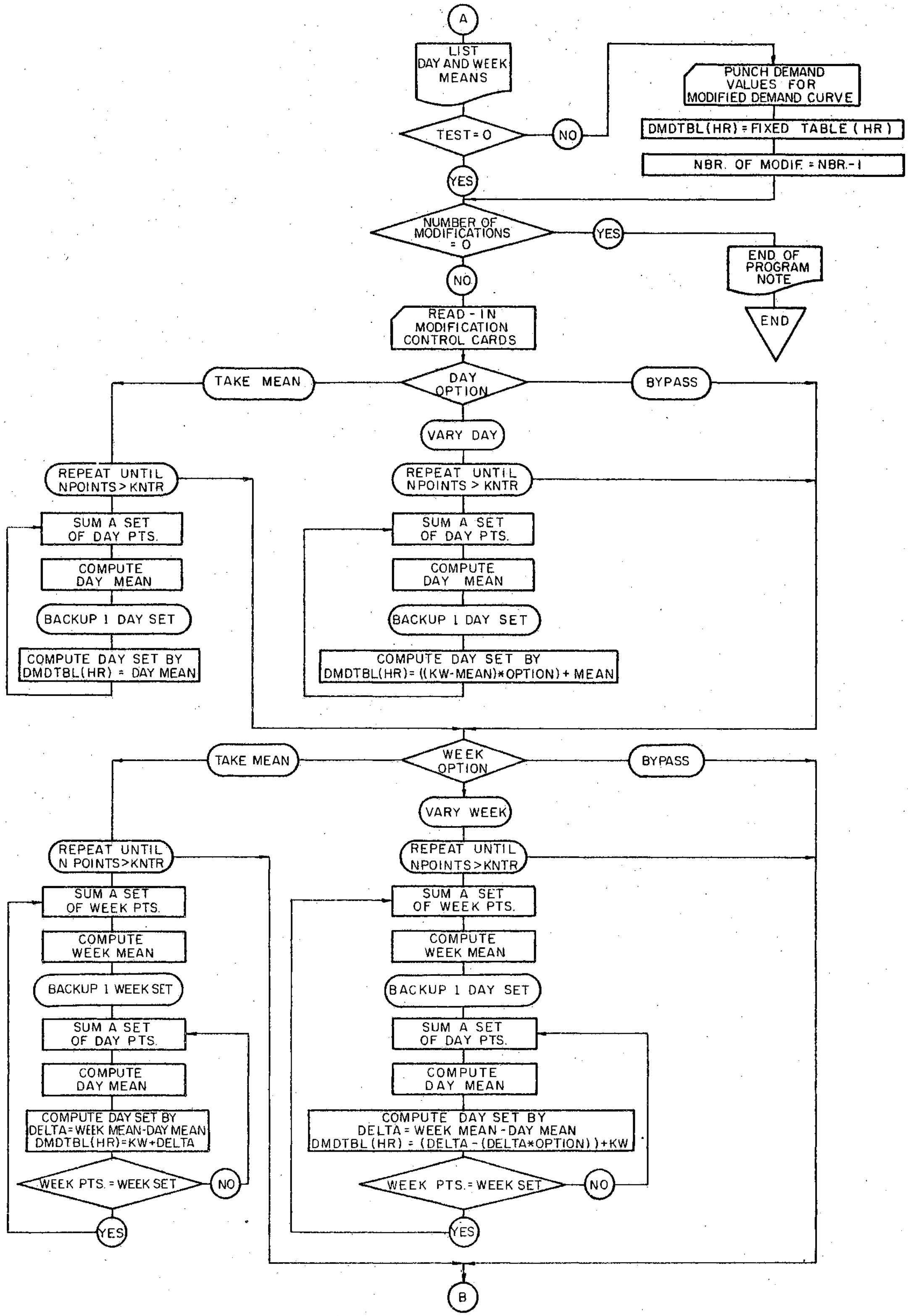
The operator parameters are used for the modification of sets of demand curve values in turn across the year. In this model design these time-period sets are independently adjusted. The sequence and structure of the parameter-curve model's operation is clarified by reference to Figure 11, the macro-logic derivation of parameter-curve model.

Mean-value options are also available for day, week, and bulkedness parameters in order to reduce computational time. The sequence of computation is day, week, peakedness, and bulkedness options. The bypass of any option is possible. The computer program always analyzes the original demand curve input to this program. Any number of modified demand curves are developable each with a demand curve punched card output; in such cases the original demand



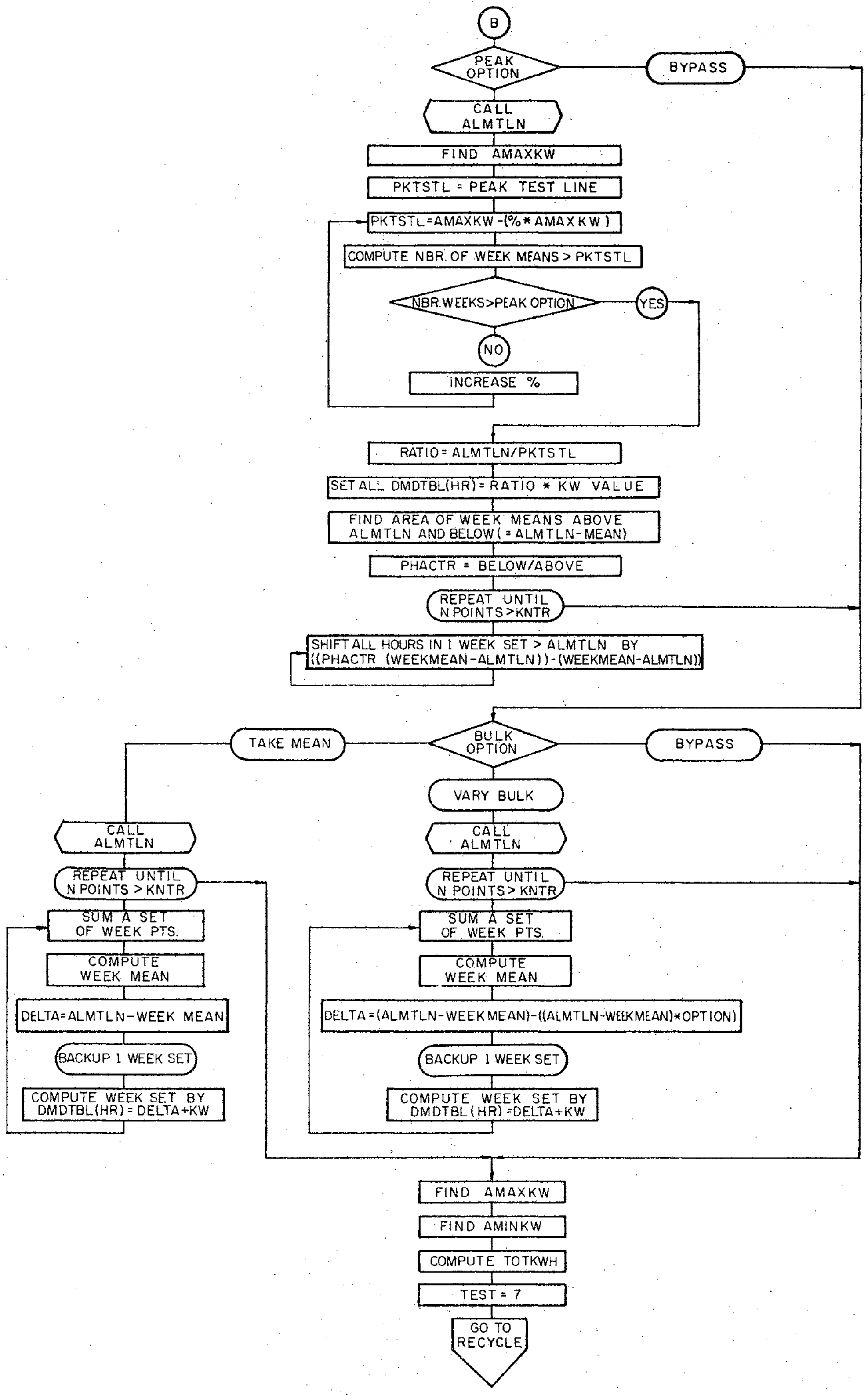
(a)

Figure 11. Macro-Logic Derivation of Parameter-Curve Model



(b)

Figure 11. (Continued)



(c)

Figure 11. (Concluded)

curve is always the curve under modification by the next given group of operator parameters.

The essential computational process of the day option is the read-in of a set, or yearly sub-set, of 24 demand curve values (assuming 8760 demand points). A daily mean kilowatt value is computed. The option percentage value is then used for modification of the hourly values above and below the daily mean such that the mean is unchanged. For example, a daily option of 60.0 per cent implies a reduction in the percentage of daily variation. Consider a set of daily points whose mean is ten kilowatts, and an hourly kilowatt value of twenty. The modified hourly value is determined as:

$$(20 - 10)(.60) + 10 = 6 + 10 = 16 .$$

In other words, the difference between the daily mean value and the hourly value is reduced to 60 per cent of itself, and this value is added to the mean. This is reflected in the computer array for the demand curve values, sub-time, by the "insertion" of 16 to replace 20 kilowatts. Consider an hourly value of five kilowatts for the same day. The new demand curve value for that particular hour of the year is determined as:

$$(5 - 10)(.60) + 10 = -3 + 10 = 7 .$$

This approach is required so that the daily mean value is kept constant. The purpose, of course, is viewed as formation of a modified demand curve whose yearly mean kilowatts and total kilowatt-hours are the same as the original demand curve. In this manner, the "scale of power plant" is maintained for later energy storage studies.

The computational process of the week option is identical in principle to the day option. However, the sequence is somewhat different. A set of points for a week are brought in from core (the array now modified by day option) and the program computes the weekly mean. The process then backs up to the first day set of points and computes the daily mean. The computation for the kilowatt shift of the daily mean is the same as the already described hourly shift. However, the process now backs up to the first hour of this day and shifts this hour by the amount of kilowatt shift for the daily mean. All hours within this day are shifted by this uniform amount. This is the necessary approach in order to maintain independence between the measures of daily variation and weekly variation according to their definitions.

Peakedness is a more complex computational process since it is essentially time-oriented. The purpose of this option is the modification of the demand curve so that the specified number of option weeks are equivalent to the recapitulational computation of peakedness according to its measurement definition.

Beginning with the now maximum value of the current demand array a series of kilowatt levels ("peak test lines") are decremented with peakedness evaluated in weeks at each line. When this peakedness value is first greater than the specified option value, a ratio is determined by the yearly mean kilowatts over this computed level. The interim purpose is the reduction (or increase) of the demand curve in proportion so that the daily and weekly variation remain independent and a psuedo-mean value exists with the desired peakedness measurement. At this point modification of the demand curve is again necessary so that the original yearly mean is re-established while in turn the new peakedness value is kept. For the modified curve a computation determines the energy above the original mean value. This area of energy, by a percentage modification of the area, then equals that area below the original yearly mean, which is above the demand values. Of note is that these series of computational processes utilize weekly sets of demand curve values.

The program then proceeds to the last option, bulkedness. The computational process is identical to that of the day option except that the full year is the utilized set with adjustments by sub-sets of a week. Demand values within each week receive uniform kilowatt shifts so that hours and days are left in the same magnitude of variation.

At this point the program examines the now several-times modified computer array of demand values, and recomputes all resultant parameters. Of note, the hourly demand values are the basis for this computation, in the same way as for the original curve determination.

An hourly set of demand values for the year are now punched for this modified curve in a suitable format coupled with the analysis listings. In addition, listings are made for drafting purposes. The program arrays are then reinitialized to the original demand curve, and the next modified demand curve is computed according to the next group of operator parameters, if any.

Interpretation of Computer Output

The interpretation of this program model is straightforward; it simply defines the parameter values for the original and modified demand curves. There is no direct computer relationship to the system simulation models. The Appendix lists other mnemonics and operational computer requirements.

Figure 12a is a sample computer output page for the analysis of the original demand curve. Figure 12b is a sample output page for a modified demand curve. The values in its heading restate the parameter option values as specified by the user; in this example, the modification bypasses all but the week option.

"YRHILO" is a resultant parameter. It is the ratio of the highest yearly kilowatt demand value over the year's minimum demand value. Its use is essentially a descriptive one.

"DALYVL" and "WEEKVL" are the respective values for the measures of daily variation and weekly variation as defined. "DLWKVL" is general information about the variation of the

```
               ENGINEER ===  A.BRUCKNER,II        SCHOOL OF INDUSTRIAL ENGINEERING, OSU,  1966
      THE FOLLOWING IS THE PARAMETER ANALYSIS FOR THE DEMAND CURVE INPUT UNCHANGED,EVERYTHING IN KILOWATTS
   KNTR=  8760     NUMBER DEMAND POINTS
KNTPTS=  8761NDLPTS=    24ADLPTS=  24.00000IWKPTS=   168NWKPTS=   192AWKPTS= 192.00000    FOR INSPECTION
   YRHILO=  0.43974E 01     YR-MAX-KW OVER YR-MIN-KW
   DALYVL=  0.53658E 00     YR.DAILY VARIATION (MIN/MAX)
   DLRGKW=  0.19828E 06     ONE-HALF YRLY AVG DALY KW RANGE
   WEEKVL=  0.77486E 00     YR.WKLY VARY(MINDAYMEANOFWK/MAX
   WKRGKW=  0.83397E 05     ONE-HALF YRLY AVG WKLY KW RANGE
   DLWKVL=  0.43539E 00     YR.WKLY.VRY(MINHROFWK/MAXHROFWK
   DWRGKW=  0.25862E 06     ONE-HALF YRLY AVG DLWK KW RANGE
   TOTKWH=  0.57593E 10     TOTAL KWH REQTS FOR YEAR
   AMAXKW=  0.13720E 07     YR.MAX.KW.REQD
   AMINKW=  0.31200E 06     YR.MIN.KW.REQD
   BULKVL=  0.11698E 00     PCT KWH(OF TOTAL)ABOVE ALMTLN
   PEAKVL=  0.47534E 00     PCT OF DEMAND PTS GRTR ALMTLN
   ALMTLN=  0.65746E 06     YEARLY MEAN KW
   ENDCRD=  0.99990E 38
```

(a)

Figure 12. Computer Output for Parameter-Curve Model

```
     THE FOLLOWING IS THE PARAMETER ANALYSIS FOR THEDEMAND CURVE AS MODIFIED BY OPTIONS (EVERYTHING IN *KILOWATTS*).

          THE OPTIONS WERE.........

          OPTDLY= -11.10000     OPTWEK=   0.50000    KOPTPK=  -10     OPTBLK= -11.10000

***PUNCHED CARDS ARE IN F10.2  *MEGAWATTS**.

     KNTR=  8760      NUMBER DEMAND POINTS

KNTPTS=  8761NDLPTS=     24ADLPTS=  24.00000IWKPTS=   168NWKPTS=   192AWKPTS= 192.00000    FOR INSPECTION

     YRHILO=  0.38828E 01     YR-MAX-KW OVER YR-MIN-KW

     DALYVL=  0.53658E 00     YR.DAILY VARIATION (MIN/MAX)

     DLRGKW=  0.19828E 06     ONE-HALF YRLY AVG DALY KW RANGE

     WEEKVL=  0.88072E 00     YR.WKLY VARY(MINDAYMEANOFWK/MAX

     WKRGKW=  0.41699E 05     ONE-HALF YRLY AVG WKLY KW RANGE

     DLWKVL=  0.46056E 00     YR.WKLY.VRY(MINHROFWK/MAXHROFWK

     DWRGKW=  0.24283E 06     ONE-HALF YRLY AVG DLWK KW RANGE

     TOTKWH=  0.57592E 10     TOTAL KWH REQTS FOR YEAR

     AMAXKW=  0.13156E 07     YR.MAX.KW.REQD

     AMINKW=  0.33882E 06     YR.MIN.KW.REQD

     BULKVL=  0.11158E 00     PCT KWH(OF TOTAL)ABOVE ALMTLN

     PEAKVL=  0.46838E 00     PCT OF DEMAND PTS GRTR ALMTLN

     ALMTLN=  0.65746E 06     YEARLY MEAN KW

     ENDCRD=  0.99990E 38
```

(b)

Figure 12. (Continued)

```
LISTING OF DAILY MEANS RELEVANT TO ABOVE PARAMETERS    IN KILOWATTS  KILOWATTS..
            1        0.47979E 06
            2        0.51671E 06
            3        0.47246E 06
            4        0.60521E 06
            5        0.60550E 06
            6        0.59529E 06
            7        0.58138E 06
            8        0.60350E 06
            9        0.57946E 06
           10        0.50342E 06
           11        0.60783E 06
           12        0.59733E 06
           13        0.59921E 06
           14        0.59808E

          347           192E 06
          348        0.64362E 06
          349        0.67708E 06
          350        0.66754E 06
          351        0.65958E 06
          352        0.61758E 06
          353        0.54950E 06
          354        0.65929E 06
          355        0.65504E 06
          356        0.65529E 06
          357        0.65196E 06
          358        0.59979E 06
          359        0.51733E 06
          360        0.52367E 06
          361        0.65575E 06
          362        0.66079E 06
          363        0.64100E 06
          364        0.62892E 06
          365        0.59917E 06
```

(c)

Figure 12. (Continued)

```
LISTING OF WEEKLY MEANS RELEVANT TO ABOVE PARAMETERS    IN KILOWATTS  KILOWATTS..
                   1       0.55090E 06
                   2       0.58412E 06
                   3       0.58023E 06
                   4       0.57896E 06
                   5       0.58499E 06
                   6       0.57593E 06
                   7       0.57003E 06
                   8       0.56821E 06
                   9       0.56164E 06
                  10       0.56080E 06
                  11       0.54885E 06
                  12       0.58093E 06
                  13       0.55693
                  14

                                    06
                           0.    39E 06
                           0.57923E 06
                   4       0.59133E 06
                  45       0.59742E 06
                  46       0.60301E 06
                  47       0.58396E 06
                  48       0.59705E 06
                  49       0.60939E 06
                  50       0.63154E 06
                  51       0.63546E 06
                  52       0.60330E 06
PHONY=     195.00          8760   8761AMAXKW=   0.1372E 07    ALMTLN=  0.6575E 06       192     0
PHONY=     222.00          8760   8761AMAXKW=   0.1372E 07    ALMTLN=  0.6575E 06       192     0
PHONY=     400.00          8760   8761AMAXKW=   0.1372E 07    ALMTLN=  0.6575E 06       192     0
PHONY=     800.00          8760   8761AMAXKW=   0.1213E 07    ALMTLN=  0.6575E 06       192     0
```

(d)

Figure 12. (Concluded)

week's maximum and minimum hourly demand values. There are three "xxRGKW" items. For purposes of visualizing the kilowatt magnitude of the variation, these values equal one-half the range of the average annual kilowatt measure of variation for, respectively, the day, week, and the day-week combination.

"TOTKWH" is the yearly total kilowatt-hour energy requirements for the given demand curve. "AMAXKW" and "AMINKW" are the maximum and minimum yearly demand curve kilowatt values. "ALMTLN" is the value for the yearly mean kilowatts.

"BULKVL" and "PEAKVL" are the values for the bulkedness and peakedness parameters already defined.

Figures 12c and 12d are examples of the listings which follow each page of computer parameters including the original curve. They are useful for drafting purposes when protrayal of a demand curve is desired at a broader view than a detailed plot of the hourly demand values. (The values that follow the fifty-second week in Figure 12d are just program internal reference messages.)

Results of Application

Applications of the parameter-curve model are shown in Figures 8, 9, and 10. Successful results are achieved for all of the demand modifications including both single and combination parameter effects. The original demand curve is modified in a planned and controlled manner with an explicit definition of the curve shape. Punched card decks of demand values are obtained for input to the system simulation models. Thus, the objectives of this model are realized by its application potential for studies of demand curve variation effects on energy storage requirements.

Figure 8 warrants particular review. This figure plots the demand in detail of daily mean kilowatt points. The heavy line is the original demand curve. It is essentially the 1965 demand curve for Oklahoma Gas and Electric Company which serves the medium-sized city of Oklahoma City, sections of Oklahoma, and border areas of Arkansas. The fine line is the plot of this demand curve when modified by an operator parameter value of 0.50 for the week option; the other three options bypass computation. In the next chapters a reference to these curves is desirable since they are the actual study's demand input data.

Remarks on System Development

A summary evaluation in Table I gives the operator parameter and resultant parameter values for a number of modified demand curves. All of the resultant values are in the range of predictable results.

Those modified demand curves based on a combination of operator parameters are less predictable, since the hourly demand values are modified in series by the number of affecting options.

There are three basic conditions which cause a degree of less than perfect independence. The first is the peaked-

TABLE I

COMPARATIVE DEMAND CURVE PARAMETER RESULTS BY USE OF THE PARAMETER-CURVE GENERATOR

OPERATOR PARAMETERS				RESULTANT PARAMETERS*					
DAY (%)	WEEK (%)	PEAK (NbR)	BULK (%)	DAY (%)	WEEK (%)	PEAK (%)	BULK (%)	YEAR HI/LO (%)	DAY-WEEK (%)
—— Original Curve ——				53.66	77.49	47.53	11.70	439.74	43.54
.50				73.79	77.49	40.23	8.82	314.34	59.14
	.50			53.66	88.07	46.83	11.16	388.28	46.06
		3		63.15	82.65	16.14	27.10	2,026.10	54.50
		47		46.92	73.62	52.84	12.58	791.68	35.94
			1.25	53.66	77.49	44.74	12.56	501.37	43.54
.60	1.10		1.25	69.35	75.51	39.04	10.75	393.80	54.37
.50	.50	40	1.15	70.53	86.45	52.32	6.05	225.02	63.21

* Total annual kilowatt-hours and yearly mean kilowatts are the same for all demand curves. Total KWH = 5,759,300,000. Yearly mean KW = 657,460.

ness option which is a result of the time-oriented definition. This option requires a computational process that has to force more strongly a change in the shape of the demand curve with several stages of curve modification. The second condition is the movement of some demand points by an absolute shift for the time-period set of data. This design decision involves a criterion of maintaining the curve variation magnitude for equipment specifications. This is more appropriate for the studies of energy systems for range-changes of a non-steady-state projection. This approach requires some "loss" of proportional modification relative to the generation of new demand curves. For analysis of a given company, the selected approach is the design because of its better analysis of one given company for a range of conditions. In any case, modification by a lower order time set (i.e. a day set is less than a week set) compensates reasonably for this effect. The third condition is also important for net result effects. As recalled, the computational processes perform on the basis of sets of days and weeks. The final calculation of the resultant parameters is in terms of hourly demand values. This is a planned approach in order to gain maximum measurement accuracy between any number of demand curves. However, this approach causes some sacrifice in precise predictability of parameter movements under modifications.

These above conditions inherently cause a degree of dependence between the separate parameters when some parameters are used in combination for demand curve modifications. That is to say, the precision of measuring the resultant parameters of the modified curve is greater than the natural independence of the sets of data. The computational movements of sets of days and weeks are logically independent. Nevertheless, an hourly value within a set can cause a minor perturbation in parameter measurement. This is most notable in the peakedness and bulkedness parameters as well as when the parameters are used in combination. For example, an hourly value might move above or below the yearly mean kilowatts when a day mean is near that value. The day and week parameters are virtually unaffected. However, that same point causes a moderate change in either or both of the bulkedness and peakedness measurements when finally measured.

This is evident by reference to Table I. During the design of this model, a choice of design-decision was selected. It was concluded that the greatest precision in measurement of the finally modified curve for its parameters is more important than preventing minor perturbations affecting independent predictability.

This conclusion is based on the original goals of capability for demand curve comparisons for common qualities at a minimum level of research cost. Therefore, the model design objectives are satisfactorily achieved on the basis of this decision for maximum precision in measurement.

CHAPTER V

DERIVATION OF SIMULATION MODELS

This chapter is concerned with the derivation of the system simulation computer models. The interpretation of the models' computer outputs is described in Chapter VI. There are three system simulation models: controlled input with cyclical storage procedure, controlled input with daily storage procedure, and uncontrolled input. "Controlled input" denotes a conventional plant where the rate of generation is continually adjusted to the present demand need. "Uncontrolled input" denotes the utilization of an unconventional energy source where the rate of generation depends upon source availability regardless of demand for energy. "Cyclical" and "daily" denote the power plant methods and model algorithms by which energy enters-stays-leaves the storage block.

Basic Concept

Ignoring legal and safety requirements for generation capacity, the technically required generation capacity (kilowatts) is equal to the maximum yearly demand value. This peak load requirement is often only for a few percent of the year coupled with a very low kilowatt-hour energy requirement. It is this condition that warrants the study of energy conversion with storage systems. Only a small amount of stored energy is required for a generally significant decrease in conventional power plant investment. There is a minimum point of power plant capacity below which enough total energy is not generated over the whole year to meet the sum of the demand requirements. Mathematically, this would be equivalent to the yearly mean kilowatts, if it were not for storage block efficiency losses.

Therefore, no matter how much storage is available, the minimum generation capacity must suffice the yearly total energy requirements plus the energy required to compensate for the storage block efficiency losses. This minimum generation capacity kilowatt level is called "ALMTLN", limit line, at which point the power plant generates at a uniform level across the year. The limit line kilowatt capacity is greater than yearly mean kilowatts except where the storage block operates at 100 per cent efficiency.

This concept is portrayed in Figure 13; "A" is the energy required at the point of demand. "B" is the total amount of energy that must enter into the storage block to satisfy the "A" requirements. "B", however, is not the amount of energy that must be stored such as hydrogen in a cavern. Thus, "B" includes the "A" energy requirements plus the energy requirements to overcome the storage block efficiency losses. It is notable even at this maximum storage case that its percentage of yearly energy require-

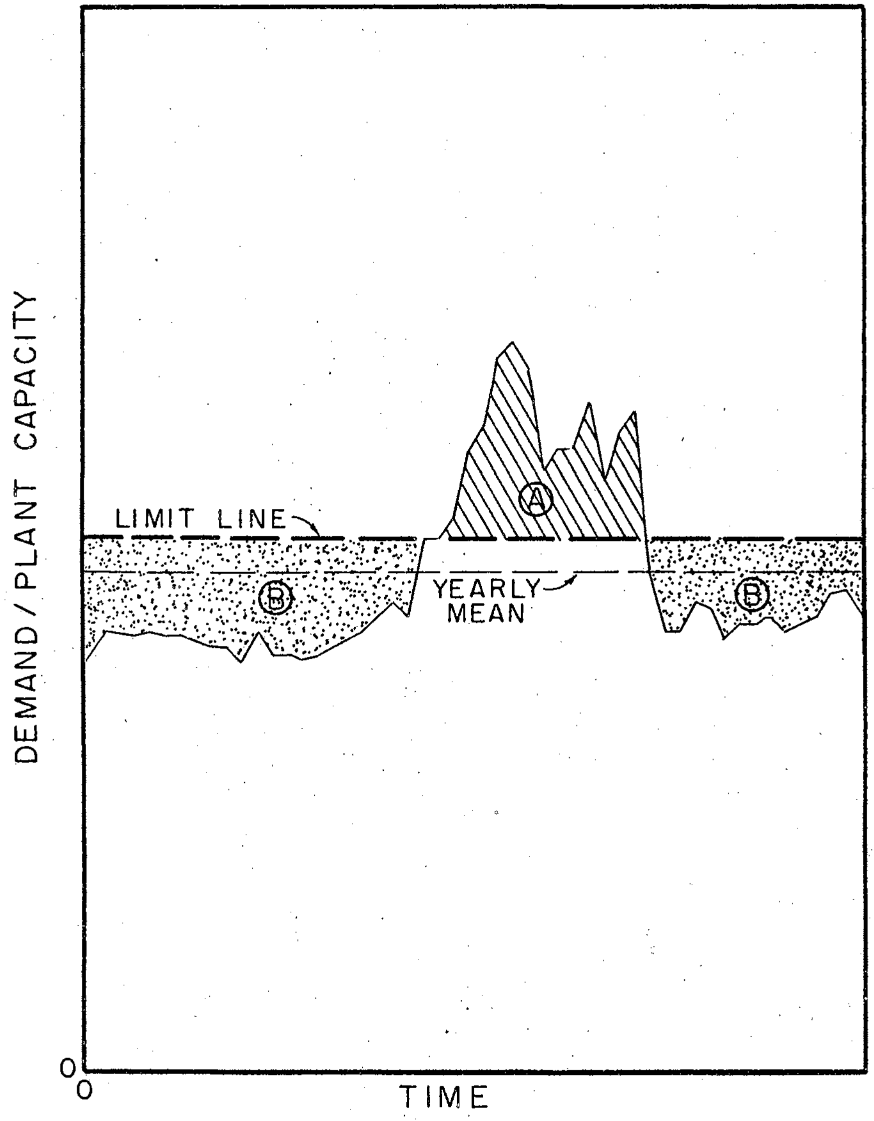


Figure 13. Portrayal of Limit Line and Energy Storage Concepts Storage block efficiency is less than one hundred per cent in this example.

ments is still relatively small. Practical considerations of economic trade-off between plant investment savings and storage block costs seldom approach the limit line. The economic optimization level for power generation usually falls someplace above the limit line.

Storage Block Efficiency

Reference to Figure 4 indicates that seven storage components are defined for individual study. The input and output components are rated in kilowatts. The "cavern" storage component is rated in kilowatt-hours. For each of these components an efficiency percentage is specified as a single percentage value for each component. The storage block compound efficiency is then the product of these seven efficiencies since they act in series. This is called "SYSFAC", system factor. The energy area "A" (Figure 13) is divided by the system factor percentage to determine the "B" energy requirements. This is the amount of energy that must enter into the storage system at the input point of the first input component, "B1" in Figure 4. The combination of the single, or point, efficiencies of the input components is called "STINFC", store-in factor efficiency. For a given time interval unit ("ADT") that energy entering the first input component times the store-in factor is the amount of energy entering into cavern storage. This amount of energy is summed over periods of input to determine the maximum cavern storage requirements (kilowatt-hours), according to the storage procedures. Similarly, the output component efficiencies are multiplied to obtain "A1INFC", "A1" input factor. The kilowatt output of "A3" is equal to the kilowatts required by the demand curve; when this value is divided by "A1" input factor, the kilowatt input rating is defined for "A1" in Figure 4.

Fuel Conversion Efficiency

The cumulative fuel efficiency as a function of system load percentage is portrayed in Figure 14. The values of this graph are for a simplified view of the complete power generation system of the Oklahoma Gas and Electric Company for 1965. The generation capacity is made up of a number of generators with the most efficient generators being used for base load. Therefore, the overall fuel conversion efficiency declines as the system load increases. This information is used to evaluate fuel costs. The price of bulk, purchased fuel is converted to cost per kilowatt-hour according to the theoretically available energy of the given fuel. Percentage system load is defined as the ratio of a kilowatt demand value over the yearly maximum demand value. Actual cost of fuel for a given hour of the year is then computed as:

$$\frac{\text{(kilowatt demand value)(dollars/kilowatt-hour of bulk fuel)}}{\text{(fuel efficiency value for that hour's system load percentage)}}$$

Total yearly fuel costs then are the summation of all hourly costs. This approach parallels the power plant practices of

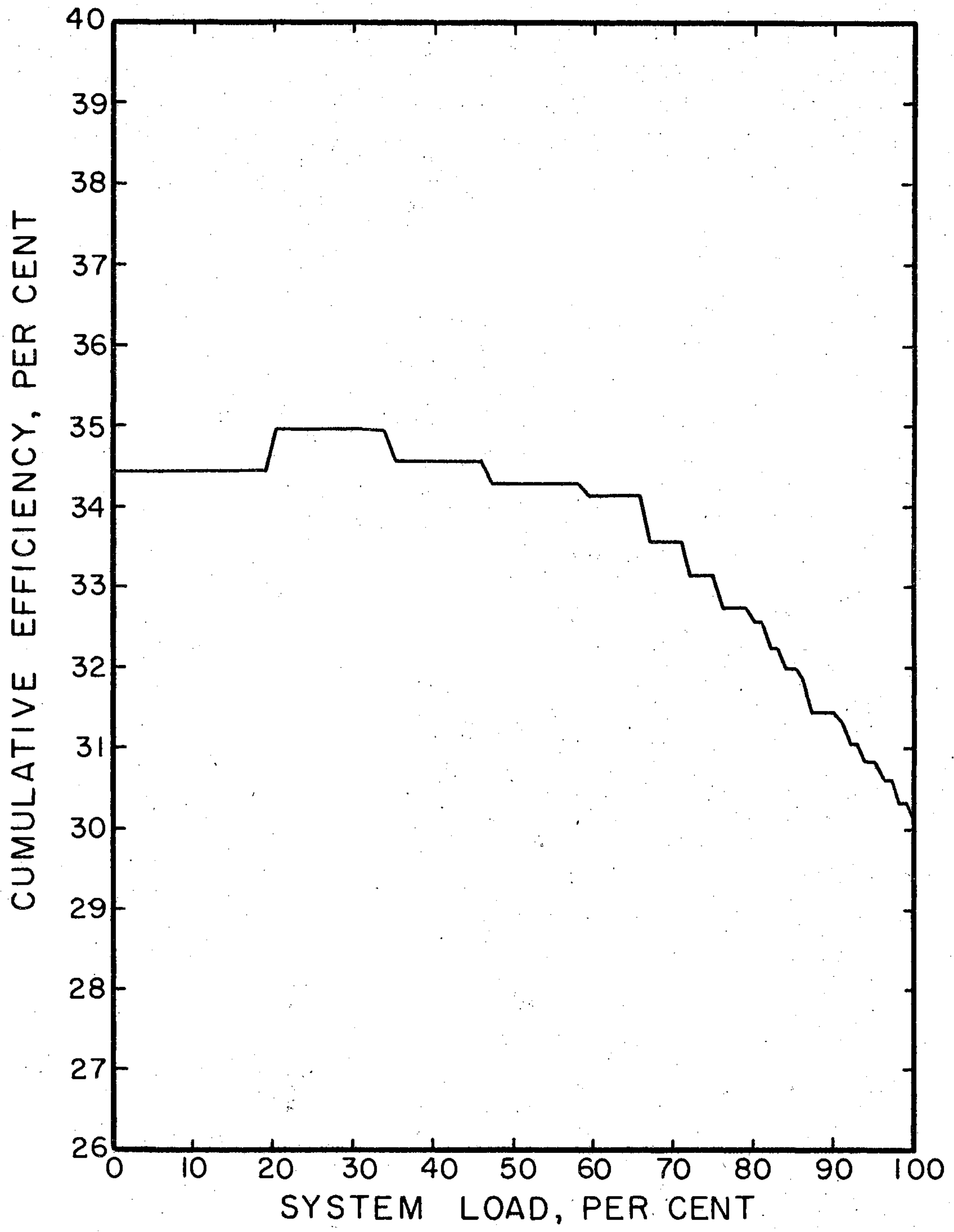


Figure 14. Cumulative Efficiency of Power Generation Fuel Conversion by Percentage Load of Plant Generation

loading generation equipment according to minimum heat rate (BTU/KWH Net) combination levels. As the energy load increases the generation units of declining efficiency are added. The design of this fuel cost computational procedure offers maximum flexibility in allowing research studies to be made on individual power plants regardless of their equipment-loading operating practices. This can be observed in Figure 14; the first generation unit loaded is a re-heat unit with slightly less efficiency than the next unit. There is no effective difference in this case since the two first units' megawatt rating is below customary minimum load. Figure 14 was developed in "jumps" of unit megawatt ratings at generation unit-average heat rates. The research user can develop as precise as efficiency chart as desired by plotting smaller heat rate increments before conversion to cumulative efficiency values.

Annual operating costs of conventional power systems include in the range of fifty per cent for fuel costs. Therefore, the cost optimization model must include this major cost component in the trade-off analysis.

Costs

Energy conversion with storage systems are evaluated for the following equipment cost parameters: storage input components, cavern storage, storage output components, and conventional power plant cost. The purpose of the computer cost output is solely one of ready decision-estimation convenience to the research user. Costs are simply linear cost extensions, i.e. no economy-of-scale analysis is made within the program. Hence, the cost parameter input values should represent reasonable-range values for the expected size of specified components.

Even though the research user of these models might have only "best estimates" of costs because the state-of-the-art precludes better information, the cost computations play a very useful role in the analysis and design of energy conversion with storage systems. They are used in the prediction of boundary conditions for feasible limits of costs if savings are to be realized; they are used to find the physical parameter value range where least costs are likely to occur. Further, they aid in determination of those equipment and efficiency areas where continued research efforts offer the greatest potential yield.

Cost parameter definitions indirectly emphasize the equipment design aspects by being based exclusively on Equivalent Annual Costs per kilowatt or kilowatt-hour. Some information, therefore, requires prediction concerning the expected life of components. Again this demonstrates a convenient approach, since the technology state-of-the-art for different components can have radically different useful lives. Consideration of a rate of return ("interest percentage") is recommended thereby emphasizing this significant restraint of a feasible system design. (In this study, where pertinent, a rate of return of eight per cent was used.)

Equivalent Annual Costs are computed by conventional engineering economy methods. Estimated first costs of equipment *per* kilowatt or kilowatt-hour are evaluated by the capital recovery factor-uniform annual series for the various projected lives. The research user can make reference to a table of these values in books like *Engineering Economics*, by Thuesen and Fabrycky, Prentice-Hall Company. Nevertheless, the research user is not obligated for development of accurate costs and lives of storage equipment components. Rough estimates can still assist in understanding boundary conditions if good estimates are used for conventional power plant cost (and fuel cost). This is since one "side" of the trade-off cost curves are well defined as the feasibly practical limit for storage sub-system costs. Accuracy of the cost input parameters is not vital in order to obtain much of the decision-making value of the cost output. It behooves the research user to make use of this information in his overall analysis of research prediction no matter how gross the cost data information.

A common engineering practice is specification of equipment in terms of output capacity. This is appropriate to equipment analogous to controlled generation. Energy storage systems, however, perform differently. Their definition is in terms of capability to receive power. Hence, besides physical characteristics, *all computer cost outputs define the required costs for the input capacities of storage equipment*.

Design of Cyclical System Simulation Model

The basic concept of trading-off plant investment in generation with storage is already discussed. This controlled input system simulation model with a "cyclical" storage procedure is very similar to the simulation model with a daily storage procedure. Their computational processes parallel each other except for the logic of storing energy over time. The name "cyclical" is based on the approach of storing energy across the yearly cycle of the demand curve.

Before discussing the general computer program, next is the description of the method logic of storing energy. The necessity for cavern storage results from the step-by-step decrease in peak power generation capacity while the demand curve stays fixed; refer to Figure 15. For any given kilowatt point on the demand curve which is greater than this adjusted power generation peak capacity, the extra demand requirements require supply of energy from the storage block. Over the year at a level below maximum demand, the power generation peak "cuts off" a quantity of demand energy. This quantity is met by stored energy at the point of demand. Therefore, the maximum stored energy reflects the efficiencies of the storage block. The cyclical storage procedure meets the demand requirements by storing across the whole cycle of the year at a new minimum level of generation. Whenever actual demand is below the new minimum generation

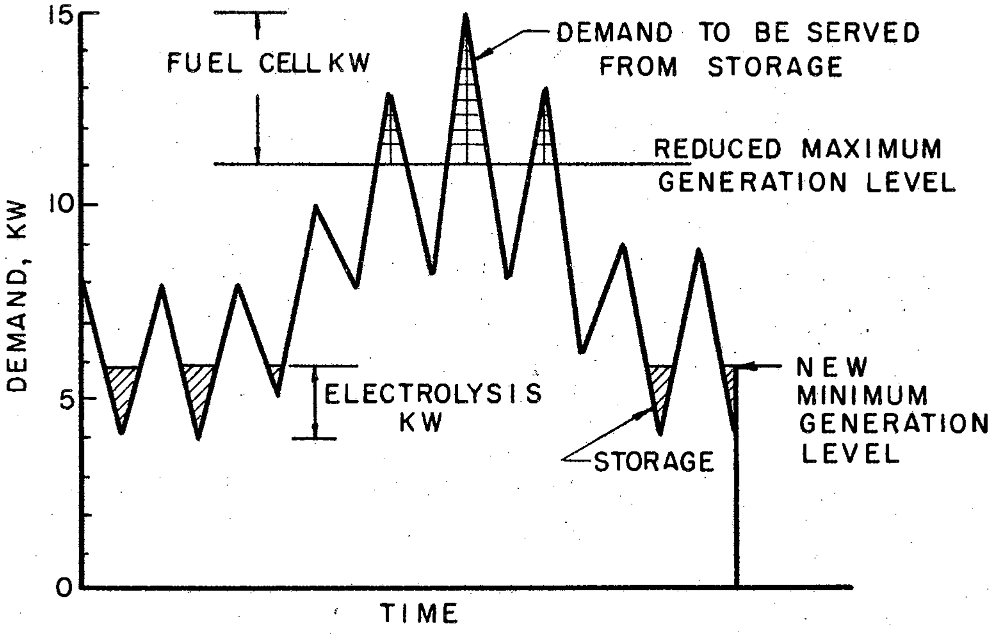


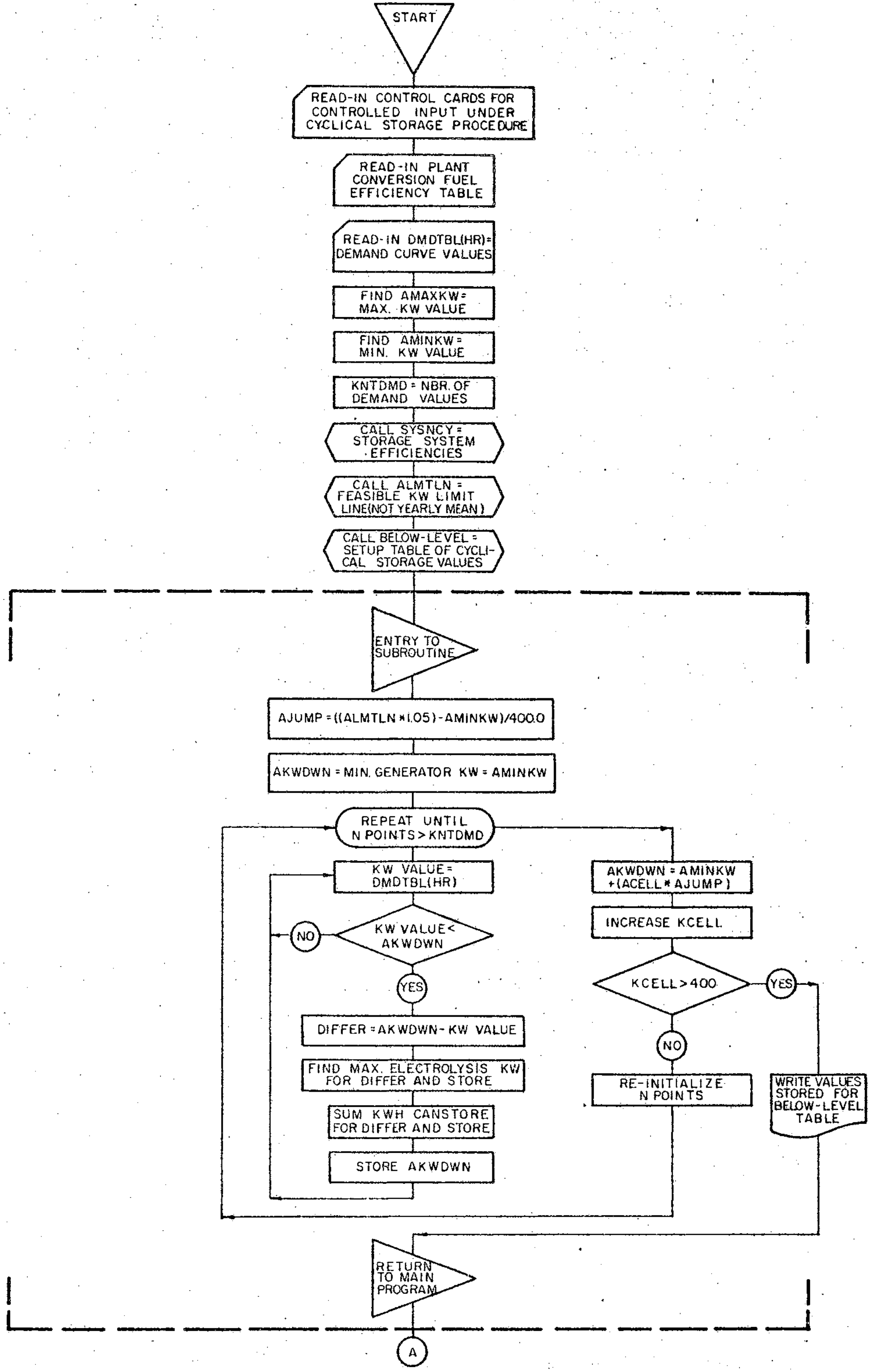
Figure 15. Portrayal of Cyclical Storage Procedure

level, energy is stored. When demand is above the new maximum generation level, then stored energy is released. If the optimum economic generation level is greater than the limit line, then the generation level runs at two uniform "plateau" levels, maximum and minimum generation. The generation level runs at the demand level only those times of the year when demand is between the two plateaux.

The ordinate kilowatt value difference between maximum demand and the new, maximum generation level specifies the "A3" kilowatt <u>output</u> requirement. The ordinate kilowatt value difference between the new minimum generation level and the demand curve minimum value specify the "B1" <u>input</u> requirement. The energy in storage which meets the cut-off peak energy requirements is the yearly sum of cut-off peak energy adjusted for storage block efficiencies.

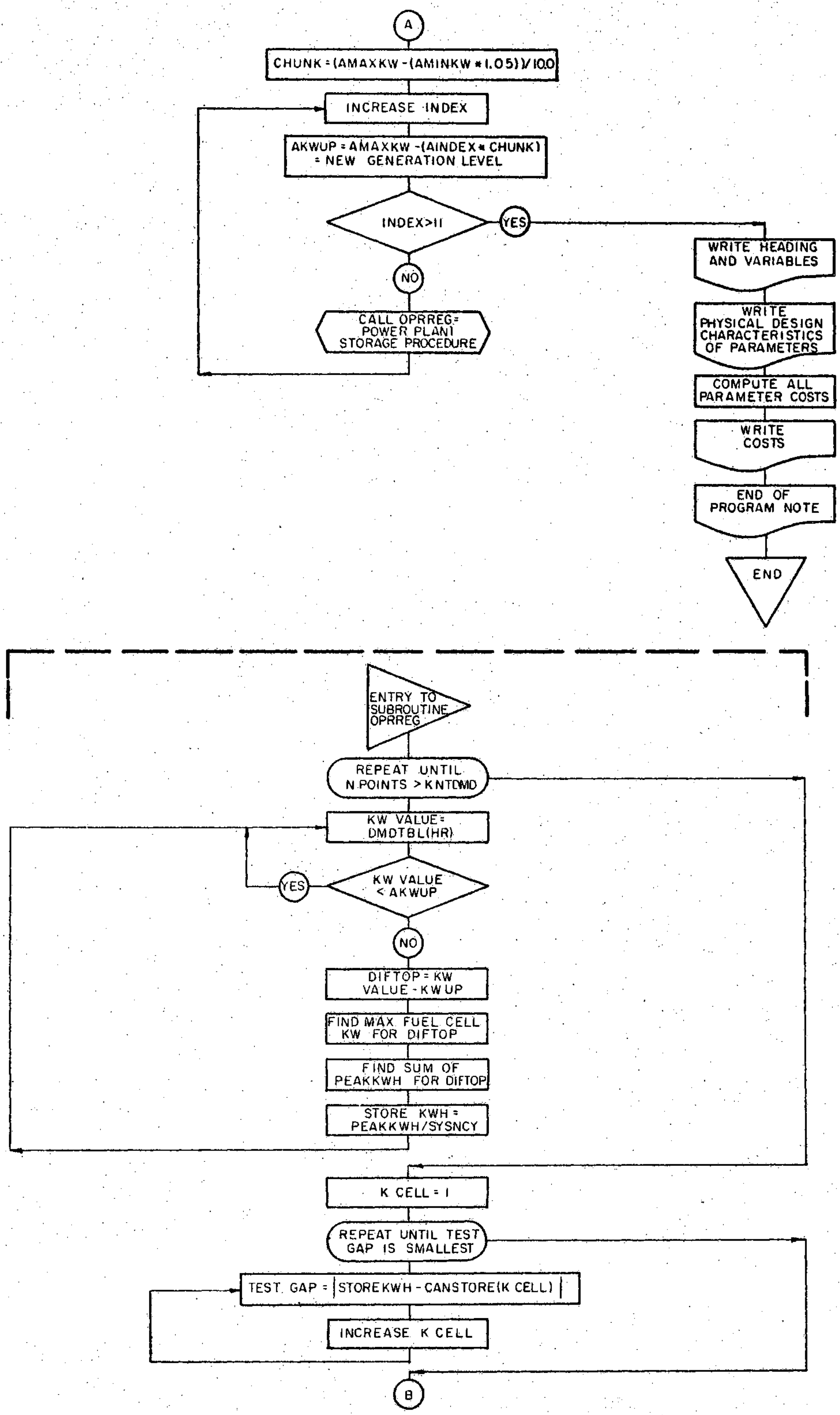
Based on this algorithm, the computer model first sets up an array, or table, of the energy that can be stored at a specific minimum generation level. Refer to Figure 16. This table is called "BLLVL", below level. In incremental steps of 0.04 per cent increase in minimum generation level kilowatts, this table is built up for the two major parameters of the amount of cavern storage and the worst case input component kilowatt value required (new minimum generation level minus minimum demand value).

The program then evaluates the amount of energy that is required across the full year by the cut-off demand peaks and the worst case output component kilowatt value. The



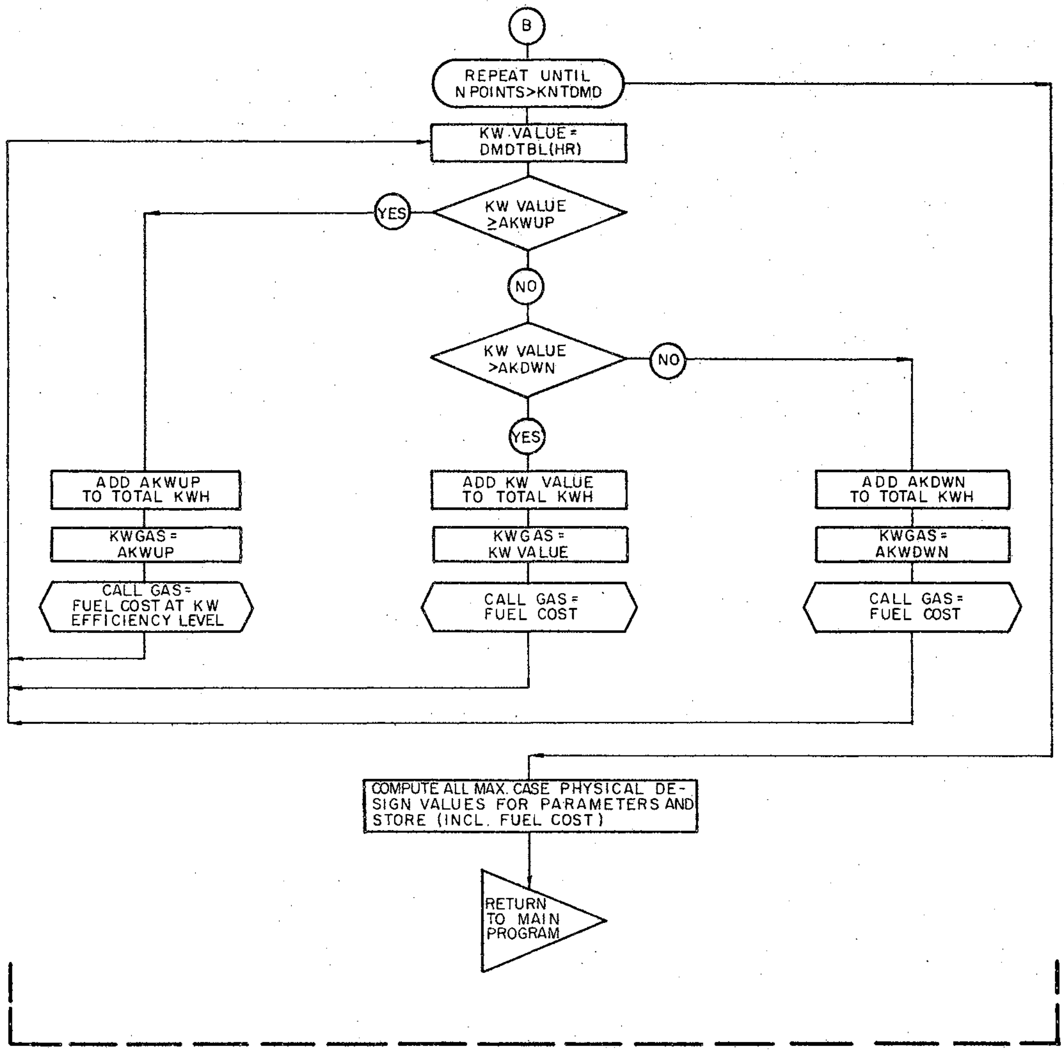
(a)

Figure 16. Macro-Logic Derivation of Simulation Model for Controlled Input Under a Cyclical Storage Procedure



(b)

Figure 16. (Continued)



(c)

Figure 16. (Concluded)

C

energy requirements are adjusted for storage block efficiencies and then merged with the below-level table's nearest energy storage value. At this point a full set of parameters is available for describing the energy storage components. After this new pattern of energy generation has been established with its two generation plateaux, the fuel cost is computed for this new pattern of generation. (Note: Depending on the desired precision by the research user, additional, small savings in fuel can be obtained by making a second computer run with the fuel efficiency curve adjusted to its maximum efficiency value at the system load percentage reflecting the new minimum generation level. This is based on the assumption that the design of a new plant would buy equipment to reflect this new minimum base load.) This procedure is repeated until the new, maximum generation level approaches the limit line.

Design of Daily System Simulation Model

The design of this controlled input system simulation model with a "daily" storage procedure is similar in structure to the simulation model with a cyclical storage procedure. The discussions about concept, storage efficiency, fuel conversion, and system costs are also relevant to this model.

The derivation of this model occurred later than the cyclical model. An evaluation of the cyclical storage system parameters indicated that an alternate storage system offered an advantageous cost picture depending upon which storage system components had greatest costs per unit of capacity.

The characteristic of this storage procedure is the storage block's frequent change between input and output of energy. In this sense, it is at the opposite end of the spectrum from cyclical storage. Between these two storage logics are possible a number of arbitrary storage approaches; it is likely that their nature represents some random or individualistic approach by a power plant. However, in terms of the research user these two systematic approaches offer determination of minimum costs for storage since one of the procedures offers the best conditions for the input-output storage component of significantly greater cost. In essence, these two storage logics "bracket" the capacity requirements for the input and output components.

The name "daily" implies a storage approach of storing energy intermittently between "daily" surges in demand. "Daily" is approximate terminology since it will be concerned with longer storage periods as the new, maximum generation levels are reduced.

The storage logic is described before discussing the computer program. Reference to Figure 17 clarifies this description. In a manner similar to cyclical storage, the maximum generation level is reduced stepwise while the demand curve stays fixed. Accordingly, for periods where demand is greater than generation the balance of energy is

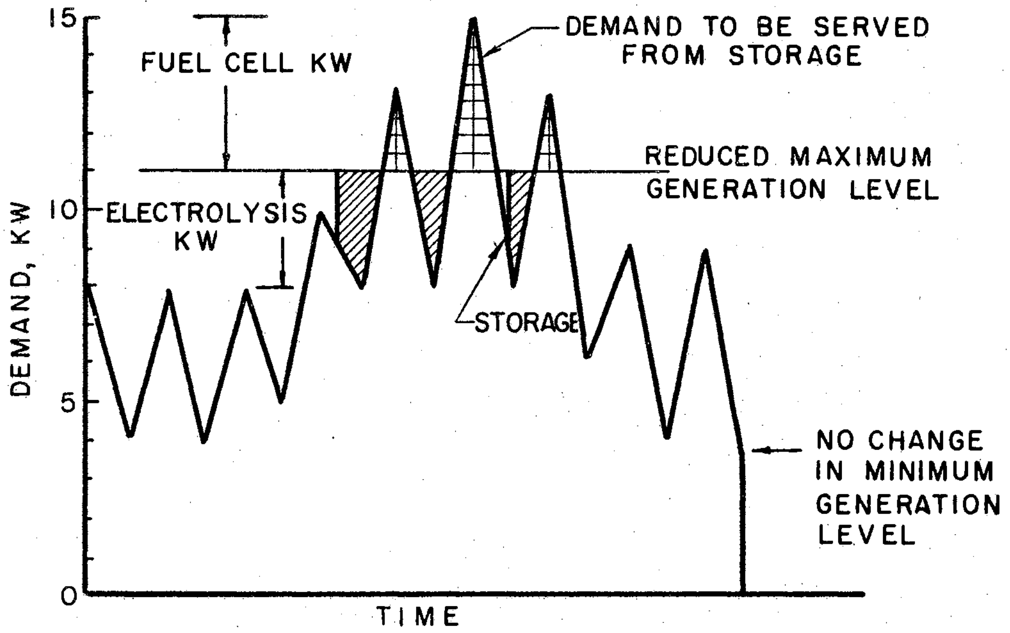


Figure 17. Portrayal of Daily Storage Procedure

supplied from storage. The computational process is started at the end of the year and is processed to the beginning of the year so that only the necessary amount of stored energy is determined. Energy is stored, whenever the demand level drops below the new, minimum generation level.

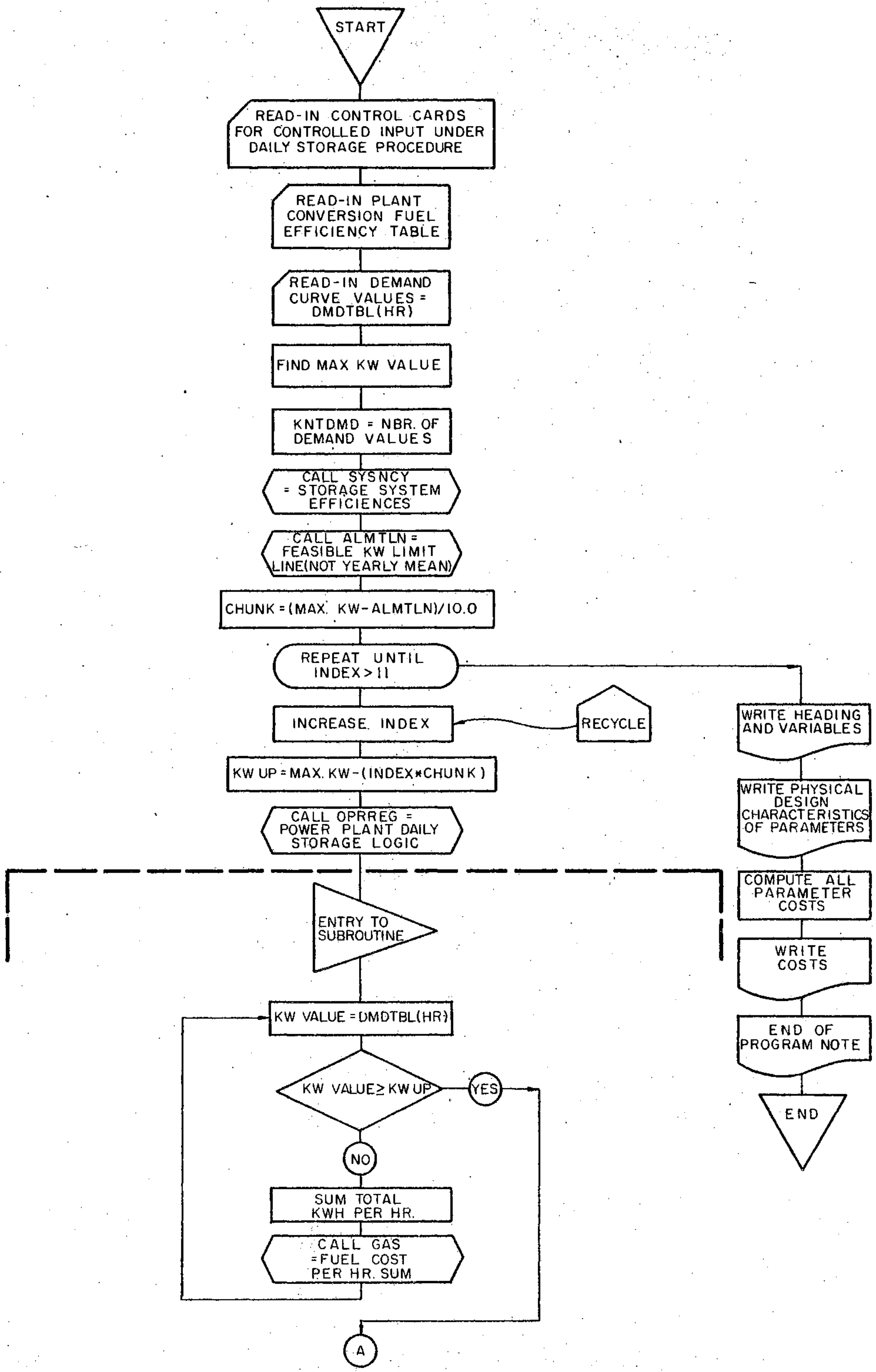
A peak of demand energy is "cut-off", by this leftward movement across the demand curve at the adjusted generation level. This amount of energy is adjusted for storage block efficiency and then is stored in the time period below the generation level which immediately precedes the requirement for stored energy. If the amount of energy is fully stored (i.e. adequate energy placed into storage) in this period preceding the use of energy, then the requirements for storage are satisfied and the corresponding cavern storage requirements are determined. However, if the energy storage availability is not adequate, the balance is carried over and is added to the next cutoff peak's requirement for storage. Thus, energy is stored and used in an intermittent and repetitive manner between "daily" cutoff peaks. The total cavern storage requirements are then equal to just the worst "daily" case plus any carried-over residuals. Different from the cyclical storage procedure, the minimum plant generation level is not changed by this storage procedure. The base load stays the same. However, peak loading at the maximum generation level is increased. The peak loading plateau is broadened, with interruptions, more than the cyclical procedure. The effects on capacity requirements of storage components between these two procedures are analyzed in Chapter VI.

The ordinate kilowatt value difference between the maximum demand and the new generation level specifies the "A3" kilowatt <u>output</u> requirements in Figure 4. However, the worst capacity case for "B1" <u>input</u> requirements is determined as the maximum difference between the new generation level and the top of the demand curve during those periods when energy is stored.

Based on this algorithm of storage, the computer model decrements the maximum demand value and establishes a new, maximum generation level; refer to Figure 18. By starting at the end of the year and moving towards the start of the year, basic energy requirements and fuel costs are under calculation until a demand value occurs which is greater than the maximum generation level.

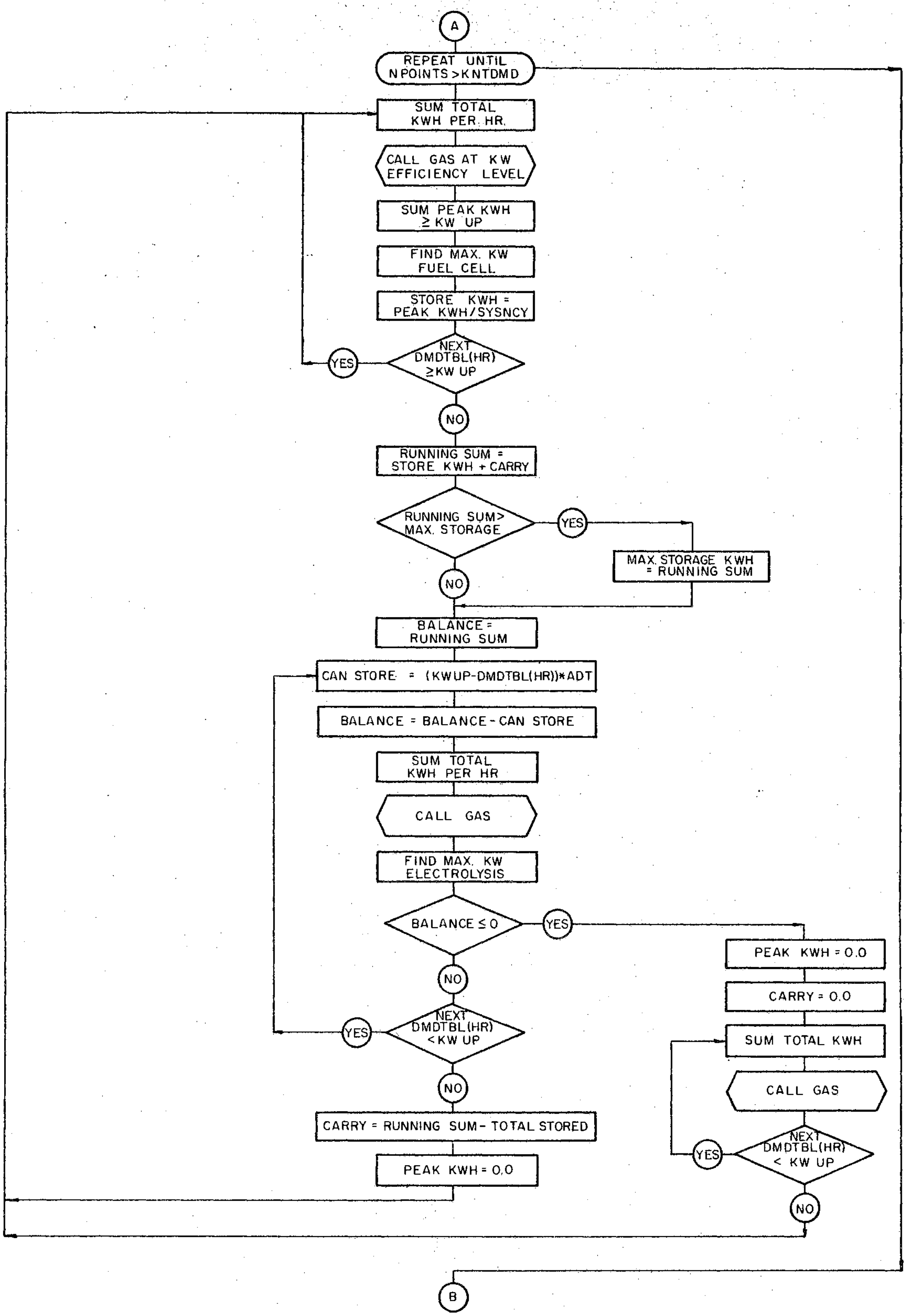
For all sequential points above this value the amount of energy peak is determined until a demand value is reached below the maximum generation level. This temporary sum is then adjusted by the storage block efficiency in order to determine the required amount of energy for storage. Then for all sequential demand points below the maximum generation level per time-unit interval, the amount-to-be-stored is reduced by that area available for storage.

This reduction continues until either there is no need left for "daily" storage or until a demand value above the maximum generation level occurs. The former condition is



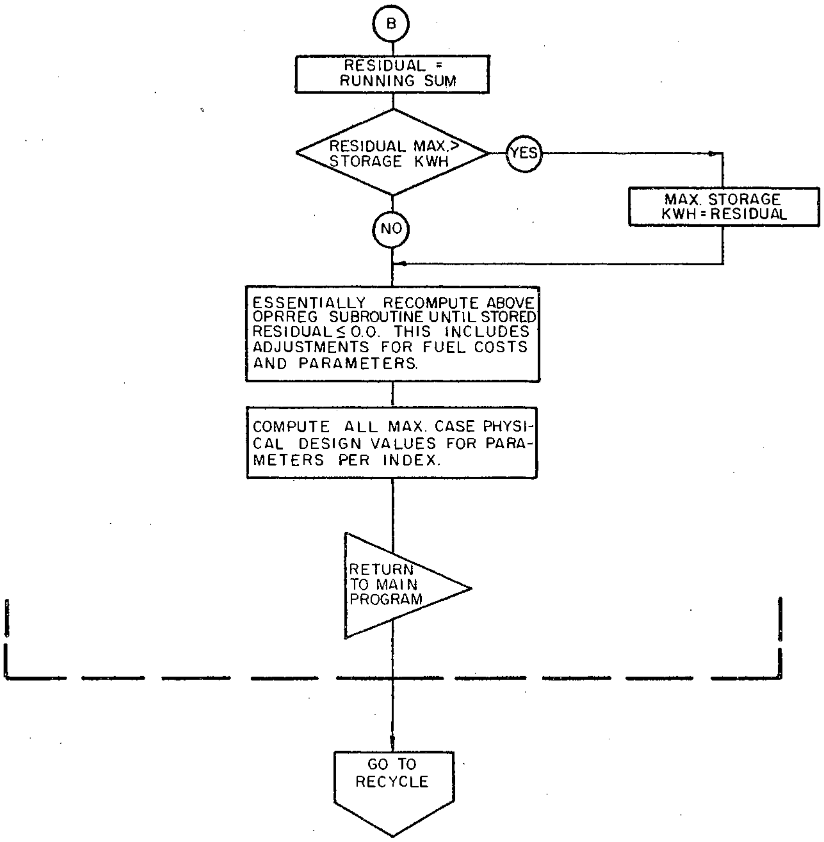
(a)

Figure 18. Macro-Logic Derivation of Simulation Model for Controlled Input Under a Daily Storage Procedure



(b)

Figure 18. (Continued)



(c)

Figure 18. (Concluded)

the amount of cavern storage for comparison to similar values for the worst case requirements. The latter condition requires carrying the unstored balance and adding it to the next adjusted peak amount-to-be stored. Ultimately, the last peak is cutoff for this particular decrement level of maximum generation. The worst case of this series of "daily" storages specifies the maximum cavern storage requirements. If, however, the amount of energy for storage is yet out of balance, then the residual carries for a reiteration of the storage procedure beginning at the end of the year. It continues to that time where the residual is zero with adjustments for the affected fuel cost time intervals. At this point the worst case establishes the parameter values, and the program proceeds again to the step for maximum generation level decrementation down to the feasible test limit.

Design of Uncontrolled Input System Simulation Model

The computational logic and nature of this model is considerably different than the prior two simulation models. The purpose is different. This model is for examination of energy source conditions different than the energy sources of present day conventional generation. However, its usefulness in research studies is not solely exclusive to problems of developing nations such as using random sources of energy like wind, or sun. This model is usable, somewhat artificially, for an examination of an *a priori* decision of conventional generation loading pattern which then makes generation independent of demand.

Even so, the basic principle of reducing generation requirements for peak load and replacing that supply of energy by stored energy is applicable to this model. The difference here is that storage is a necessity. No demand curve is capable of supply by only an uncontrolled source of energy; storage is necessary if the two time functions are to be made feasibly compatible for satisfaction of demand.

The problem then becomes one not of finding the most economic trade-off point between conversion and storage as in the former simulation models for conventional plants. The problem is the determination of how much storage is <u>necessary</u> for the successful supply of a demand curve. This is a criterion for the design of this model. Nevertheless, after evaluations of experimental studies, the induction is that possibilities of economic trade-off optimization exist.

This trade-off situation does not invalidate the criterion; it is still necessary to determine a sufficient system. However, an economic trade-off optimization exists <u>after</u> a sufficient condition of storage capacity is determined. An example serves for clarification of this point. Consider a basic energy system with storage like some region using wind generation. Storage is necessary for the satisfaction of the specified demand curve. However, by doubling their number of wind generators, this region probably reduces, depending on individual costs, the amount of storage sub-system costs. This reduction might cause a lesser total annual cost for satisfaction of the same demand curve.

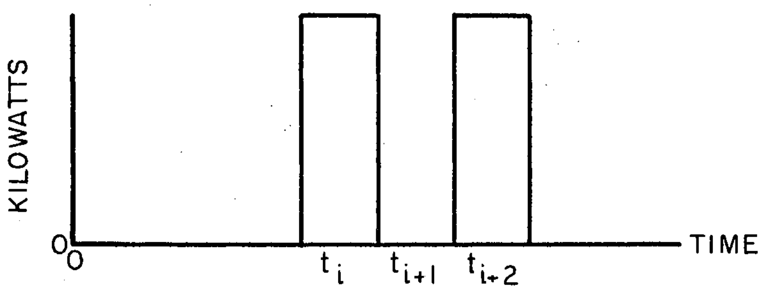
The premise of design is the most economic combination of equipment which meets the specified demand curve. This premise is emphasized as a basic assumption because if in the above case an over-capacity number of generators were the most economical, a surplus amount of energy would result. According to the premise it is "thrown away", whereas in reality a non-planned use might develop; this is random power. The specified demand curve stays unchanged because otherwise the original system for satisfaction is re-defined.

The general references to the computation of storage block efficiencies are still applicable to this model. There is no fuel cost. No fuel cost is the basic argument for a system like this in a developing nation context or general savings context. There is, however, a function for the efficiency of the generation equipment in conversion of the energy source to output energy. Costs of the whole system are computed similarly to the other models. However, the research user probably has not too firm costs for any part of the trade-off model for good evaluations of the limiting conditions. Additionally, when this model is concerned with studying a special situation in conventional generation equipment, the addition of fuel cost is necessary. The computer output specifies the total energy required; efficiency adjustments for fuel in this special situation are according to the percentage of system load levels of the user's pre-defined generation pattern.

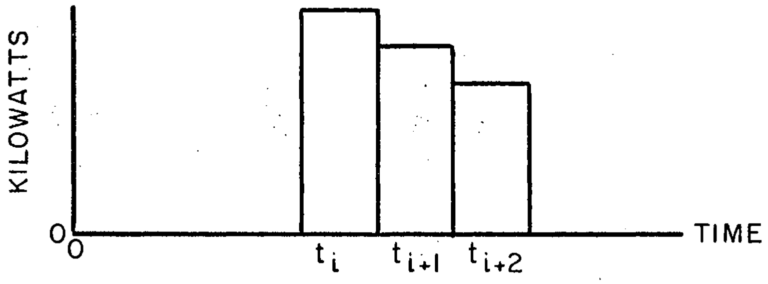
Most of the data required for a conventional system is also required by this model. There is one major additional input of the same magnitude as the demand curve; in the same chronology an identical number of time-unit values is necessary. This additional input is the "theoretical power density curve" for the unconventional energy source. The scale of these values is defined in terms of kilowatts per square foot across a time of one year of the random source potential energy. The computational procedure requires a small generation value as a denominator. This scale of power density is a practicable choice. An unconventional power source likely includes many single units in parallel (e.g. solar cells) whose total becomes an effective magnitude of energy. The conversion efficiency of one unit is the same for the aggregate without regard to scale. The conversion efficiency function develops the actual output, or "transformed power density curve". Since the demand and power density curves are independent, the purpose of this power density function is the definition of the "gap" between the two curves where storage is necessary for some duration.

This energy gap is the foundation for the computational approach in the uncontrolled model (see Figure 5). The next discussion shows that the storage logic is similar to the daily storage procedure and that any cyclical method of storage is always more costly.

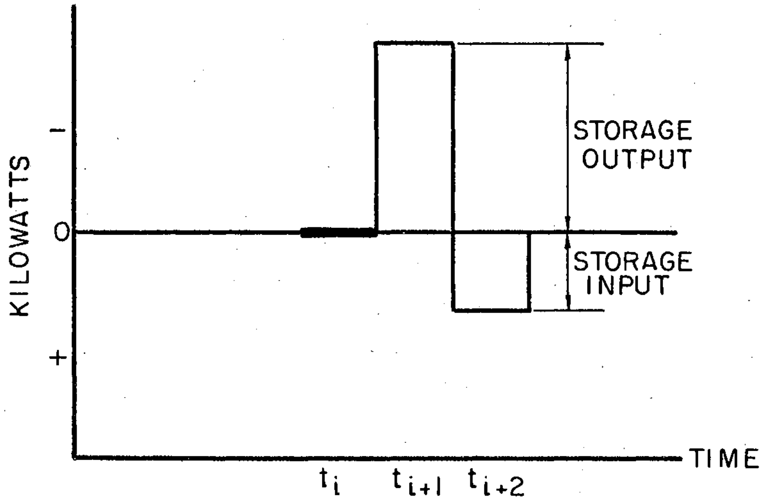
The storage algorithm is included in the following discussion of the computer model. Reference to Figure 19 clarifies the computation of this storage procedure. From the theoretical power density curve the program develops the transformed power density curve according to the conversion efficiency function; refer to Figure 20. The effective power is totalled over the year for the square foot power source. This is divided into the amount of demand curve energy as a starting point for determination of the requirements for an adequate generation with storage system. At this point two computer arrays, demand and transformed power density, are available and are nearly equal in magnitude. (Power density is forced to be less so that a first point interpolation case is established.) The demand array (i.e. computer table of chronological demand values) is subtracted from the power density array to form a third array, deficit-surplus array. The chronological sequence of values is identical for all three arrays. In this computation parameter values are obtained for the storage input and output components. Figure 19 portrays these storage logic relationships. A deficit (-) implies the requirement for stored energy; a surplus (+) implies the input of energy to the storage system. A zero value indicates that the energy source output equals the demand need at the particular unit-time period. The deficit values are absolutely summed and adjusted for storage block efficiencies; the



POWER DENSITY CURVE (MULTIPLIED)
(a)

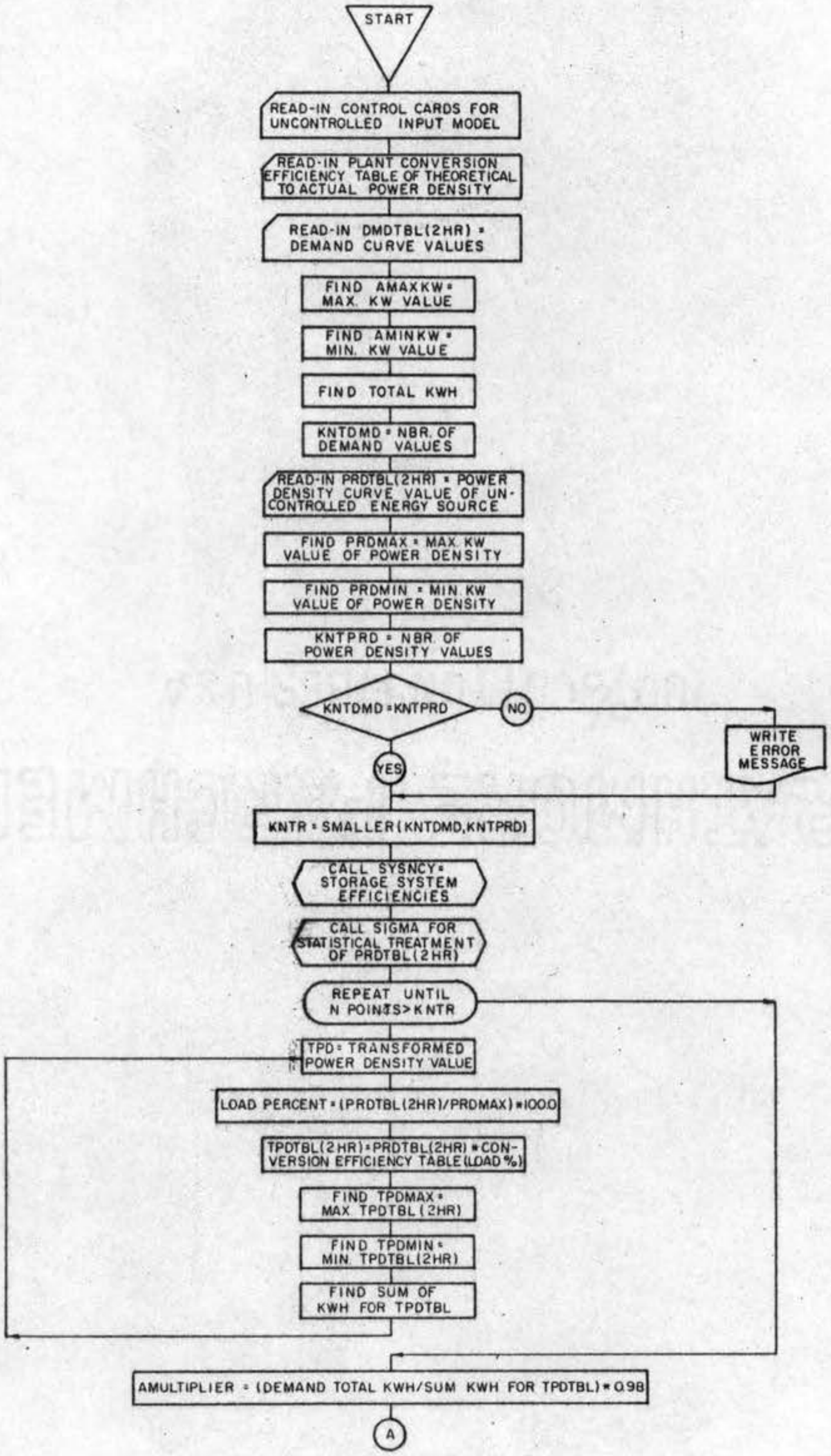


DEMAND CURVE
(b)



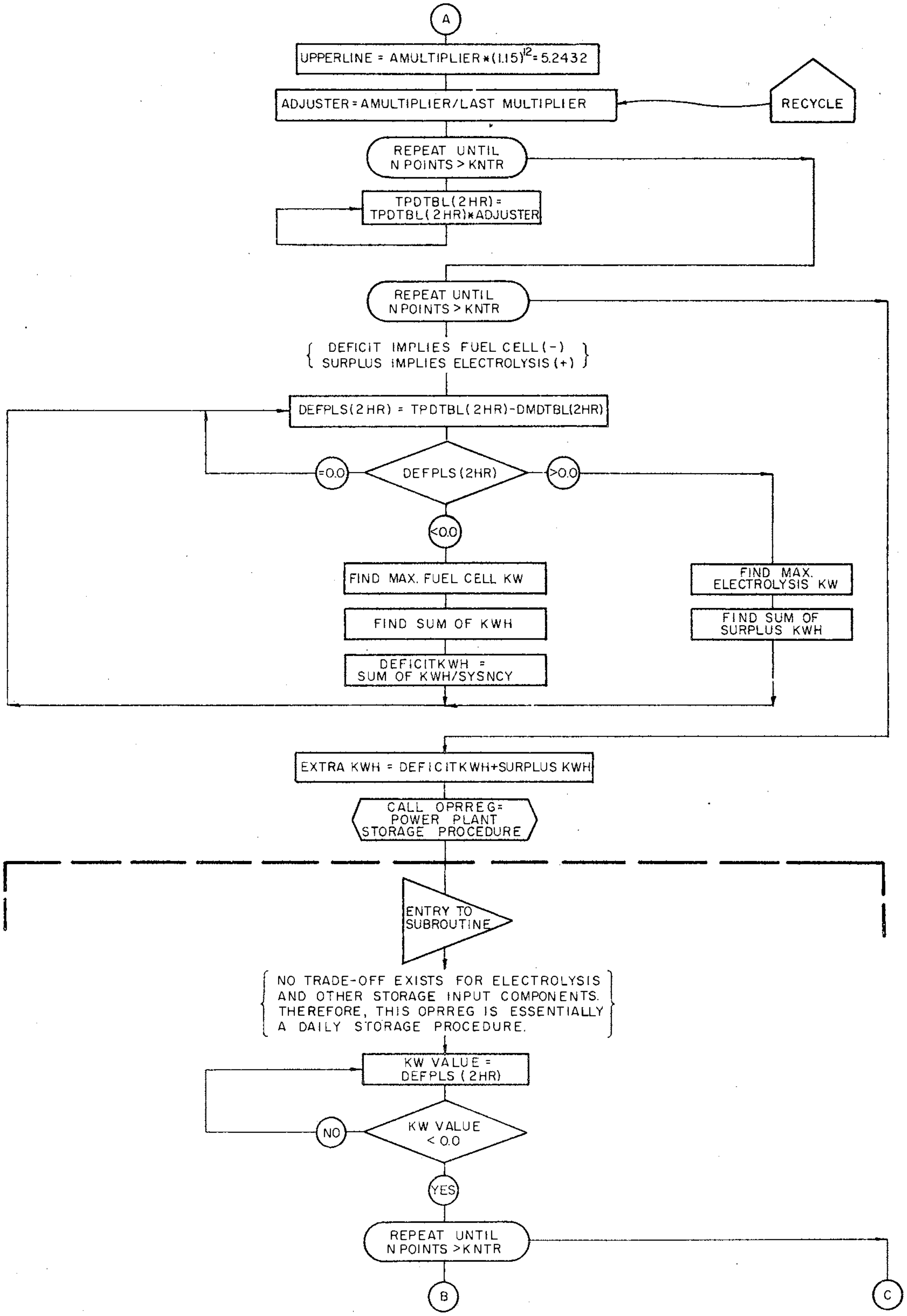
DEFICIT-SURPLUS ARRAY
(c)

Figure 19. Portrayal of Storage Algorithm in Uncontrolled Input Model



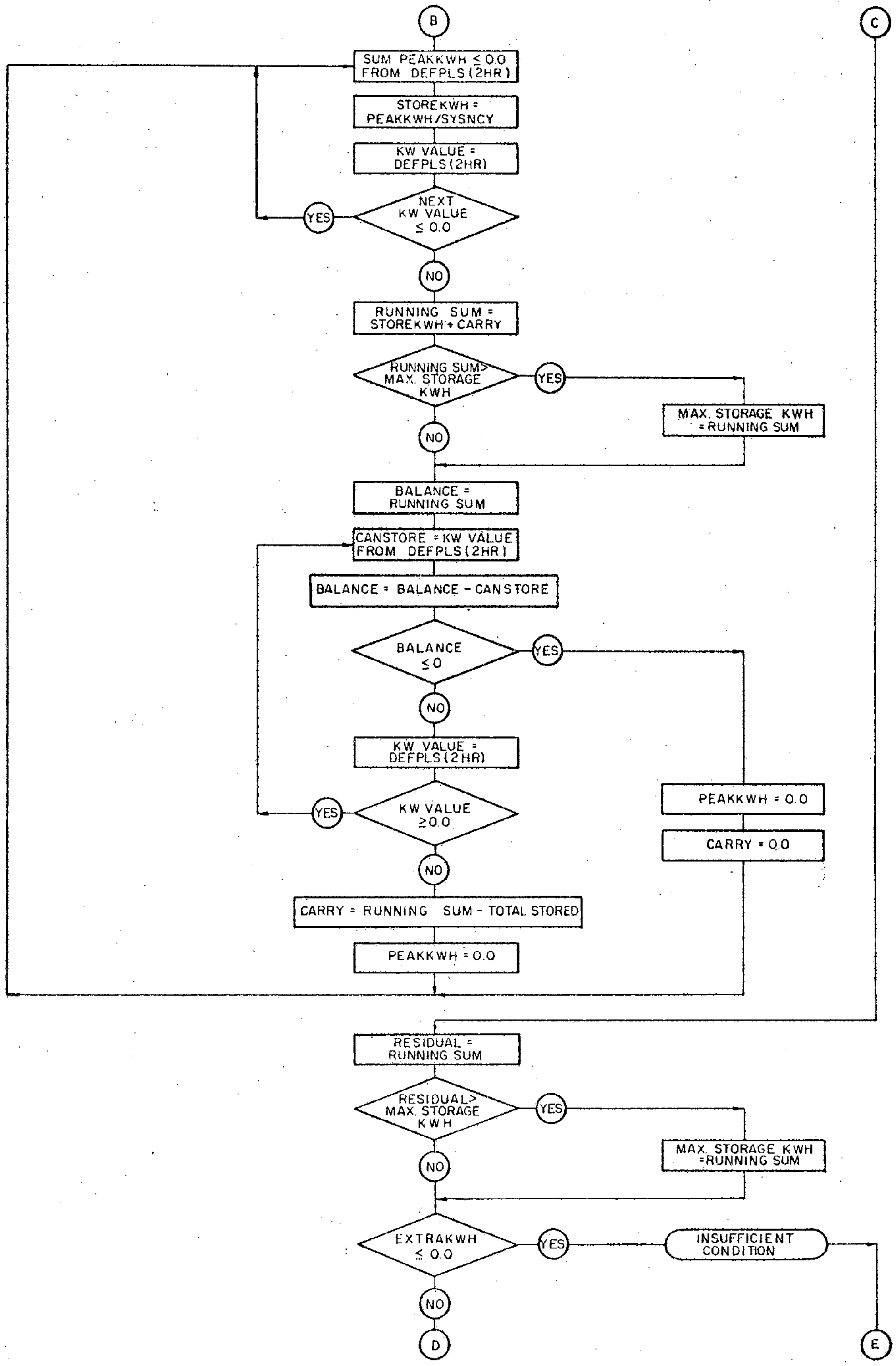
(a)

Figure 20. Macro-Logic Derivation of Simulation Model for Uncontrolled Input



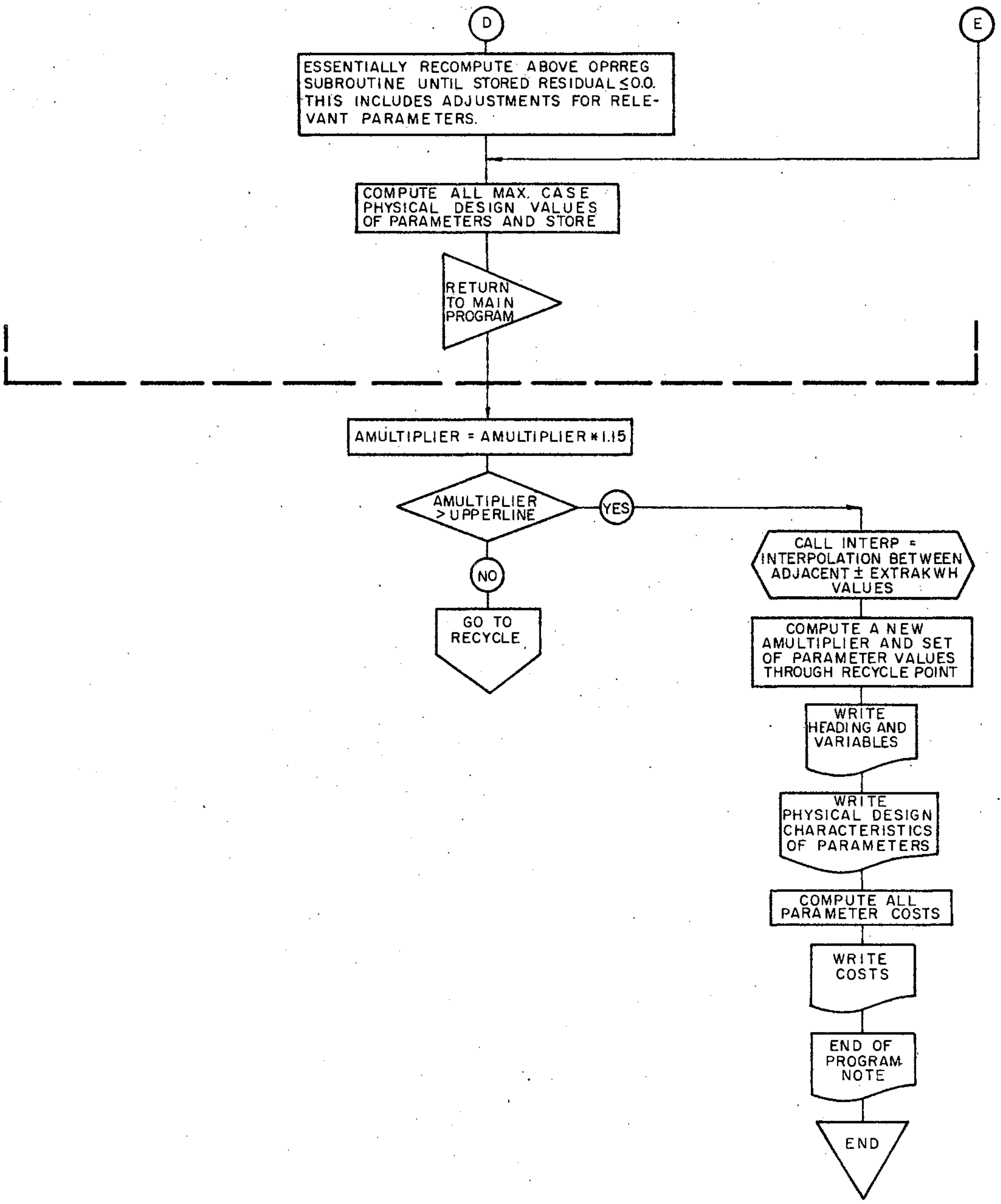
(b)

Figure 20. (Continued)



(c)

Figure 20. (Continued)



(d)

Figure 20. (Concluded)

114

surplus values are summed. The algebraic total of these two sums equals the energy system surplus. Whenever this energy surplus sum passes into the positive value range a feasible energy system exists. The program now determines the cavern storage requirements by a computational method similar to that of the daily storage procedure for the controlled input model. Refer to Figure 19; the computation process utilizes the deficit-surplus array for this evaluation. The input component capacities are already defined by this deficit-surplus array under the criterion of storing enough energy to satisfy the demand curve. Accordingly, there is no alternative to the capacity requirements for the input components. Hence, if a cyclical storage procedure were applied, there would exist no trade-off between capacity requirements for input components and cavern storage (where output components are fixed as a controlled variable). Costs of the whole storage block are always lower for a daily storage procedure in an uncontrolled input model.

After making adjustments for energy residuals, a new multiplier factor is computed. This factor is used to increase the "size" of the transformed power density curve for another series of deficit-surplus array and storage component calculations. This recycling is continued until the available energy from the transformed power density is approximately five times the requirements of the demand curve. The program then transfers to an interpolation section where a new multiplier factor is linearly computed between adjacent plus-and-minus energy system surplus values. A complete iteration cycle is performed with this multiplier factor for determination of the storage component specifications at the point where the system is a just-satisfied feasible system.

The multiplier factor adjusts the transformed power density curve. This generated power output still must exceed the demand energy to compensate for storage block efficiencies. Hence, if the storage efficiencies are too low the system is not satisfied within the above limits, and it is very unlikely that such a system is ever economically feasible. An error message is written for the case where a system is not satisfied even at five times the energy required by the demand curve.

It is this multiplied-buildup of the power density array which enables the study of over-satisfied systems, i.e. a system generating more kilowatt-hours than required for physical feasibility. For the same reason as above, the economic feasibility of a system, this enlargement of the power density array is limited to a multiple of five. The most economic system may be greater than the just-satisfied demand system. If so, there is extra energy generated. Though of possible utility, this extra energy is considered outside of the utilization of the demand system. Moreover, its availability is very erratic. Under a special case, an over-satisfied system can require no storage sub-system; this is called a super-satisfied energy system.

Remarks on System Development

The derivations of the three system simulation models are developed in Chapter V. The overall position of these models in energy storage study applications is clarified by the operational system design in Chapter III.

With reference to Chapter II, the derivations of these models are evaluated as wholly within the constraints of the relevant design criteria. Moreover, the accomplishment of the simulation objectives is indicated by the capabilities of these simulation models (within the operational system). The use of these models is demonstrated in the computer output interpretations of the next chapter.

CHAPTER VI

INTERPRETATION OF THE COMPUTER MODELS

This chapter describes in detail the interpretation of the computer outputs for the system simulation models of Chapter V. Following each of the descriptions about interpretation, a section discusses the application of these simulation results to the design of such power plant systems.

Only the basic computer mnemonics are defined for the output pages. These definitions are the ones necessary to the engineer for his practical use in system studies and design applications. Figures 21 and 22 present an overall view of the mnemonics for the research user's reference.

Figure 21 schematically represents the basic mnemonics appropriate to the controlled input model under a cyclical storage procedure. The same portrayal is suitable for the daily storage model except that there is no "DWNKW". The portrayal is useful for the uncontrolled input model only in a sense of analogous relationships. Figure 22 cross-identifies the mnemonics associated with the individual components of the storage block. This identification is suitable for all three system simulation models. "DMINMX" is the effective kilowatts utilized by the demand curve; it is equal to the output from the "A3" component. Reference

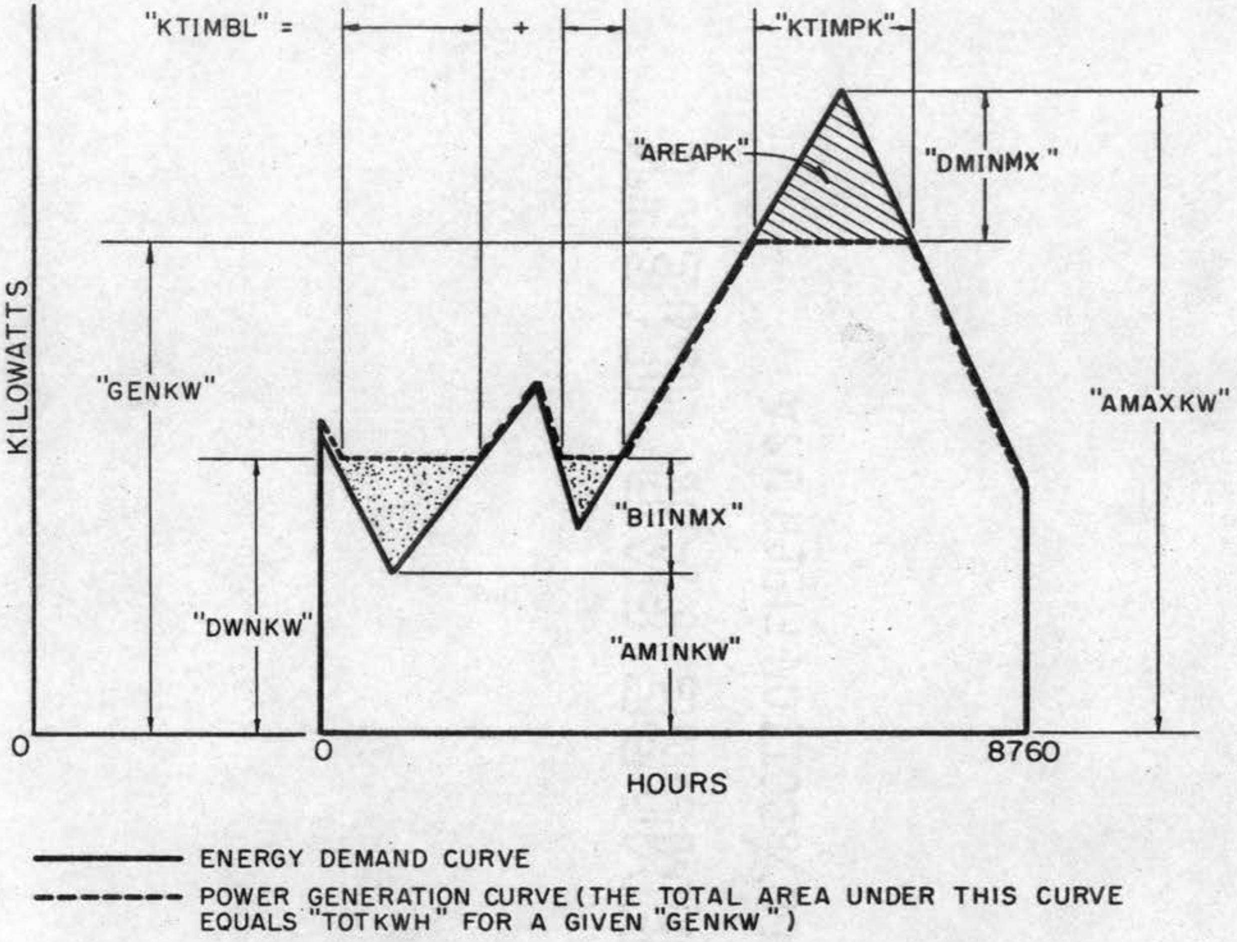
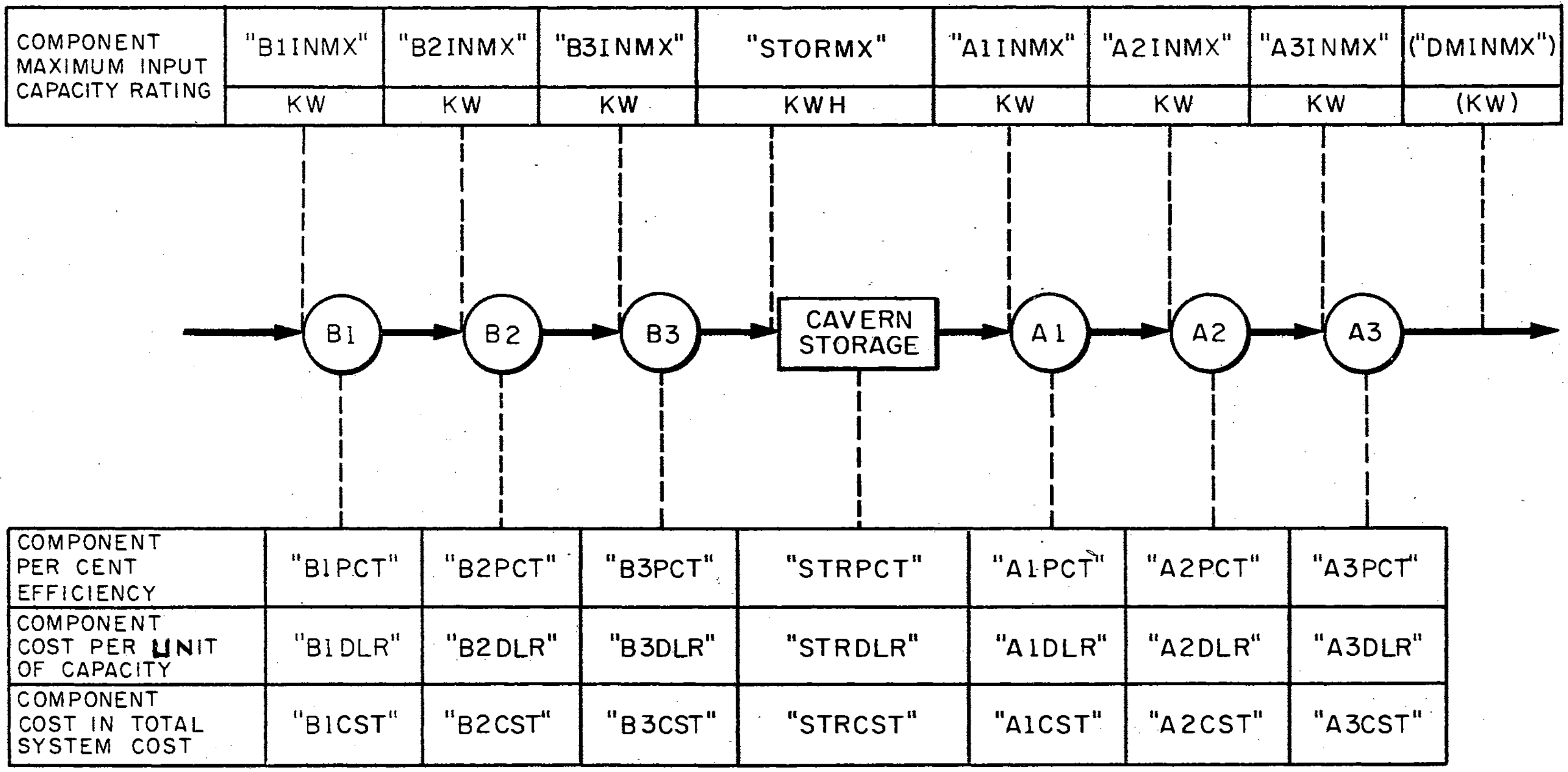


Figure 21. Representation of Computer Output Mnemonics of Controlled Input Generation Model Under a Cyclical Storage Procedure for a Hypothetical Demand Curve



COMPONENT MAXIMUM INPUT CAPACITY RATING	"B1INMX"	"B2INMX"	"B3INMX"	"STORMX"	"A1INMX"	"A2INMX"	"A3INMX"	("DMINMX")
	KW	KW	KW	KWH	KW	KW	KW	(KW)

COMPONENT PER CENT EFFICIENCY	"B1PCT"	"B2PCT"	"B3PCT"	"STRPCT"	"A1PCT"	"A2PCT"	"A3PCT"
COMPONENT COST PER UNIT OF CAPACITY	"B1DLR"	"B2DLR"	"B3DLR"	"STRDLR"	"A1DLR"	"A2DLR"	"A3DLR"
COMPONENT COST IN TOTAL SYSTEM COST	"B1CST"	"B2CST"	"B3CST"	"STRCST"	"A1CST"	"A2CST"	"A3CST"

Figure 22. Identification of Computer Output Mnemonics for Storage Block

to Figures 4 and 5 show the relative block positions within the simulation logic models.

Interpretation of Computer Output for Cyclical Storage Model

This section describes the computer output for the controlled input system simulation model under a cyclical storage procedure. Figure 23a both pictorializes the basic energy storage model and lists the input parameters of storage component efficiencies. Figure 23b lists the storage component kilowatt specifications for various levels of new maximum generation. "GENKW" is the required power plant <u>output</u> capacity; the first row is for the case of <u>no</u> energy storage. The input components, "B1INMX", etc., are the worst case kilowatt requirements for the particular generation level. The values listed specify <u>input</u> capacity. "STORMX" specifies the maximum kilowatt-hour size of cavern storage; the negative sign is used <u>only</u> to highlight storage. The output components, "A1INMX", etc., are the worst case component requirements for each generation level. The values listed specify <u>input</u> capacity. "DMINMX" is the maximum kilowatt requirement for a unit of time by the demand curve; it is equal to the output from "A3". Figure 23c lists other relevant values for each generation level. "GSDLLR" is the fuel cost in dollars. "TOTKWH" is the total yearly kilowatt-hours generated; only the value for generation with no storage is the kilowatt-hours required by demand. "AREAPK" is the kilowatt-hour requirements of

```
              ENGINEER... ARTHUR BRUCKNER,II     SCHOOL OF INDUSTRIAL ENGINEERING, OKLAHOMA STATE UNIVERSITY, 1966.

              THIS OUTPUT IS EXCLUSIVELY FOR AN OPERATING REGIME OF FILL-FROM-BOTTOM LOGIC STRUCTURE.
   (TOP) IS DAILY STORAGE PROCEDURE ** (BOTTOM) IS CYCLICAL STORAGE PROCEDURE.
              STORAGE IS EVALUATED ON A YEARLY DEMAND BASIS.


                       --------------------------------------------
                       /                                          /
              ************              *********              ********
LOGIC MODEL...*CONVERSION*--B1--B2--B3--*STORAGE*--A1--A2--A3--*DEMAND*
              ************              *********              ********

OUTPUT MEASUREMENT UNITS...       KW   KW   KW     KWH     KW   KW   KW

COMPONENT EFFICIENCIES...
                B1PCT =    0.9500
                B2PCT =    1.0000
                B3PCT =    1.0000
                STRPCT=    0.9900
                A1PCT =    0.6000
                A2PCT =    1.0000
                A3PCT =    1.0000
```

(a)

Figure 23. Computer Output of Simulation Model for Controlled Input Under a Cyclical Storage Procedure

```
GENKW        B1INMX       B2INMX       B3INMX       STORMX        A1INMX       A2INMX       A3INMX       DMINMX
*****        ******       ******       ******       ******        ******       ******       ******       ******

0.1372E 07   0.           0.           0.           0.            0.           0.           0.           0.
0.1309E 07   0.6595E 05   0.6266E 05   0.6266E 05   -0.7649E 06   0.1057E 06   0.6341E 05   0.6341E 05   0.6341E 05
0.1245E 07   0.9025E 05   0.8574E 05   0.8574E 05   -0.6291E 07   0.2114E 06   0.1268E 06   0.1268E 06   0.1268E 06
0.1182E 07   0.1157E 06   0.1099E 06   0.1099E 06   -0.2330E 08   0.3170E 06   0.1902E 06   0.1902E 06   0.1902E 06
0.1118E 07   0.1423E 06   0.1352E 06   0.1352E 06   -0.5642E 08   0.4227E 06   0.2536E 06   0.2536E 06   0.2536E 06
0.1055E 07   0.1724E 06   0.1638E 06   0.1638E 06   -0.1071E 09   0.5284E 06   0.3170E 06   0.3170E 06   0.3170E 06
0.9916E 06   0.2048E 06   0.1946E 06   0.1946E 06   -0.1762E 09   0.6341E 06   0.3804E 06   0.3804E 06   0.3804E 06
0.9282E 06   0.2384E 06   0.2264E 06   0.2264E 06   -0.2649E 09   0.7397E 06   0.4438E 06   0.4438E 06   0.4438E 06
0.8648E 06   0.2765E 06   0.2627E 06   0.2627E 06   -0.3780E 09   0.8454E 06   0.5072E 06   0.5072E 06   0.5072E 06
0.8013E 06   0.3159E 06   0.3001E 06   0.3001E 06   -0.5183E 09   0.9511E 06   0.5707E 06   0.5707E 06   0.5707E 06
0.7379E 06   0.3599E 06   0.3419E 06   0.3419E 06   -0.7069E 09   0.1057E 07   0.6341E 06   0.6341E 06   0.6341E 06
```

(b)

Figure 23. (Continued)

```
GENKW         GSDLLR        TOTKWH        AREAPK        KTIMPK    KTIMBL        DWNKW
*****         ******        ******        ******        ******    ******        ******
----------------------------------------------------------------------------------------

----------------------------------------------------------------------------------------
0.1372E 07    0.1153E 08    0.5759E 10    0.                 0         0    0.3120E 06
----------------------------------------------------------------------------------------
0.1309E 07    0.1153E 08    0.5760E 10    0.4543E 06        23        87    0.3780E 06
----------------------------------------------------------------------------------------
0.1245E 07    0.1153E 08    0.5762E 10    0.3737E 07        95       415    0.4023E 06
----------------------------------------------------------------------------------------
0.1182E 07    0.1154E 08    0.5770E 10    0.1384E 08       231      1006    0.4277E 06
----------------------------------------------------------------------------------------
0.1118E 07    0.1155E 08    0.5785E 10    0.3351E 08       394      1554    0.4543E 06
----------------------------------------------------------------------------------------
0.1055E 07    0.1160E 08    0.5808E 10    0.6360E 08       563      2003    0.4844E 06
----------------------------------------------------------------------------------------
0.9916E 06    0.1165E 08    0.5840E 10    0.1047E 09       740      2502    0.5168E 06
----------------------------------------------------------------------------------------
0.9282E 06    0.1170E 08    0.5879E 10    0.1573E 09       928      2952    0.5504E 06
----------------------------------------------------------------------------------------
0.8648E 06    0.1178E 08    0.5935E 10    0.2245E 09      1176      3483    0.5885E 06
----------------------------------------------------------------------------------------
0.8013E 06    0.1189E 08    0.5998E 10    0.3078E 09      1470      4018    0.6279E 06
----------------------------------------------------------------------------------------
0.7379E 06    0.1210E 08    0.6082E 10    0.4199E 09      2214      4934    0.6719E 06
----------------------------------------------------------------------------------------
```

(c)

Figure 23. (Continued)

```
          CONSTANTS  =====
ADT =  1.0000
AMAXKW = 0.1372E 07
AMINKW = 0.3120E 06
KNTDMD =  8760
KHRTIM =  8760
DLRKWH = 0.6826172E-03
QIMLIN = 0.7046E 06
TSTLIM = 0.7379E 06
SYSFAC =      0.56429999
STINFC =      0.95000000
JDEX =  11
KNTPSS =      0
KCELL= 401
```

(d)

Figure 23. (Continued)

```
GENKW        B1CST        B2CST        B3CST        STRCST       A1CST        A2CST        A3CST        GENCST
*****        $$$$$        $$$$$        $$$$$        $$$$$$       $$$$$        $$$$$        $$$$$        $$$$$$

0.1372E 07   0.           0.           0.           -0.          0.           0.           0.            0.9801E 07

0.1309E 07   0.6595E 05   0.           0.            0.9569E 04  0.1057E 06   0.           0.            0.9348E 07

0.1245E 07   0.9025E 05   0.           0.            0.7871E 05  0.2114E 06   0.           0.            0.8895E 07

0.1182E 07   0.1157E 06   0.           0.            0.2914E 06  0.3170E 06   0.           0.            0.8442E 07

0.1118E 07   0.1423E 06   0.           0.            0.7058E 06  0.4227E 06   0.           0.            0.7989E 07

0.1055E 07   0.1724E 06   0.           0.            0.1339E 07  0.5284E 06   0.           0.            0.7536E 07

0.9916E 06   0.2048E 06   0.           0.            0.2204E 07  0.6341E 06   0.           0.            0.7083E 07

0.9282E 06   0.2384E 06   0.           0.            0.3314E 07  0.7397E 06   0.           0.            0.6630E 07

0.8648E 06   0.2765E 06   0.           0.            0.4729E 07  0.8454E 06   0.           0.            0.6177E 07

0.8013E 06   0.3159E 06   0.           0.            0.6484E 07  0.9511E 06   0.           0.            0.5724E 07

0.7379E 06   0.3599E 06   0.           0.            0.8843E 07  0.1057E 07   0.           0.            0.5271E 07

*
B1DLR =     1.000000
B2DLR =     0.000000
B3DLR =     0.000000
STRDLR =     0.012510
A1DLR =     1.000000
A2DLR =     0.000000
A3DLR =     0.000000
GENDLR =     7.143400
```

(e)

Figure 23. (Continued)

```
**WARNING****ALL CCSTS ARE BASED CN CONSTANT RATE $DOLLARS PER UNIT OF CAPACITY IN KW OR KWH.

THEREFCRE USE CCST CATA CNLY FOR TEST PURPCSES.

**NOTE**ALL DOLLARS/KW,KWH BASED ON EQUIVALENT ANNUAL COSTS FOR ANY RATE OF RETURN (I./.).

ON INPUT CARDS, CENTS BEGIN IN COLUMN SEVEN.

(EQUIVALENT ANNUAL TOTAL SYSTEM COST) = (ENPCST)+(GENCST)+(GSDLLR)                 ))

.
       GENKW            ENPCST            OUTCST            TOTAL SYSTEM ANNUAL COST
       *****            $$$$$$            $$$$$$            $$$$$$$$$$$$$$$$$$$$$$$$

 C.1372E C7       -0.               0.                                  0.2133E 08

 0.1309E C7        0.1812E 06       0.1716E 06                          0.2106E 08

 C.1245E C7        0.3803E 06       0.3016E 06                          0.2081E 08

 C.1182E C7        0.7242E 06       0.4327E 06                          0.2070E 08

 0.1118E C7        0.1271E 07       0.5650E 06                          0.2081E 08

 0.1055E C7        0.204CE 07       0.7008E 06                          0.2118E 08

 0.9916E 06        0.3043E 07       0.8389E 06                          0.2178E 08

 C.9282E C6        0.4292E 07       0.9781E 06                          0.2262E 08

 0.8648E C6        0.5851E C7       0.1122E 07                          0.2381E 08

 C.8C13E 06        0.775CE 07       0.1267E 07                          0.2537E 08

 C.7379E 06        0.1026E 08       0.1417E 07                          0.2763E C8
```

(f)

Figure 23. (Concluded)

the demand that were cut-off by a new generation level. "KTIMPK" is the number of hours of the year in which energy is drawn (in some amount) from the storage block. "KTIMBL" is the number of hours in the year in which some energy is placed into storage. "DWNKW" is the kilowatt output capacity specification for the new, minimum generation level; it assists in design of plant.

Figure 23d lists some relevant values. "ADT" is the user-specified value of the time interval between demand points. "AMAXKW" and "AMINKW" are the yearly maximum and minimum demand values. "DLRKWH" is the raw fuel cost in dollars per kilowatt-hour. "QIMLIN" is the limit line; "TSTLIM" is the feasible test limit. A feasible test limit is used in establishment of the smallest new generation level value in order to reduce computer "looping" time for residual storage checks in some models.

Figures 23e and 23f are the cost output pages for all storage components and power plant at each new generation level. The first row is the cost for a power plant without storage. The user-specified values for Equivalent Annual Cost per unit capacity are listed below the generation levels. "ENPCST" is the sub-total for input and output components. "OUTCST" is the sub-total for all storage components. "TOTAL SYSTEM ANNUAL COST" is equal to the "Equivalent Annual Cost" method in engineering economy.

Design of a Power Plant with a Cyclical Storage Procedure

Assuming that the state-of-the-art commercial costs were satisfactory for some type of energy storage system, the plant designer obtains his capacity design specifications from this computer output. The mix of generators base their capacities on the new maximum and minimum generation levels. One generator or group of generators have their sum of output capacity ratings equal to "DWNKW" for base load generation for best fuel efficiency. The input capacity specifications are given for the storage components at worst case levels.

The decision for how much trade-off between generation and storage only needs reference to the minimum cost value in the total annual cost column; this value is $20,700,000 at 1,182,000 kilowatts generation capacity in Figure 23f. In order to reach the start position for a steady state operation, the designer refers to "AREAPK" and then makes an adjustment by the storage block compound efficiency. When that much energy is stored, the system is balanced and ready for startup. This is a very conservative calculation; a graphical analysis of the demand curve with regard to the calendar develops a reduced storage amount for startup. Maintenance of generators has its downtime planned in a similar manner.

Interpretation of Computer Output for Daily Storage Model

This section describes the computer output for the controlled input system simulation model under a daily storage procedure. Figures 24a, 24b, 24c, 24d, 24e, and 24f are related to those of the cyclical storage model, except that there is no "DWNKW" since the minimum generation level is unchanged in this model. It is re-emphasized that all storage input and output components have specifications in terms of input capacities. Storage cost extensions are made accordingly as input capacity costs. Power generation costs are based on output ratings.

Design of a Power Plant with a Daily Storage Procedure

If the research user were using this model for determination of the design specifications of an energy conversion plant with storage, he refers to the computer output for his specifications. By examination of the Equivalent Annual Cost column in the computer output, the designer selects that new, maximum generation level ("GENKW") at least annual cost. For example, in Figure 24f the appropriate "GENKW" value is 991,600 kilowatts. The generator level capacity is in conventional terms of rated output. The corresponding set of storage system components then establish the worst case design capacities for this generator level.

The designer gives extra consideration to the purchase mix of generators since it is necessary that the equipment

```
             ENGINEER... ARTHUR BRUCKNER,II     SCHOOL OF INDUSTRIAL ENGINEERING, OKLAHOMA STATE UNIVERSITY, 1966.

             THIS OUTPUT IS EXCLUSIVELY FOR AN OPERATING REGIME OF FILL-FROM-TOP LOGIC STRUCTURE.

     (TOP) IS DAILY STORAGE PROCEDURE ** (BOTTOM) IS CYCLICAL STORAGE PROCEDURE.

             STORAGE IS EVALUATED ON A YEARLY DEMAND BASIS.


                        -------------------------------------------
                        /                                         /
               ************               *********               ********
 LOGIC MODEL...*CONVERSION*--B1--B2--B3--*STORAGE*--A1--A2--A3--*DEMAND*
               ************               *********               ********

 OUTPUT MEASUREMENT UNITS...       KW   KW   KW       KWH       KW   KW   KW

 COMPONENT EFFICIENCIES...
                B1PCT =    0.9500
                B2PCT =    1.0000
                B3PCT =    1.0000
                STRPCT=    0.9900
                A1PCT =    0.6000
                A2PCT =    1.0000
                A3PCT =    1.0000
```

(a)

Figure 24. Computer Output of Simulation Model for Controlled Input Under a Daily Storage Procedure

```
GENKW        B1INMX       B2INMX       B3INMX       STORMX        A1INMX       A2INMX       A3INMX       DMINMX
*****        ******       ******       ******       ******        ******       ******       ******       ******


0.1372E 07   0.           0.           0.           0.            0.           0.           0.           0.
0.1309E 07   0.2786E 06   0.2647E 06   0.2647E 06   -0.3233E 06   0.1057E 06   0.6341E 05   0.6341E 05   0.6341E 05
0.1245E 07   0.5392E 06   0.5122E 06   0.5122E 06   -0.1036E 07   0.2114E 06   0.1268E 06   0.1268E 06   0.1268E 06
0.1182E 07   0.5708E 06   0.5422E 06   0.5422E 06   -0.2177E 07   0.3170E 06   0.1902E 06   0.1902E 06   0.1902E 06
0.1118E 07   0.5794E 06   0.5504E 06   0.5504E 06   -0.3483E 07   0.4227E 06   0.2536E 06   0.2536E 06   0.2536E 06
0.1055E 07   0.5440E 06   0.5168E 06   0.5168E 06   -0.6285E 07   0.5284E 06   0.3170E 06   0.3170E 06   0.3170E 06
0.9916E 06   0.5266E 06   0.5002E 06   0.5002E 06   -0.2029E 08   0.6341E 06   0.3804E 06   0.3804E 06   0.3804E 06
0.9282E 06   0.5062E 06   0.4809E 06   0.4809E 06   -0.6153E 08   0.7397E 06   0.4438E 06   0.4438E 06   0.4438E 06
0.8648E 06   0.5098E 06   0.4843E 06   0.4843E 06   -0.1593E 09   0.8454E 06   0.5072E 06   0.5072E 06   0.5072E 06
0.8013E 06   0.4463E 06   0.4240E 06   0.4240E 06   -0.3244E 09   0.9511E 06   0.5707E 06   0.5707E 06   0.5707E 06
0.7379E 06   0.4259E 06   0.4046E 06   0.4046E 06   -0.5252E 09   0.1057E 07   0.6341E 06   0.6341E 06   0.6341E 06
```

(b)

Figure 24. (Continued)

```
GENKW         GSDLLR        TOTKWH        AREAPK        KTIMPK    KTIMBL        SUMRUN
*****         ******        ******        ******        ******    ******        ******
-------------------------------------------------------------------------------------------

-------------------------------------------------------------------------------------

0.1372E 07    0.1153E 08    0.5759E 10    0.                 0         0        0.
0.1309E 07    0.1153E 08    0.5760E 10    0.4543E 06        23        21        0.
0.1245E 07    0.1154E 08    0.5765E 10    0.3737E 07        95        81        0.
0.1182E 07    0.1157E 08    0.5776E 10    0.1384E 08       231       179        0.
0.1118E 07    0.1159E 08    0.5795E 10    0.3351E 08       394       274        0.
0.1055E 07    0.1164E 08    0.5817E 10    0.6360E 08       563       440        0.
0.9916E 06    0.1169E 08    0.5847E 10    0.1047E 09       740       733        0.
0.9282E 06    0.1175E 08    0.5885E 10    0.1573E 09       928      1196        0.
0.8648E 06    0.1179E 08    0.5933E 10    0.2245E 09      1176      1738        0.
0.8013E 06    0.1190E 08    0.5999E 10    0.3078E 09      1470      2614        0.
0.7379E 06    0.1210E 08    0.6089E 10    0.4199E 09      2214      4562        0.
```

(c)

Figure 24. (Continued)

```
          CONSTANTS  =====

ADT =   1.0000

AMAXKW = 0.1372E 07

AMINKW = 0.3120E 06

KNTDMD =   8760

KHRTIM =   8760

DLRKWH = 0.6826172E-03

QIMLIN = 0.7046E 06

TSTLIM = 0.7379E 06

SYSFAC =       0.56429999

STINFC =       0.95000000

JDEX =  11

KNTPSS =       0
```

(d)

Figure 24. (Continued)

```
GENKW        B1CST        B2CST     B3CST     STRCST        A1CST         A2CST     A3CST     GENCST
*****        $$$$$        $$$$$     $$$$$     $$$$$$        $$$$$         $$$$$     $$$$$     $$$$$$

0.1372E 07   0.           0.        0.        -0.           0.            0.        0.        0.9801E 07
0.1309E 07   0.2786E 06   0.        0.        0.4044E 04    0.1057E 06    0.        0.        0.9348E 07
0.1245E 07   0.5392E 06   0.        0.        0.1296E 05    0.2114E 06    0.        0.        0.8895E 07
0.1182E 07   0.5708E 06   0.        0.        0.2724E 05    0.3170E 06    0.        0.        0.8442E 07
0.1118E 07   0.5794E 06   0.        0.        0.4358E 05    0.4227E 06    0.        0.        0.7989E 07
0.1055E 07   0.5440E 06   0.        0.        0.7862E 05    0.5284E 06    0.        0.        0.7536E 07
0.9916E 06   0.5266E 06   0.        0.        0.2538E 06    0.6341E 06    0.        0.        0.7083E 07
0.9282E 06   0.5062E 06   0.        0.        0.7697E 06    0.7397E 06    0.        0.        0.6630E 07
0.8648E 06   0.5098E 06   0.        0.        0.1993E 07    0.8454E 06    0.        0.        0.6177E 07
0.8013E 06   0.4463E 06   0.        0.        0.4058E 07    0.9511E 06    0.        0.        0.5724E 07
0.7379E 06   0.4259E 06   0.        0.        0.6570E 07    0.1057E 07    0.        0.        0.5271E 07

B1DLR =     1.000000
B2DLR =     0.000000
B3DLR =     0.000000
STRDLR =     0.012510
A1DLR =     1.000000
A2DLR =     0.000000
A3DLR =     0.000000
GENDLR =     7.143400
```

(e)

Figure 24. (Continued)

```
**WARNING****ALL COSTS ARE BASED ON CONSTANT RATE $DOLLARS PER UNIT OF CAPACITY IN KW OR KWH.

THEREFORE USE COST DATA ONLY FOR TEST PURPOSES.

**NOTE**ALL DOLLARS/KW,KWH BASED ON EQUIVALENT ANNUAL COSTS FOR ANY RATE OF RETURN (I./.).

ON INPUT CARDS, CENTS BEGIN IN COLUMN SEVEN.

(EQUIVALENT ANNUAL TOTAL SYSTEM COST) = (ENPCST)+(GENCST)+(GSDLLR)                 ))

.

      GENKW            ENPCST            OUTCST              TOTAL SYSTEM ANNUAL COST
      *****            $$$$$$            $$$$$$              $$$$$$$$$$$$$$$$$$$$$$$$

 0.1372E 07       -0.                0.                                   0.2133E 08

 0.1309E 07        0.3883E 06        0.3843E 06                           0.2127E 08

 0.1245E 07        0.7635E 06        0.7505E 06                           0.2120E 08

 0.1182E 07        0.9151E 06        0.8878E 06                           0.2092E 08

 0.1118E 07        0.1046E 07        0.1002E 07                           0.2063E 08

 0.1055E 07        0.1151E 07        0.1072E 07                           0.2033E 08

 0.9916E 06        0.1414E 07        0.1161E 07                           0.2019E 08

 0.9282E 06        0.2016E 07        0.1246E 07                           0.2039E 08

 0.8648E 06        0.3348E 07        0.1355E 07                           0.2131E 08

 0.8013E 06        0.5456E 07        0.1397E 07                           0.2308E 08

 0.7379E 06        0.8053E 07        0.1483E 07                           0.2542E 08
```

(f)

Figure 24. (Concluded)

run at the new peak level for relatively more extended time periods. Other design considerations are similar to those of cyclical storage.

Interpretation of Computer Output for Uncontrolled Input Model

This section describes the computer output for the uncontrolled input system simulation model. Figure 25a portrays the basic model; it lists the input storage efficiencies. It also lists the computed values for maximum power and yearly energy of the theoretical and transformed power density curves. Figure 25b lists the storage parameter values according to levels of generation output in kilowatts ("GOUTKW"). The storage parameter values, e.g. "B1INMX", are input capacity ratings in the specified units. "XTRKWH" is the value for the energy system surplus energy; only the values with a plus sign satisfy the demand curve requirements.

In those cases where "XTRKWH" is negative, the parameter values listed on all output pages are not necessarily valid. Beginning at the "GOUTKW" value of 0.1489E+07, this line and all following lines for all output pages do not necessarily list valid parameter values. In this particular study, the nature of the power density curve (and its maximum kilowatt rating) super-satisfied the maximum demand curve value before the upper limit of computational passes. Figure 39 portrays the super-satisfied case where no storage

```
                    ENGINEER... ARTHUR BRUCKNER,II     SCHOOL OF INDUSTRIAL ENGINEERING, OKLAHOMA STATE UNIVERSITY, 1966.

          THIS OUTPUT IS EXCLUSIVELY FOR AN ENERGY CONVERSION WITH STORAGE SYSTEM, WHERE THE ENERGY SOURCE IS UNCONTROLLED.

          STORAGE IS EVALUATED ON A YEARLY DEMAND BASIS.


                                                       ============================================
                                                       =                                          =
                    *THEC.POWER****  *****  *CONVERSION*              *********              ********
LOGIC MODEL...      *DENSITY INPUT*==*0/0*==*GENERATED *==B1==B2==B3==*STORAGE*==A1==A2==A3==*DEMAND*
                    ***************  *****  *OUTPUT*****  **  **  **  *********  **  **  **  ********

OUTPUT MEASUREMENT UNITS...                               KW  KW  KW     KWH     KW  KW  KW

COMPONENT EFFICIENCIES...
                         B1PCT =   0.9500
                         B2PCT =   1.0000
                         B3PCT =   1.0000
                         STRPCT=   0.9900
                         A1PCT =   0.6000
                         A2PCT =   1.0000
                         A3PCT =   1.0000


POWER DENSITY FUNCTION CONSTANTS...
                                   PRDMAX =   0.10000E 00  KW/FTSQ
                                   TPDMAX =   0.30150E-01  KW/FTSQ

                                   SUMPRD =   0.87599E 03YEARLY KWH PER SQFT OF PRD
                                   SUMTPD =   0.26411E 03YEARLY KWH PER SQFT OF TPD
```

(a)

Figure 25. Computer Output of Simulation Model for Uncontrolled Input

```
KW---GOUTKW KW---B1INMX KW---B2INMX KW---B3INMX KWH--STORMX KW---A1INMX KW---A2INMX KW---A3INMX KW---DMINMX KWH--XTRKWH
 0.6438E 06  0.3318E 06  0.3152E 06  0.3152E 06  0.8767E 09  0.1190E 07  0.7142E 06  0.7142E 06  0.7142E 06 -0.6800E 09
 0.7404E 06  0.4284E 06  0.4070E 06  0.4070E 06  0.5158E 09  0.1029E 07  0.6176E 06  0.6176E 06  0.6176E 06  0.4105E 09
 0.8514E 06  0.5394E 06  0.5125E 06  0.5125E 06  0.1916E 09  0.8443E 06  0.5066E 06  0.5066E 06  0.5066E 06  0.1519E 10
 0.9791E 06  0.6671E 06  0.6338E 06  0.6338E 06  0.2734E 08  0.6314E 06  0.3789E 06  0.3789E 06  0.3789E 06  0.2735E 10
 0.1126E 07  0.8140E 06  0.7733E 06  0.7733E 06  0.3313E 07  0.3866E 06  0.2320E 06  0.2320E 06  0.2320E 06  0.4086E 10
 0.1295E 07  0.9829E 06  0.9338E 06  0.9338E 06  0.3978E 06  0.1051E 06  0.6308E 05  0.6308E 05  0.6308E 05  0.5588E 10
 0.1489E 07  0.1177E 07  0.1118E 07  0.1118E 07 -0.         -0.         -0.         -0.         -0.          0.7290E 10
 0.1713E 07  0.1401E 07  0.1331E 07  0.1331E 07 -0.         -0.         -0.         -0.         -0.          0.9247E 10
 0.1969E 07  0.1657E 07  0.1575E 07  0.1575E 07 -0.         -0.         -0.         -0.         -0.          0.1150E 11
 0.2265E 07  0.1953E 07  0.1855E 07  0.1855E 07 -0.         -0.         -0.         -0.         -0.          0.1406E 11
 0.2605E 07  0.2293E 07  0.2178E 07  0.2178E 07 -0.         -0.         -0.         -0.         -0.          0.1706E 11
 0.2995E 07  0.2683E 07  0.2549E 07  0.2549E 07 -0.         -0.         -0.         -0.         -0.          0.2048E 11
 0.3445E 07  0.3133E 07  0.2976E 07  0.2976E 07 -0.         -0.         -0.         -0.         -0.          0.2442E 11
 0.7040E 06  0.3920E 06  0.3724E 06  0.3724E 06  0.6435E 09  0.1090E 07  0.6540E 06  0.6540E 06  0.6540E 06  0.2164E 08
                    **LAST LINE(ROW 14)ABOVE REFERENCE NOTE**

THE LAST LINE ABOVE IS THE INTERPOLATED CASE FOR JUST-FEASIBLE SOLUTION (XTRKWH=0.0). A FULL RECOMPUTATION IS MADE
WITH THE NEW,INTERPOLATED VALUE FOR THE AMLPLY FACTOR.
```

(b)

Figure 25. (Continued)

```
 KW---GOUTKW KW---GINPKW KWH--PRDKWH KWH--TPDKWH KWH--DMDKWH KWH--RCVKWH KWH--USEKWH KWH--PKEKWH KTIMPK KTIMBL KTMXTR FCTR-AMLPLY
  0.6438E 06  0.2135E 07  0.1871E 11  0.5640E 10  0.5755E 10  0.6165E 09  0.1296E 10  0.7316E 09   4434   4326      0  0.2135E 08
  0.7404E 06  0.2456E 07  0.2151E 11  0.6486E 10  0.5755E 10  0.1146E 10  0.7353E 09  0.4150E 09   2154   4508   2096  0.2456E 08
  0.8514E 06  0.2824E 07  0.2474E 11  0.7458E 10  0.5755E 10  0.1943E 10  0.4237E 09  0.2391E 09   1264   1862   5634  0.2824E 08
  0.9791E 06  0.3248E 07  0.2845E 11  0.8577E 10  0.5755E 10  0.2936E 10  0.2006E 09  0.1132E 09    758    842   7160  0.3248E 08
  0.1126E 07  0.3735E 07  0.3272E 11  0.9864E 10  0.5755E 10  0.4139E 10  0.5371E 08  0.3031E 08    376    282   8102  0.3735E 08
  0.1295E 07  0.4295E 07  0.3762E 11  0.1134E 11  0.5755E 10  0.5589E 10  0.1486E 07  0.8384E 06     30     38   8692  0.4295E 08
  0.1489E 07  0.4939E 07  0.4327E 11  0.1304E 11  0.5755E 10  0.7290E 10 -0.         -0.                0      0   8760  0.4939E 08
  0.1713E 07  0.5680E 07  0.4976E 11  0.1500E 11  0.5755E 10  0.9247E 10 -0.         -0.                0      0   8760  0.5680E 08
  0.1969E 07  0.6532E 07  0.5722E 11  0.1725E 11  0.5755E 10  0.1150E 11 -0.         -0.                0      0   8760  0.6532E 08
  0.2265E 07  0.7512E 07  0.6580E 11  0.1984E 11  0.5755E 10  0.1408E 11 -0.         -0.                0      0   8760  0.7512E 08
  0.2605E 07  0.8639E 07  0.7567E 11  0.2282E 11  0.5755E 10  0.1706E 11 -0.         -0.                0      0   8760  0.8639E 08
  0.2995E 07  0.9934E 07  0.8702E 11  0.2624E 11  0.5755E 10  0.2048E 11 -0.         -0.                0      0   8760  0.9934E 08
  0.3445E 07  0.1142E 08  0.1001E 12  0.3017E 11  0.5755E 10  0.2442E 11 -0.         -0.                0      0   8760  0.1142E 09
  0.7040E 06  0.2335E 07  0.2045E 11  0.6167E 10  0.5755E 10  0.9186E 09  0.8969E 09  0.5061E 09   2930   5644    186  0.2335E 08
                **LAST LINE(ROW 14)ABOVE REFERENCE NOTE**

  THE LAST LINE ABOVE IS THE INTERPOLATED CASE FOR JUST-FEASIBLE SOLUTION (XTRKWH=0.0). A FULL RECOMPUTATION IS MADE
  WITH THE NEW,INTERPOLATED VALUE FOR THE AMLPLY FACTOR.
```

(c)

Figure 25. (Continued)

```
SOME CONSTANTS...
                   ADT     =   2.000000
                   AMAXKW  =  0.1358E 07
                   AMINKW  =  0.31200E 06
                   KNTR    =   4380
                   KNTDMD  =   4380
                   TOTKWH  =  0.575477E 10
                   KNTPRD  =   4380
                   KNTTPD  =      0
                   KNIPP   =      0
                   KNTDIF  =      0
                   JDEX    =     15
                   PLRNEW  =  0.2335E 08
                   ADDR    =  0.1997E 07
                   CHECK   =      0.00000000
                   SNEAKY  =     22.22000003
                   SYSFAC  =      0.56429999
                   STINFC  =      0.95000000
                   TIMADD  =      4.00000000
                   TIMXTR  =    186.00000000
                   TIMPK   =   2930.00000000
                   TIMBL   =   5644.00000000
                   TIMTWO  =   1562.00000000
                   TIMORG  =    662.00000000
                   JPHAKE  =   3266
                   KBAL    =   3266
                   RUNSUM  = -0.24185495E 05
                   SLIPPY  =      7.00000000
                   RESID   =  0.
                   PLSKWH  =     0.
                   DEFKWH  =  0.
                   XRAKWH  =  0.
                   PKARE   =  0.
```

(d)

Figure 25. (Continued)

```
                                        $$....TOTAL SYSTEM AND COMPONENT COSTS....$$
****WARNING**ALL COSTS ARE BASED ON CONSTANT RATE DOLLARS PER UNIT OF CAPACITY IN KW OR KWH.
              THEREFORE,USE COST DATA ONLY FOR APPROXIMATE TEST PURPOSES.
****NOTE**ON INPUT CARDS,ALL DOLLAR$/KW,KWH REPRESENT EQUIVALENT ANNUAL COSTS AT SOME RATE OF RETURN(I O/O).

KW...GCUTKW   $$....B1CST  $$....B2CST  $$....B3CST  $$...STRCST  $$....A1CST  $$....A2CST  $$....A3CST     $$...GOUTCS
 0.6438E 06    0.3318E 06   0.           0.           0.1097E 08   0.1190E 07   0.           0.              0.4599E 07
 0.7404E 06    0.4284E 06   0.           0.           0.6453E 07   0.1029E 07   0.           0.              0.5289E 07
 0.8514E 06    0.5394E 06   0.           0.           0.2397E 07   0.8443E 06   0.           0.              0.6082E 07
 0.9791E 06    0.6671E 06   0.           0.           0.3420E 06   0.6314E 06   0.           0.              0.6994E 07
 0.1126E 07    0.8140E 06   0.           0.           0.4144E 05   0.3866E 06   0.           0.              0.8044E 07
 0.1295E 07    0.9829E 06   0.           0.           0.4977E 04   0.1051E 06   0.           0.              0.9250E 07
 0.1489E 07    0.1177E 07   0.           0.          -0.          -0.          -0.          -0.              0.1064E 08
 0.1713E 07    0.1401E 07   0.           0.          -0.          -0.          -0.          -0.              0.1223E 08
 0.1969E 07    0.1657E 07   0.           0.          -0.          -0.          -0.          -0.              0.1407E 08
 0.2265E 07    0.1953E 07   0.           0.          -0.          -0.          -0.          -0.              0.1618E 08
 0.2605E 07    0.2293E 07   0.           0.          -0.          -0.          -0.          -0.              0.1861E 08
 0.2995E 07    0.2683E 07   0.           0.          -0.          -0.          -0.          -0.              0.2140E 08
 0.3445E 07    0.3133E 07   0.           0.          -0.          -0.          -0.          -0.              0.2461E 08
 0.7040E 06    0.3920E 06   0.           0.           0.8051E 07   0.1090E 07   0.           0.              0.5029E 07
              **LAST LINE(ROW 14)ABOVE REFERENCE NOTE**
 THE LAST LINE ABOVE IS THE INTERPOLATED CASE FOR JUST-FEASIBLE SOLUTION (XTRKWH=0.0). A FULL RECOMPUTATION IS MADE
 WITH THE NEW,INTERPOLATED VALUE FOR THE AMLPLY FACTOR.
INPUT CONSTANTS...
                  B1DLR =      1.000000
                  B2DLR =      0.000000
                  B3DLR =      0.000000
                  STRDLR=      0.012510
                  A1DLR =      1.000000
                  A2DLR =      0.000000
                  A3DLR =      0.000000
                  GENDLR=      7.143400
```

(e)

Figure 25. (Continued)

```
                                  $$....TOTAL SYSTEM AND COMPONENT COSTS....$$

   (TOTAL SYSTEM EQUIVALENT ANNUAL COST) = (BBBCST)+(STRCST)+(AAACST)+(GOUTCS)

  **NOTE.....                                     FUEL COST CONSIDERED ZERO (WIND,SUN,ETC.


KW...GOUTKW     $$...BBBCST  $$...STRCST  $$...AAACST    $$...BSACST  $$...GOUTCS     $$...TOTEAC


 0.6438E 06      0.3318E 06   0.1097E 08   0.1190E 07     0.1249E 08   0.4599E 07      0.1709E 08

 0.7404E 06      0.4284E 06   0.6453E 07   0.1029E 07     0.7910E 07   0.5289E 07      0.1320E 08

 0.8514E 06      0.5394E 06   0.2397E 07   0.8443E 06     0.3781E 07   0.6082E 07      0.9863E 07

 0.9791E 06      0.6671E 06   0.3420E 06   0.6314E 06     0.1641E 07   0.6994E 07      0.8635E 07

 0.1126E 07      0.8140E 06   0.4144E 05   0.3866E 06     0.1242E 07   0.8044E 07      0.9286E 07

 0.1295E 07      0.9829E 06   0.4977E 04   0.1051E 06     0.1093E 07   0.9250E 07      0.1034E 08

 0.1489E 07      0.1177E 07  -0.          -0.             0.1177E 07   0.1064E 08      0.1181E 08

 0.1713E 07      0.1401E 07  -0.          -0.             0.1401E 07   0.1223E 08      0.1363E 08

 0.1969E 07      0.1657E 07  -0.          -0.             0.1657E 07   0.1407E 08      0.1573E 08

 0.2265E 07      0.1953E 07  -0.          -0.             0.1953E 07   0.1618E 08      0.1813E 08

 0.2605E 07      0.2293E 07  -0.          -0.             0.2293E 07   0.1861E 08      0.2090E 08

 0.2995E 07      0.2683E 07  -0.          -0.             0.2683E 07   0.2140E 08      0.2408E 08

 0.3445E 07      0.3133E 07  -0.          -0.             0.3133E 07   0.2461E 08      0.2774E 08

 0.7040E 06      0.3920E 06   0.8051E 07   0.1090E 07     0.9533E 07   0.5029E 07      0.1456E 08

               **LAST LINE(ROW 14)ABOVE REFERENCE NOTE**

 THE LAST LINE ABOVE IS THE INTERPOLATED CASE FOR JUST-FEASIBLE SOLUTION (XTRKWH=0.0). A FULL RECOMPUTATION IS MADE
 WITH THE NEW,INTERPOLATED VALUE FOR THE AMLPLY FACTOR.
```

(f)

Figure 25. (Continued)

```
                    $$....TOTAL SYSTEM AND COMPONENT COSTS....$$
    BUT,**IF**IT HAPPENS THAT GENDLR INPUT IS BASED ON GENERATOR=GINPKW, THEN THE COSTS ARE LISTED BELOW.

KW...GOUTKW  KW...GINPKW     $$...BSACST  $$...GINPCS     $$...TOTEAC


 0.6438E 06   0.2135E 07      0.1249E 08   0.1525E 08      0.2774E 08

 0.7404E 06   0.2456E 07      0.7910E 07   0.1754E 08      0.2545E 08

 0.8514E 06   0.2824E 07      0.3781E 07   0.2017E 08      0.2395E 08

 0.9791E 06   0.3248E 07      0.1641E 07   0.2320E 08      0.2484E 08

 0.1126E 07   0.3735E 07      0.1242E 07   0.2668E 08      0.2792E 08

 0.1295E 07   0.4295E 07      0.1093E 07   0.3068E 08      0.3177E 08

 0.1489E 07   0.4939E 07      0.1177E 07   0.3528E 08      0.3646E 08

 0.1713E 07   0.5680E 07      0.1401E 07   0.4057E 08      0.4198E 08

 0.1969E 07   0.6532E 07      0.1657E 07   0.4666E 08      0.4832E 08

 0.2265E 07   0.7512E 07      0.1953E 07   0.5366E 08      0.5561E 08

 0.2605E 07   0.8639E 07      0.2293E 07   0.6171E 08      0.6400E 08

 0.2995E 07   0.9934E 07      0.2683E 07   0.7097E 08      0.7365E 08

 0.3445E 07   0.1142E 08      0.3133E 07   0.8161E 08      0.8474E 08

 0.7040E 06   0.2335E 07      0.9533E 07   0.1668E 08      0.2621E 08
                 ↑
          **LAST LINE(ROW 14)ABOVE REFERENCE NOTE**

                                        REFER TO PRECEEDING PAGE.
```

(g)

Figure 25. (Concluded)

equipment is needed. The exception is the row of listed parameters for 0.7040E+06, which is valid; it is the interpolated case for a just-satisfied system. "-0." is equal to zero; the leading sign has no significance.

A super-satisfied energy system can occur only where the transformed power density curve has no values equal to zero for any hour of the year. It may not occur even in this case, when any time-unit power density value is small. When this power density value is multiplied, and this lowest value is still less than the maximum demand curve kilowatt value, then the energy system is over-satisfied but is not super-satisfied.

Figure 25c lists additional design information parameters also according to the generation output levels; "GINPKW" is the corresponding maximum <u>input</u> level of generation, i.e. maximum energy source input capacity rating. "PRDKWH" is the input source energy potential received by the total generation block. "TPDKWH" is the generated net output from the energy source; this energy is utilized in storage or directly by the demand requirements. "DMDKWH" is the net amount of energy that is required by the demand curve. "RCVKWH" is the amount of energy that enters the storage block. "USEKWH" is the amount of energy required to enter the storage block if the demand curve requirements are to be met; the gross energy required to meet demand curve net requirements. "PKEKWH" is the net amount of energy required by the demand curve for a particular level of generation output. "KTIMPK", "KTIMBL", and "KTMXTR" are the hours per year that energy is drawn from storage, placed into storage, and neither drawn nor placed into storage, respectively. "FCTR-AMLPLY" is a key design information parameter. It specifies the total number of square-foot power-density generation units that are required. For example, the number of square feet of solar cells where the power density curve was computer input-defined for one square foot.

In Figure 25d the pertinent values are "KNTR", "KNTDMD", and "KNTPRD". The first value is the array counter used in computation. The second value is the count of the input values for the demand curve. The third value is the number of input values for the power density curve. It is preferable for accuracy that all three values be equal.

Figures 25e, 25f, and 25g list the cost computations. All storage component costs are based on <u>input</u> requirements. Typically, generation equipment is specified by output rating and cost ("GOUTCS"). However, it is more likely that generation equipment for uncontrolled input systems is based on input capacity rating and costs ("GINPCS"). Cost summaries are given for both situations since this model is used for analysis of conventional plants. All costs are defined as Equivalent Annual Costs at some selected rate of return.

Design of an Uncontrolled System Power Plant

The approach to the design of a power plant based on uncontrolled input is not too dissimilar to that of controlled input. An underlying consideration, however, is the more probabilistic nature of many uncontrolled input energy sources. Depending upon the firmness for which the demand curve requires satisfaction, the designer needs further subsidiary estimates (using the computer model) in allowance for the variations expected in the power density curve. The computer model readily performs these analyses when it is provided with new power density curves for expected varying conditions of the energy source. It is observed, however, that the over-satisfied case of a feasible system is not an accurate estimate of component specifications whereby variations in demand are compensated, since there is a trade-off between various components. Nevertheless, some of the generation "slack" is partially picked up by the energy system surplus in the over-satisfied systems.

In the same manner as in previous models, the designer obtains the worst case parameter specifications for the storage components from the computer output for a particular level of generated output from the energy source. This generation level is based on the least Equivalent Annual Cost row from the cost output. The capacity rating, however, for the generation system is based on a translation to the scale and type of generation system. The "AMLPLY" factor specifies the number of "square feet" of power density "units". For example, an appropriate economy-of-scale wind generator unit might be the equivalent of 100 square feet of power density units. Therefore, the number of generators ordered would be 0.01 times "AMLPLY". Further, it is noted that generation capacity is based on either "GOUTKW" or "GINPKW", and the number of generation units is correspondingly defined. For this same wind generator at a "GOUTKW" of "0.8514E+06", the "AMLPLY" value is "0.2824E+08"; refer to Figure 25c. This is equivalent to 282,400 wind generators which have an aggregate output capacity of 851,400 kilowatts. For the given "GOUTKW" value the corresponding "GINPKW" is "0.2824E+07" which specifies an aggregate input capacity of 2,824,000 kilowatts, or equals 282,400 one-hundred square feet wind generators each of 10 kilowatt input capacity rating. (The same digits for AMLPLY and GINPKW are coincidental.)

The physical design of all equipment requires consideration of the higher movement level of equipment loading. In the controlled models, in general, between time intervals there is a more gradual change in the kilowatt load on a unit in addition to load plateaux and base loads. Relatively speaking, the uncontrolled model requires larger and more frequent movements over the full capacity range of a system component. Of course, this depends significantly on the amount of difference in "shape" of the demand curve and power density curve. A direct example is solar energy where zero to maximum loading of a generation unit (and other components) can occur within twenty-four hours.

Remarks on System Development

The computer output interpretation is explained in this chapter for the three system simulation models. For given storage technology parameters these computer outputs are shown for a complete set of equipment specifications for power plant design.

The general position of these computer outputs in energy storage applications is charted in the operational system design of Chapter III. With reference to Chapter II the applicable design criteria are met in terms of the data arrangement and parameter coverage of these computer outputs. Within the overall operational system the established research objectives are supported by this computer output presentation of information. The satisfaction of research objectives and design criteria is demonstrated by model applications to a variety of energy system studies in the next chapter.

CHAPTER VII

SIMULATION STUDY RESULTS

This chapter is concerned with the application approaches of the simulation system for energy storage studies. Actual results are used for description of various research approaches. Obviously, these results have not encompassed the whole picture of energy conversion and storage, since there are an unlimited range of parameter values and combinations of different parameters. The potential studies are multiplied also by the number of developing storage technologies. Therefore, only the nature of research categories and approaches are demonstrated.

Nature of Research Study Applications

A consideration is the type of study for which this simulation system is needed. There are two groups of people with primary interest in the application of these models. The first is the plant design engineer. The second is the research-and-development engineer. There are three major input variables of direct concern to these two groups. These input parameters are: (1) the demand curve, (2) storage system component efficiencies, and (3) equipment costs of the whole energy system. It is the movement of one or more of these parameters and its effects on the energy conversion with storage system which concern the engineers.

The plant design engineer is required to establish the power capacities for all plant equipment. His studies are based on some existing storage technology. The cost and efficiency values are assumed available for the storage equipment. For the particular plant under study, simulation results are required for the variation effects of the demand curve. These results can be the explicit design specifications of the plant versus those of similar category plants. Or, the results can be the specifications for a plant under different "steady-state" demand conditions where projections are made for the most reliable set of specifications. Or, if a plant has an energy storage system, but requires expansion because of added customers, then the results are the adjusted storage equipment specifications which are necessary for the new demand curve pattern.

The research and development engineer is less concerned with a specific demand curve, although a representative demand curve is desired for the type or region of demand. His basic concern is one of the feasibility of some storage technology—the requirements necessary for an economically feasible storage system. The key input variables of concern here are the efficiencies and costs of the storage components. The required information is which aspect of which component offers the best research potential for a feasible energy system.

The life, first cost, and efficiency of all components require investigation for their effects on the overall energy conversion with storage system. The simulation results indicate the effects on the combined system for an incremental change in some parameter value. Interpretation of these results establish the cost or efficiency boundaries which must be met for system feasibility. These simulation results also identify the "bottleneck" component that holds back economic feasibility because of a too low efficiency or too high unit cost of the component. The simulation results can compare different storage technologies for the technology of lowest annual cost.

Examination of other input parameters is possible, such as efficiency of power generation and cost of fuel. In the most typical circumstance of a simulation study, whether plant design or storage technology research, the engineer analyzes the interrelating effects onto the combined system for a change of only one parameter of an individual component (or demand curve). In this manner the most detailed information about effects is built up from several studies for the area of concern.

In the next sections, results are described which reflect the various orientations of the types of research applications. Variations in single demand curve parameters are portrayed for the plant designer. A case study application is developed for explanation of a research-and-development series of studies.

Variation of Demand Curve Parameter

This section is more of concern to a plant designer of an energy conversion with storage system. In this example study, the requirements for storage components are analyzed in terms of a variation of the demand curve by a demand curve parameter change. In this example, the demand curve operator parameter of the week option is set at 0.50 which is a reduction in the original weekly variation. The fine line in Figure 8 represents this modified demand curve. Table I lists the resultant parameters. For this application of the simulation system all other parameters are fixed. The following table lists the relevant parameters.

TABLE II

PARAMETER REFERENCE TABLE

Parameter	Original Demand Curve	Modified Demand Curve
Demand Curve	Original	0.50 week option
Storage Efficiencies	-same for both-	
Input Components	-same for both-	
Cavern Storage	-same for both-	
Output Components	-same for both-	
Annual Costs/Unit Capacity	-same for both	
Fuel Cost	-same for both-	
Generator Conversion Efficiency	-same for both-	

The original resultant parameter for weekly variation is 77.5 per cent; the modified resultant parameter for weekly variation is 88.1 per cent. Four simulation studies are graphed in Figures 26, 27, and 28. The two demand curves are each analyzed by the two storage procedures of the controlled input simulation model.

Figure 26 is a graph of the capacity requirements for the fuel cell, or storage output components. Both curves are straight lines because the fuel cell is used as a "controlled variable" in the simulation models; it is increased at a constant rate. When a demand curve is modified by any parameter, the hourly values are subject to change. In this case of a parameter reduction the maximum demand value for the year is reduced within the set of a week's reduction. This is the cause for the kilowatt difference at the no-storage point of power generation. All points in the demand curve are modified by the demand curve variation. Since the demand curves are not alike, there is a slight change in the feasible storage limit generation kilowatts as a result of computational methods. The physical storage limit kilowatts are the same, however, since the storage block efficiencies are the same.

Figure 27 is a graph of the capacity requirements for electrolysis, or storage input components. In this case differences between the storage methods are evident. The reason is the same for the kilowatt difference at the no-storage point and at the storage limit line as it is for the

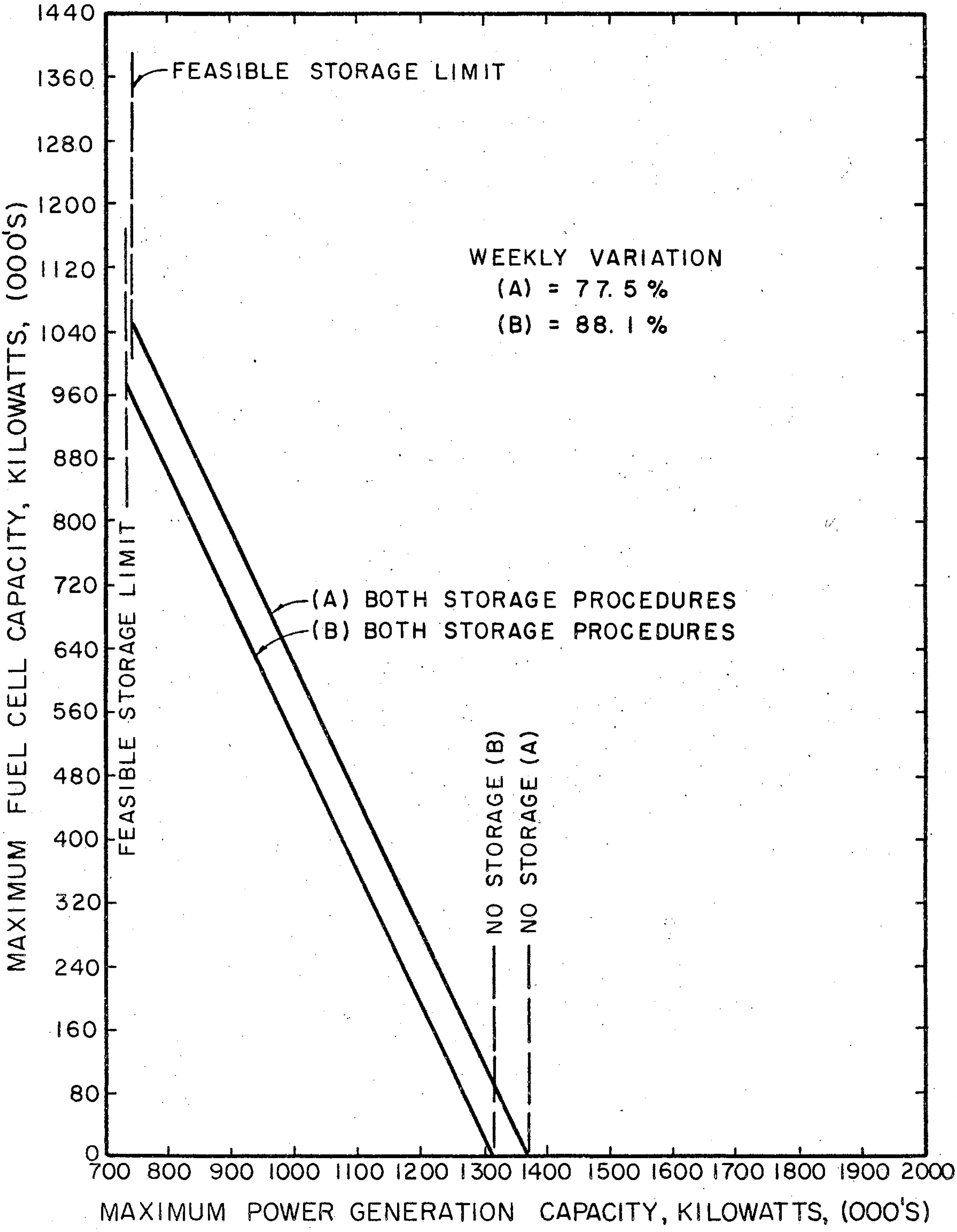


Figure 26. The Effects of Demand Curve Variation on
Fuel Cell Requirements
The original demand curve case is (A).

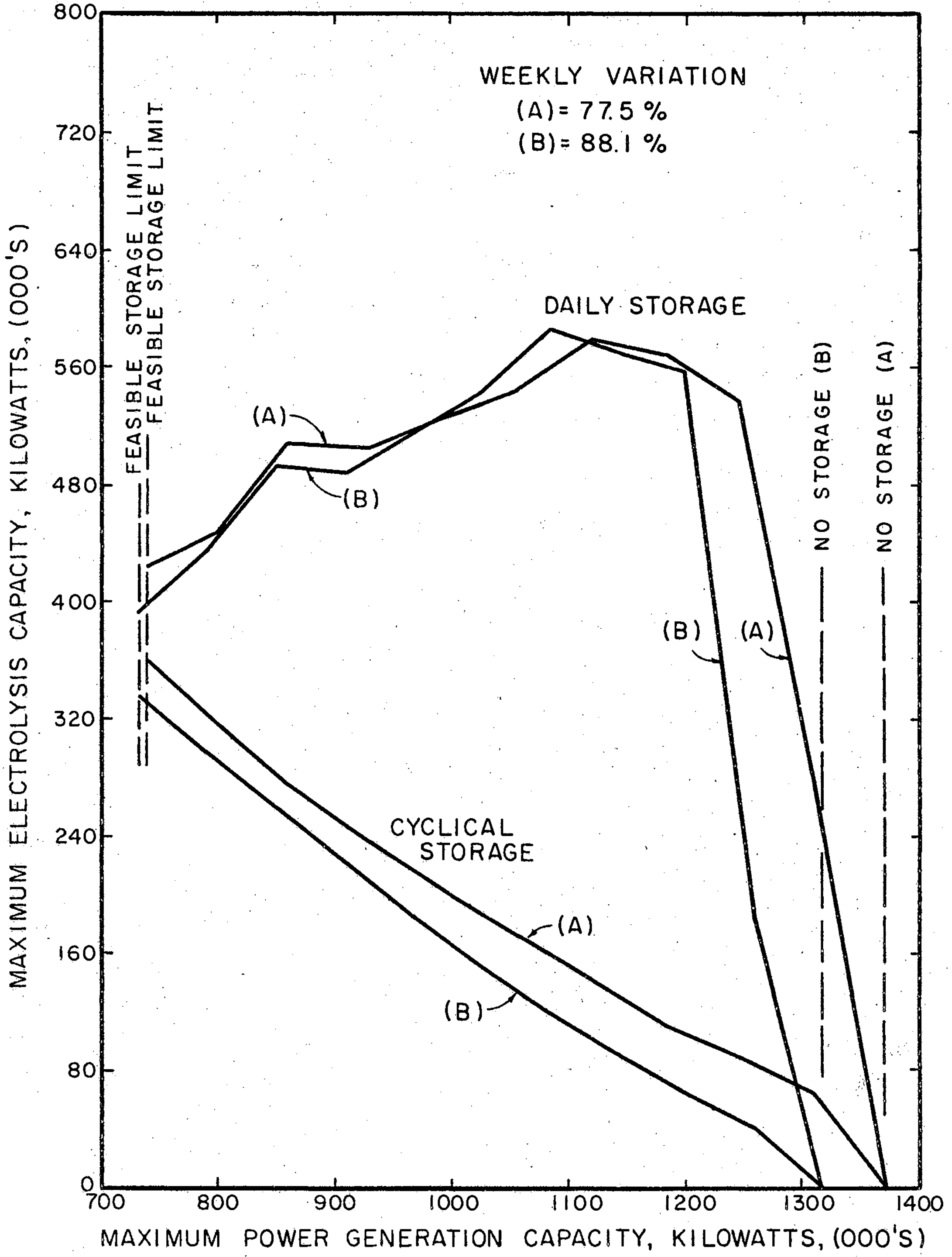


Figure 27. The Effects of Demand Curve Variation on Electrolysis Requirements by Storage Procedure
The original demand curve case is (A).

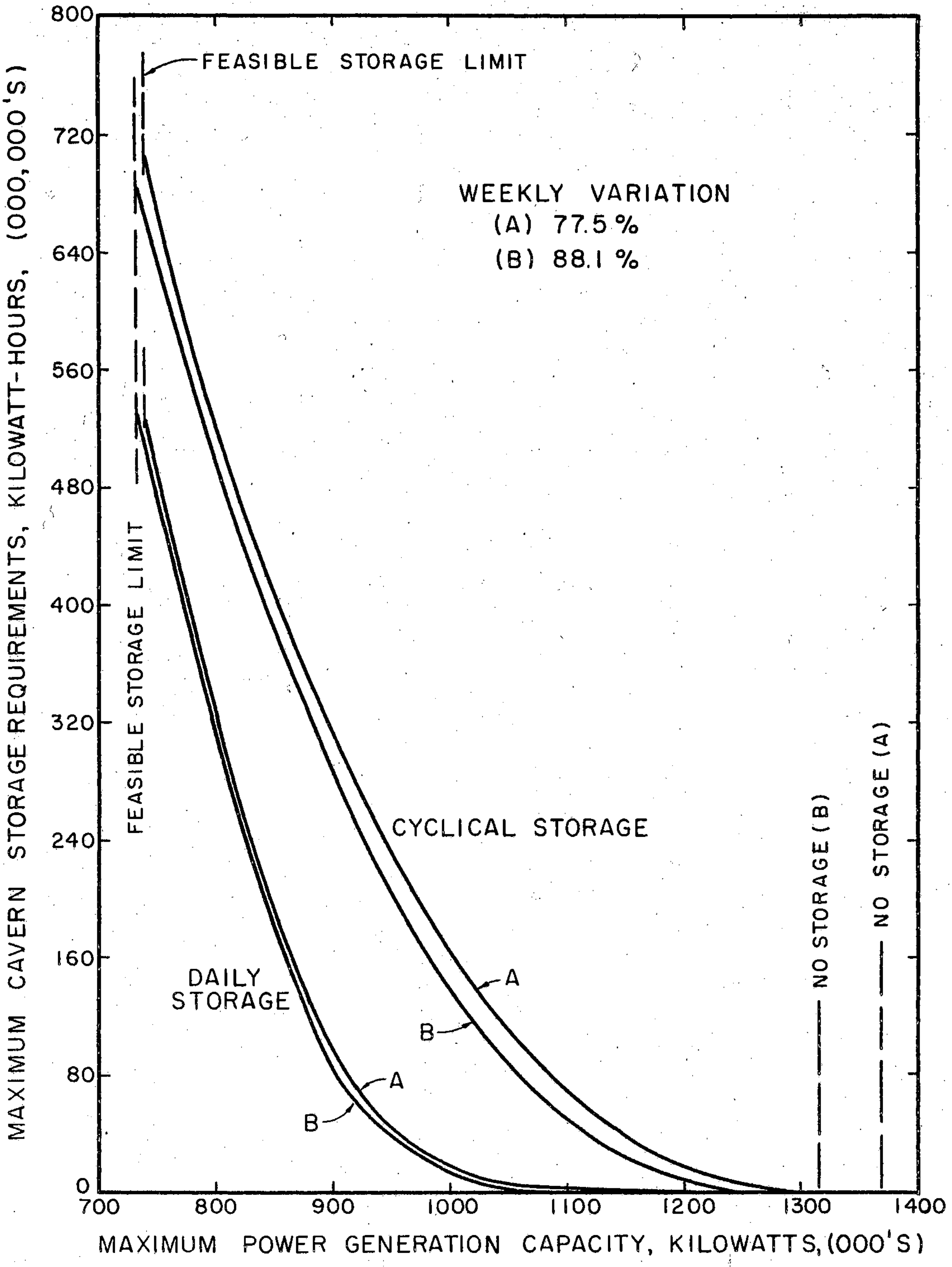


Figure 28. The Effects of Demand Curve Variation on Cavern Storage Requirements by Storage Procedure
The original demand curve case is (A).

fuel cell. The algorithm for cyclical storage allots storage across the year in uniformly increasing quantities. This is shown in the graph for each cyclical storage line. Each line is an individual calculation of worst case electrolysis requirements for the respective demand curves. Since the demand curves are different, no conclusions should be made about the slope rates between the two curves. Of course, the overall position of the curves to each other is relevant. This relationship is discussed at the end of this section.

A different pattern is portrayed for the electrolysis requirements under a daily storage procedure. For both demand curves, the electrolysis requirements rapidly "jump" to their maximum levels. This capacity jump results from the algorithmic determination of the worst case daily "valley" as the maximum generation capacity is reduced. When the deep "valleys" during the summer months are cut-off, the worst case valleys require less electrolysis capacity. This is shown in the graph by the down-slope of kilowatt requirements to the left of 1,100,000 kilowatts of generation capacity. The more erratic nature of daily storage electrolysis requirements is observed; these daily requirements are more affected by shape and kilowatt range of the demand curve than are the requirements for cyclical storage. Therefore, estimate projections for daily storage electrolysis requirements are less reliable between different demand curves.

Figure 28 is a graph of the capacity requirements for "cavern" storage in kilowatt-hours. Again, these requirements are the maximum case requirements during the year for held-energy storage. The reason is the same for the kilowatt difference at the no-storage generation point and at the storage limit line. The significant difference between the storage methods is seen. Both storage methods have a slow rate of increase during the high ranges of generation capacity. This reflects the low kilowatt-hour quantities of energy required to supplant the high peaks of the demand curve. As the maximum generation line lowers, the energy magnitude rapidly increases. This is seen in the graph for both storage procedures. The abscissa values of this graph, when compared to the ordinate values of Figure 8, highlight the changes in energy requirements. For both demand curve lines of the cyclical storage procedure the cavern requirements ascend more rapidly than daily storage. This results from the cyclical algorithm which accumulates energy needs across the year. For both demand curves under the daily storage procedure, the cavern storage increases at a much slower rate to a lower point of power generation. Cavern storage then increases more rapidly even though with still significantly less kilowatt-hour requirements. However, reference to areas "A" and "B" in Figure 13 explain that the cavern storage requirements converge for the <u>same</u> demand curve regardless of storage method.

Following the preparation of these graphs, the plant design user is prepared for examination of the results affected by a variation in the demand curve input data. It is observed that for any storage procedure the kilowatt or kilowatt-hour storage component requirements are less for most cases where the weekly variation is less (i.e. higher percentage). The exception is the input component requirements under a daily storage procedure. They are relatively equal for these two particular demand curves. It is also observed that there is a trade-off in requirements for electrolysis and cavern storage between the two storage procedures. At this point the user needs to decide which demand curve most nearly represents the demand curve-to-be after plant construction. Or, if the two demand curves represent the expected range of demand curve shape, then the design engineer might choose the most conservative values for each storage component according to the cost-evaluated generation level choice of storage procedure.

The selection of this minimum system cost is based on the total annual costs as indicated in Figures 23f, and 24f. In the situation where the year-end actual curve falls between the two demand curves, the total annual savings from use of a storage system require a decremental adjustment for the excess capacity requirements of each component's conservative selection. These capacity differences are indicated by the graphs when a vertical line is drawn at the point where the maximum power generation capacity corresponds to the lowest cost. The lowest cost generation points differ by both storage procedure and demand curve. Accordingly, even though the storage costs are greater with a lower percentage variation the savings in generation capacity are also greater between demand curves at the same generation level, and for the same storage procedure. Therefore, the user needs also to consider the absolute savings from the selection of the conservative design.

Where the demand curve is fairly stable but the pattern is changed by new customers the selection of the most economic generation point is straightforward. At the minimum system cost's corresponding generation capacity point a vertical line indicates the increase (or decrease) in storage component capacities necessary for satisfaction of the new demand curve. Only the marginal change in capacity requirements needs equipment supplementation. The most economical generation capacity for the new demand curve simulation is according to whichever storage procedure offers the least storage cost.

The demand variation study shows that a reduction in demand curve variation reduces the capacity requirements for storage equipment. The proportion of change, however, is not proportional to the change in the input parameter. The percentage of change in the input parameter is not a reliable indication of resultant effects. Relative gain decisions are possible only by individual cost analyses.

Variation of Storage Block Efficiency Parameter

This section is of concern to both the plant designer and the research engineer. In this example, the effects are examined for an overall increase in storage block efficiency. The overall improvement is a result of an efficiency increase in an output component of storage. The original demand curve of Figure 8 is used for this study. The efficiency of the output component is increased from 48.75 to 60.00 per cent. All other parameters are kept the same between the studies. The following table lists the relevant parameters.

TABLE III

PARAMETER REFERENCE TABLE

Parameter	Original Study	Comparison Study
Demand Curve	Original	Same
Storage Efficiencies	0.4585	0.5643
Input Components	0.9500	0.9500
Cavern Storage	0.9900	0.9900
Output Components	0.4875	0.6000
Annual Costs/Unit Capacity	-same for both-	
Fuel Cost	-same for both-	
Generator Conversion Efficiency	-same for both-	

It is seen that the combined storage block efficiency increases from 45.85 per cent to 56.43 per cent efficiency as a result of a percentage efficiency improvement of 23.08 per cent in the fuel cell. Four research studies are graphed in Figures 29, 30, and 31. The same demand curve is analyzed by the two storage procedures for the two levels of storage efficiency.

Figure 29 is a graph of the capacity requirements for the fuel cell. Both curves are straight lines because the output component acts as the "controlled variable". The capacity ratings are based on maximum input requirements. Input requirements are affected by component efficiencies. The two lines are identical when the efficiency of that component is 100.0 per cent, since the output needs are the same. Since the demand curve is identical for all studies, the no-storage point for generation capacity is identical. The feasible storage limits are not the same because of the difference in overall efficiency. With reference to Figure 13, the simulation study with a higher efficiency has a smaller "B" energy requirement. Hence, the physical limit line is lower.

Figure 30 is a graph of the electrolysis capacity requirements. Storage method differences are noted here. These differences are a direct result of the different methods of storing energy. The "growth" of the cyclical storage lines is similar to those in the study of demand curve variation. As the generation requirements are reduced the differences in capacity ratings increase. This is an effect of system efficiency requiring less stored energy and in turn a lesser kilowatt rating of the input components to transfer that energy by the cyclical logic.

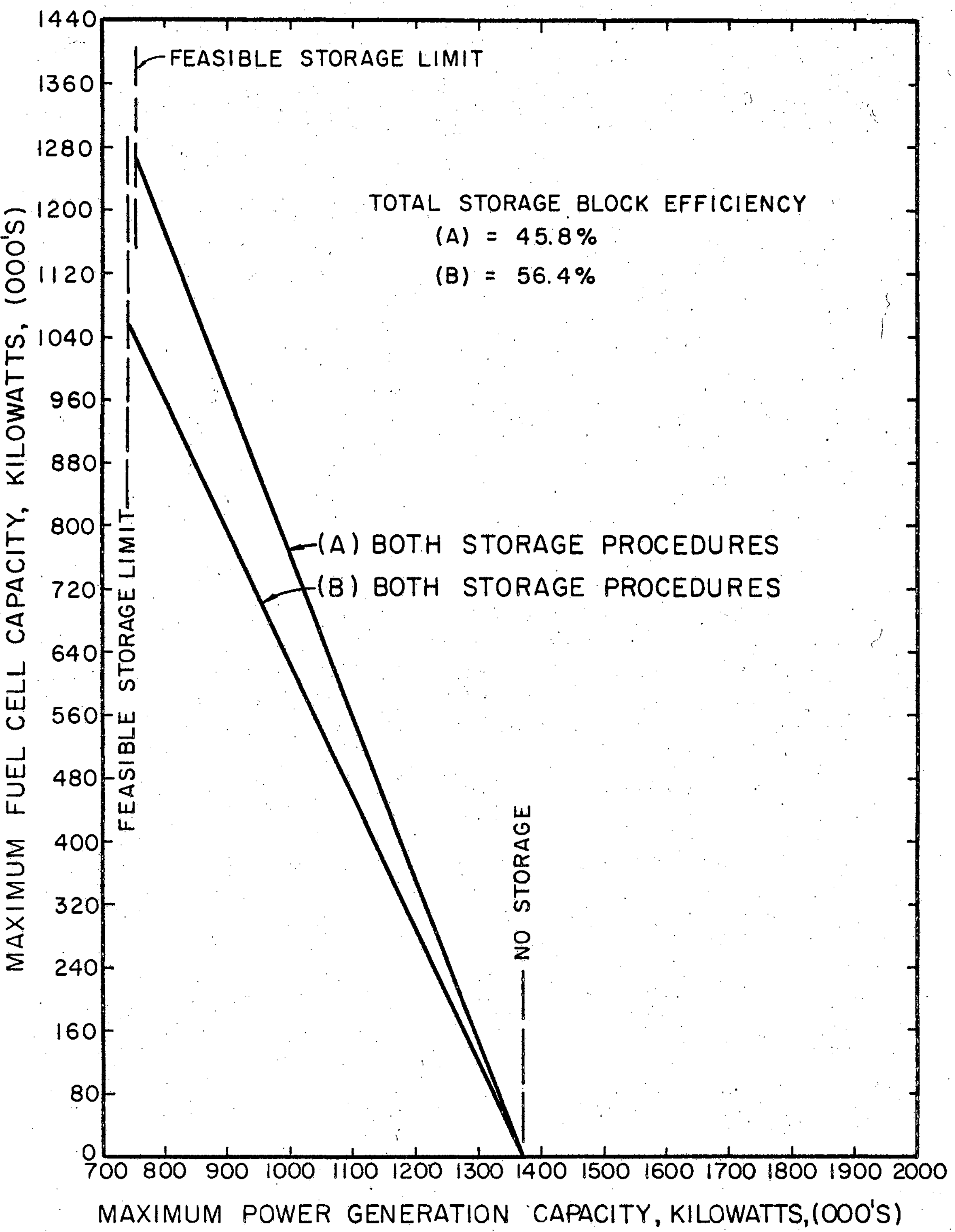


Figure 29. The Effects of Storage Block Efficiency Variation on Fuel Cell Requirements The original case is (A).

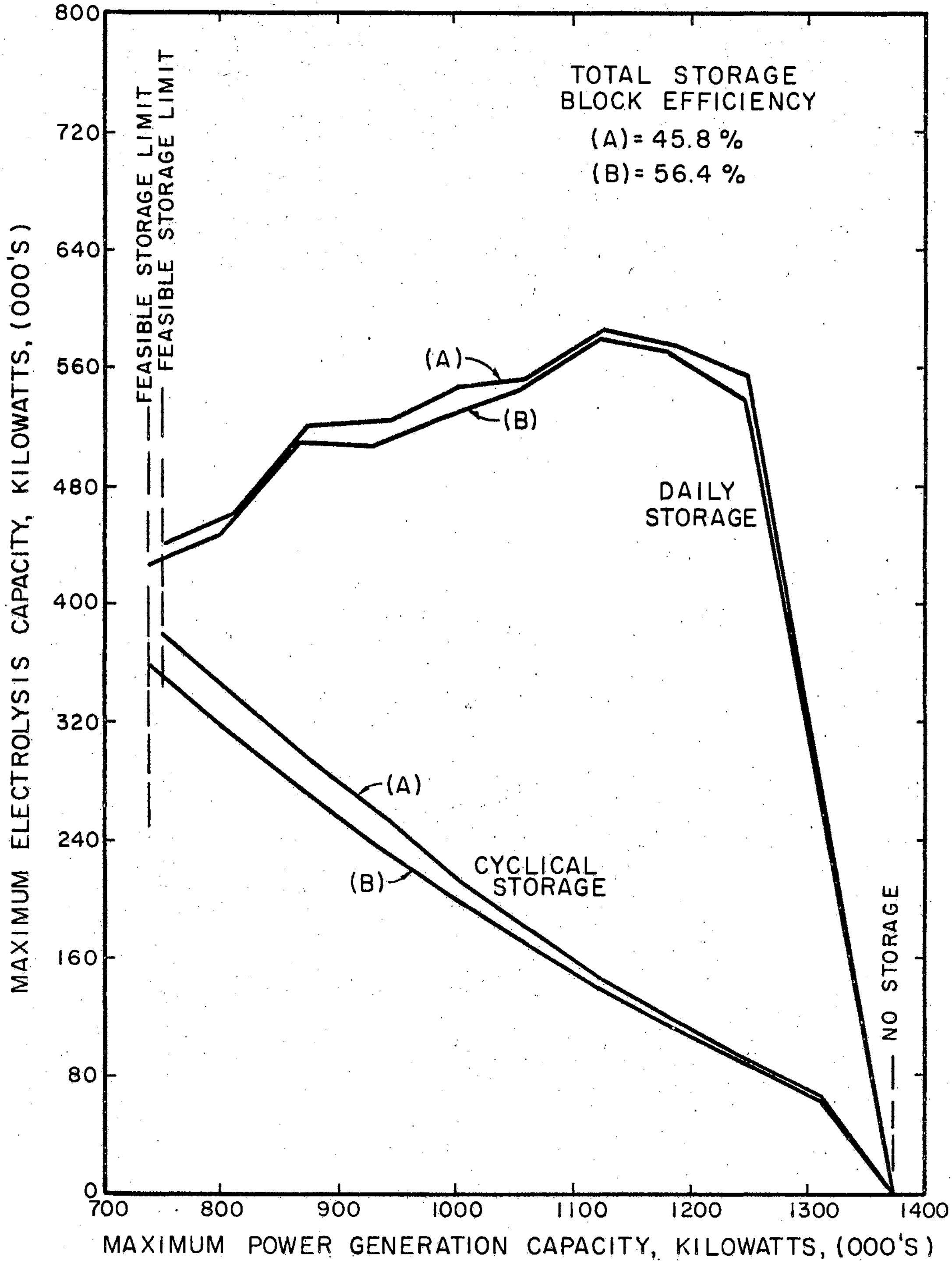


Figure 30. The Effects of Storage Block Efficiency Variation on Electrolysis Requirements by Storage Procedure
The original case is (A).

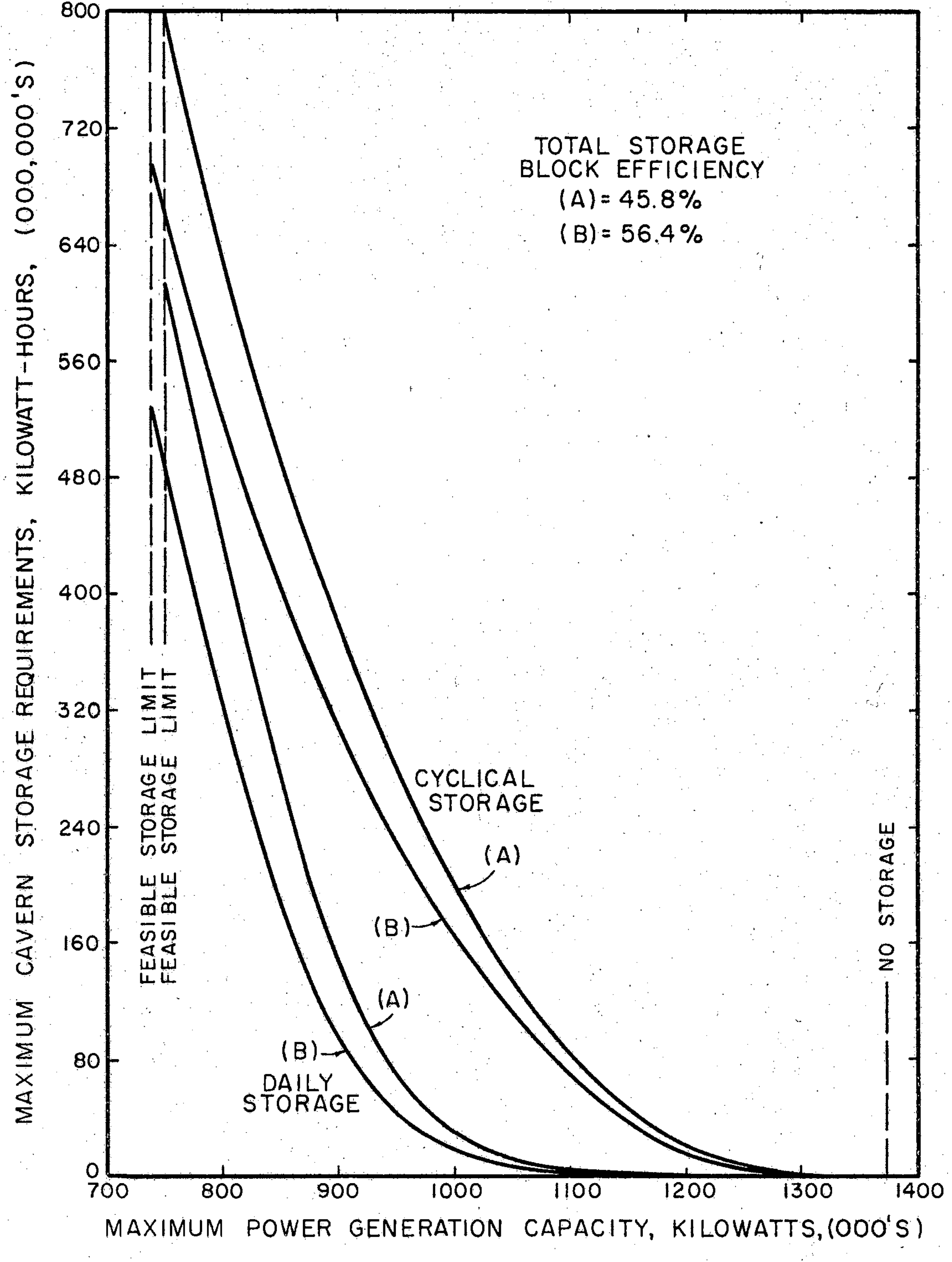


Figure 31. The Effects of Storage Block Efficiency Variation on Cavern Storage Requirements by Storage Procedure The original case is (A).

The case of daily storage is different. The erratic pattern of electrolysis requirements is closely similar to the studies of demand curve variations. This erratic nature is a function of demand curve shape. This graph shows that the worst case requirements for this demand curve virtually override the gains realized from an increased storage block efficiency for this study where the demand curves are alike. A slight change in a demand curve, however, causes a different worst case which affects both efficiency-level electrolysis requirements. Therefore, with an improved storage block efficiency the daily storage procedure requirements are no more or less than the case with less efficiency.

Figure 31 is a graph of the capacity requirements for kilowatt-hour potential energy storage over time. The patterns are similar to those in the demand curve variation studies. Figure 31 does indicate the lesser capacity requirement and consistently increasing difference in requirements for the energy system operating at a higher storage efficiency. A system operating at higher efficiency requires less energy in storage. At the same time as the generation level is reduced, the higher efficiency system increases at a slower rate, since the increase in energy storage is less than the reduction in generation requirements on a comparative basis.

After preparation of these graphs, the design or research user can evaluate the effects on the overall power system by an increase in storage block efficiency from an efficiency increase in one component. The situation is relevant to the decision about the worth of a new component. He observes that for any storage component the capacity needs are reduced for higher efficiency (with only negligible savings for the electrolysis requirements under daily storage). He further notes that the storage efficiency differences between component requirements are increased as generation levels are reduced with a sub-trade-off between electrolysis and cavern storage by storage method.

The decision problem is resolved by direct examination of total annual costs. For both efficiencies and both storage procedures it is necessary to determine respectively the annual savings at the best generation level of each and not the same generation level. The simulation study with the most savings determines the appropriate equipment capacities, storage method, and generation level. When a new replacement purchase is under consideration, then the problem is one of savings gain by the marginal cost increase for the particular storage component. The increase in savings is the difference between the old savings and the new savings at the best new generation level. For the portrayed graphs it is noticed that the improvement in one component decreases the required capacities of all components. Best realizable savings assume the possible resale of the excess capacity units for all components as well as the adjustments in generation capacity. A formal engineering economy study is warranted under the actual re-sale conditions in existence. However, a desirable alternative exists. The one storage component when installed increases the overall efficiency and the overall energy capabilities of the power system. In other words, the power plant can expand its market by the addition of only one component when new customers exist or if an increased safety factor of power is desirable. This may not be true for electrolysis requirements under daily storage because of the eventually down-sloping capacities as generation capacity is reduced. In the typical situation, a line drawn horizontally from the present efficiency line for a given generation level indicates roughly the amount of generator reduction possible to serve the same curve. This offers only the roughest possible indication of enlarged power system capabilities. The interlocking computations from the number of storage components and other input variables prevent any determination of increased power generation for the system. It is necessary to use a new demand curve enlarged according to future trends. The simulation results from this new study can be used to examine the growth in production by installation of a higher efficiency component where a system is already in going operation.

An increase in the efficiency of a storage component decreases the equipment requirements. The choice of storage procedure does not physically change the equipment. The choice of storage procedure affects the plant operating decisions about when to store energy. Since the change in equipment requirements does not reflect the proportional increase in storage efficiency, system specification decisions require individual total cost studies.

Case Study Results for an Aphodid Storage Component

The case study is oriented towards the research-and-development engineer. A new storage technology is studied where little prior energy system knowledge is available. In this case the primary concern is the feasibility of an aphodid "system" in place of the output storage components. The first step is made to evaluate best known aphodid data for feasibility. Later steps concern the research directions and boundary values necessary if an economical system is to be realized. In the two previous studies of variation and efficiency no emphasis was placed on finding the limiting conditions or analysis of costs in detail. These two past studies are suitable more for existing plants and storage technologies. For the study in this section a more detailed analysis is made as it would be done by a research user to explore all the factors affecting the economic feasibility of a new storage technology.

Figure 32 portrays a possible equipment arrangement of a storage block utilizing an aphodid burner setup. It is noted that the solid-lined figures "replace" the fuel cell and associated output components. The indicated generator is the final step to convert stored energy to electricity;

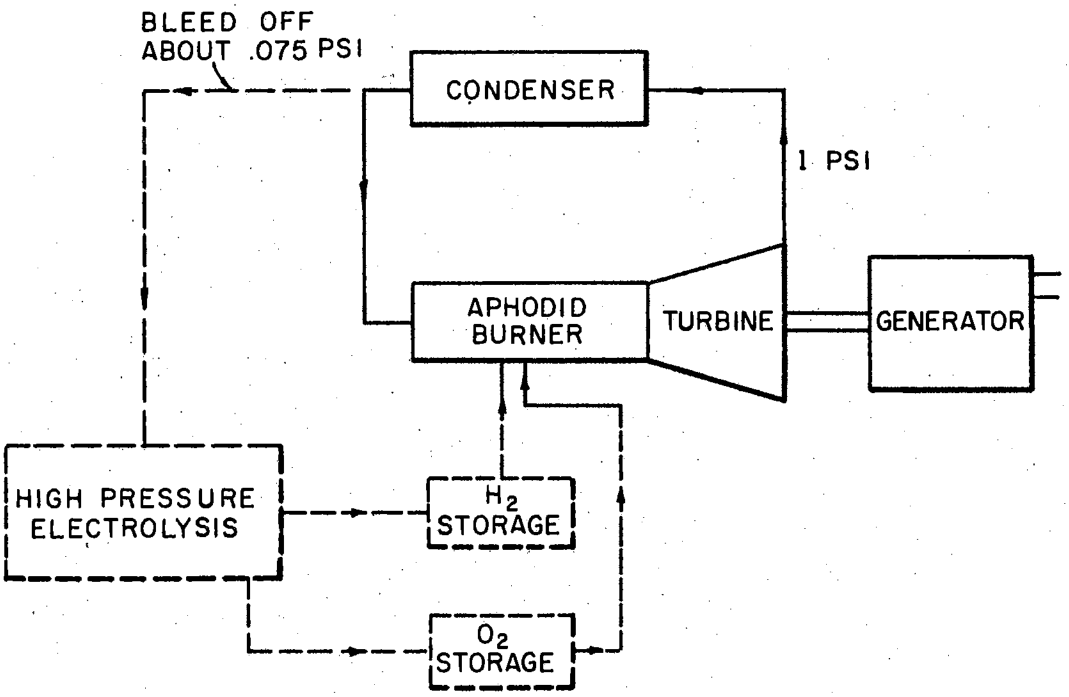


Figure 32. Storage Block Schematic of an Aphodid Sub-System

it is not the plant generator. An aphodid arrangement differs from conventional steam-turbine generation in that the boiler costs are eliminated.

For this study the original demand curve of Figure 8 is used without change. Reference is also made to the previous Figures 29, 30, and 31 relative to the original demand curve. Best known costs for the present state-of-the-art are used in combination with representative costs in this region for fuel and conventional generation equipment.

The remainder of this section is oriented to the stepwise approach that a research engineer might follow for a feasibility study. The first step for existing conditions and known data is used to establish the "go-not-go" case of economic feasibility relative to conventional generation without storage. The succeeding step explores the boundary conditions for storage block efficiencies. The next step is to "force backwards" from the savings boundaries for determination of maximum storage unit costs when a system is still not economically feasible.

Table IV lists the initial stage costs as predicted according to best knowledge before this step. Electrolysis costs are established as a judgement estimate. Present state-of-the-art prevents a better cost picture for the capacity rating of electrolysis required for this magnitude of application. Life of electrolysis is estimated as equal to conventional generation as an indication of desirable commercial requirements. Cavern storage is charged for only hydrogen at the time of the studies; cavern storage is an estimate based on a large-scale extrapolation of current technology costs. Lives and costs of conventional generation reflect the Oklahoma region conditions. Aphodid costs are developed from a comparison to conventional generation costs less the requirements for high pressure boiler equipment. All costs are based on a true annual rate of return of eight per cent. First costs are based in terms of reasonable scale magnitudes.

TABLE IV

EQUIPMENT COST REFERENCE TABLE

Equipment	First Cost per Unit Capacity ($/kw,kwh)	Life (years)	Capital Recovery Factor (i=0.08)	Equivalent Annual Cost per Unit Capacity ($/kw,kwh)
Power Plant Generation				
	82.25	33	0.08685	7.1434
Storage Costs				
Input (elec)	23.00	33	0.08685	2.0000
Cavern	0.1563	100	0.08004	0.01251
Output (aphodid)	47.25	33	0.08685	4.1034

The fuel conversion efficiency table is the same as Figure 14. Fuel costs are $0.0006826 per kilowatt-hour of purchased bulk fuel.

Table V lists the other input variable values used for the first step of this study.

TABLE V

PARAMETER REFERENCE TABLE

Parameter	Initial Step
Demand Curve	Original
Storage Block Efficiencies	0.4585
Input	0.9500
Cavern	0.9900
Output	0.4875

With this input data, computer simulation runs of a power plant are performed. A run is made for both daily and cyclical storage procedures. The storage component capacity ratings are identical to those in Figures 29, 30, and 31 for the lower efficiency value ("A"). Total System Annual costs for this study are portrayed in Figure 33 for both storage procedures. Detailed component costs are shown in Figures 34 and 35. It is observed that no total system cost point lies below the total system cost point for no storage (i.e. conventional plant). Therefore, the system with its present cost and efficiency parameters is not economically feasible for the *given* demand curve.

The research user can now modify either component efficiencies, or unit costs as the approach for estimating boundary conditions. Typically, only one of these parameters is moved at a time in order to determine its singular effects onto the present state of information. In this example, the research user observed in Figure 33 that between

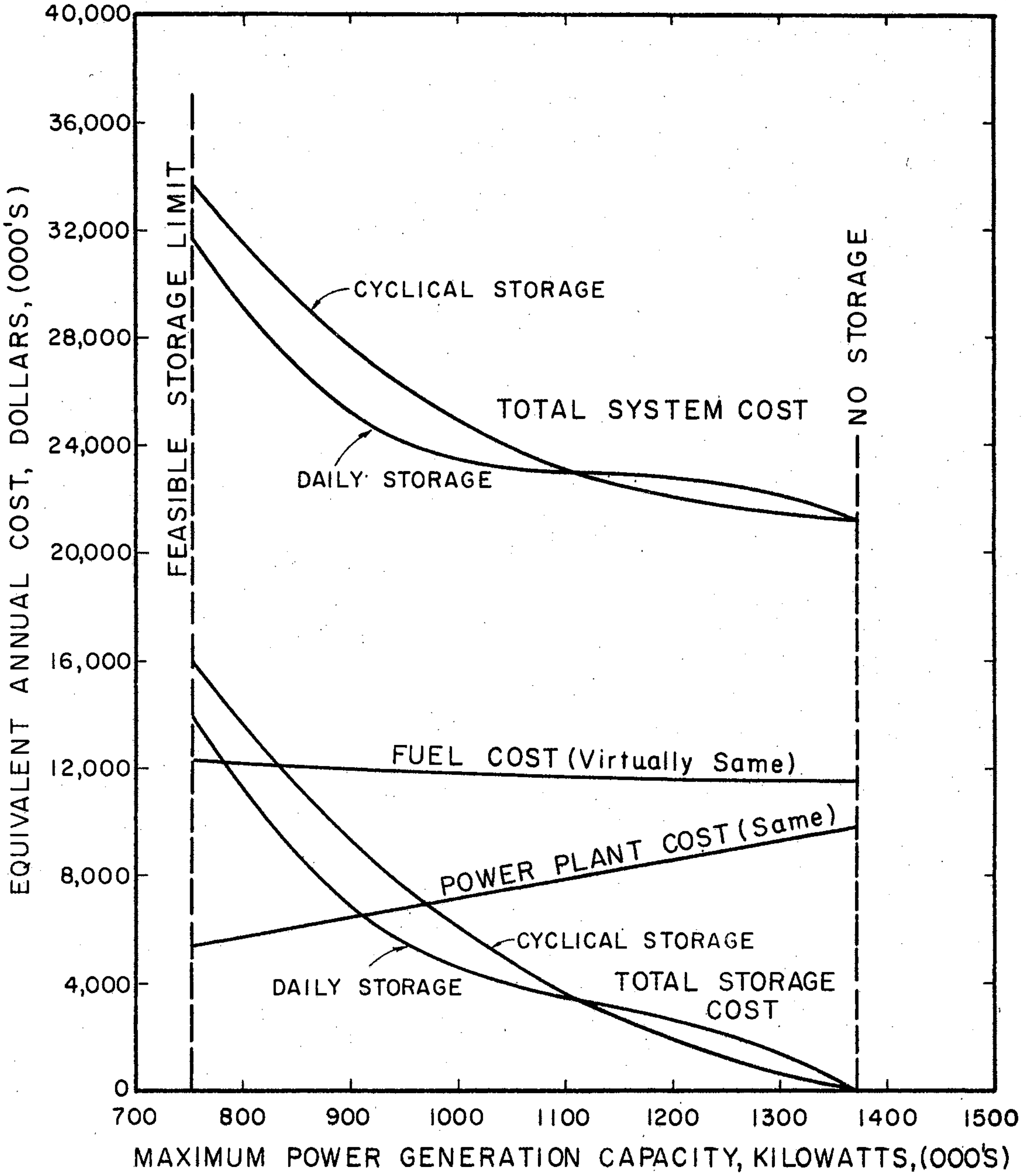


Figure 33. The Effects of Storage Procedures on Total Annual Costs of Energy System This data is for the 45 per cent storage block efficiency case.

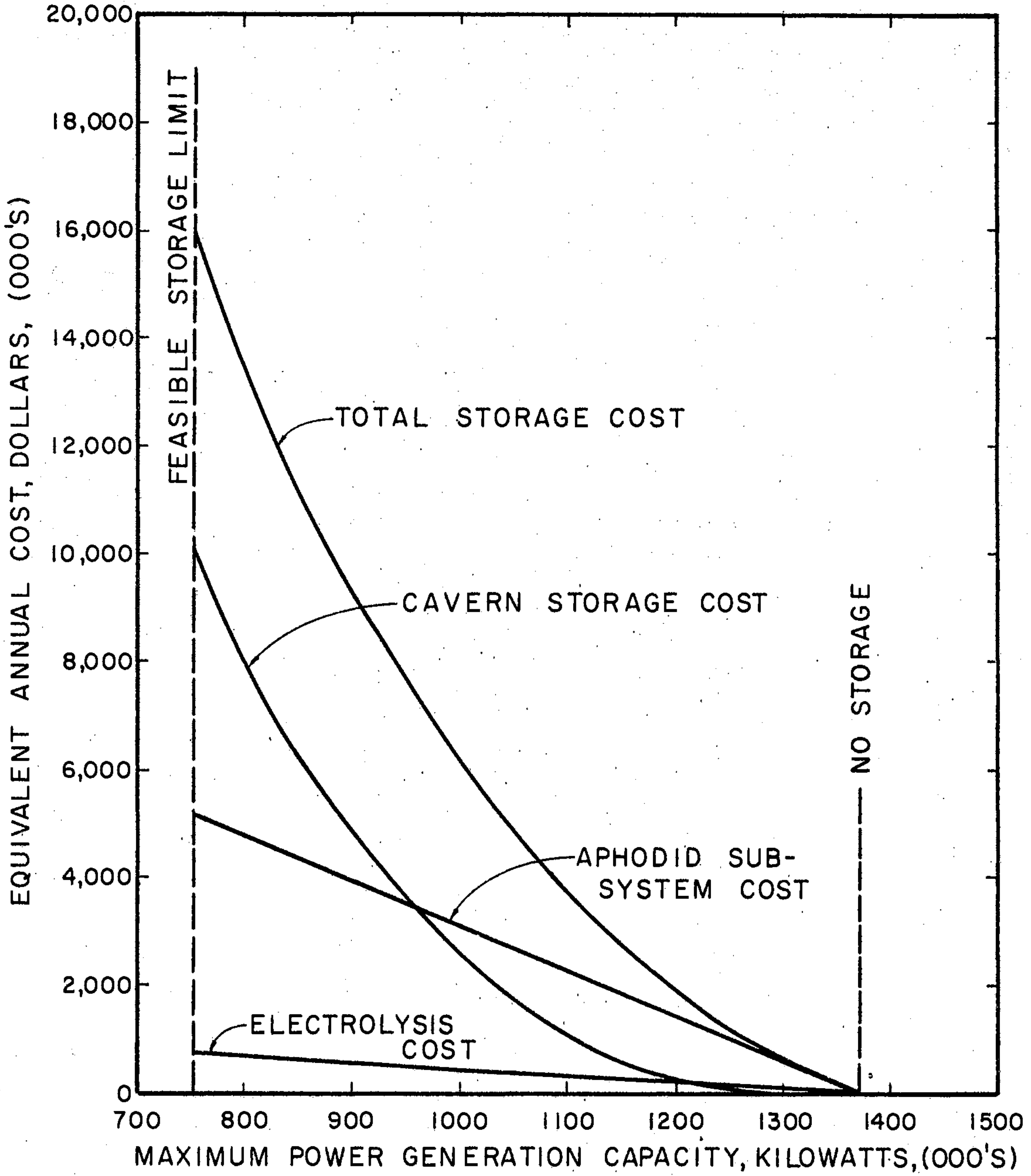


Figure 34. Storage Block Component Costs for Cyclical Storage Procedure
This data is for the 45 per cent storage block efficiency case.

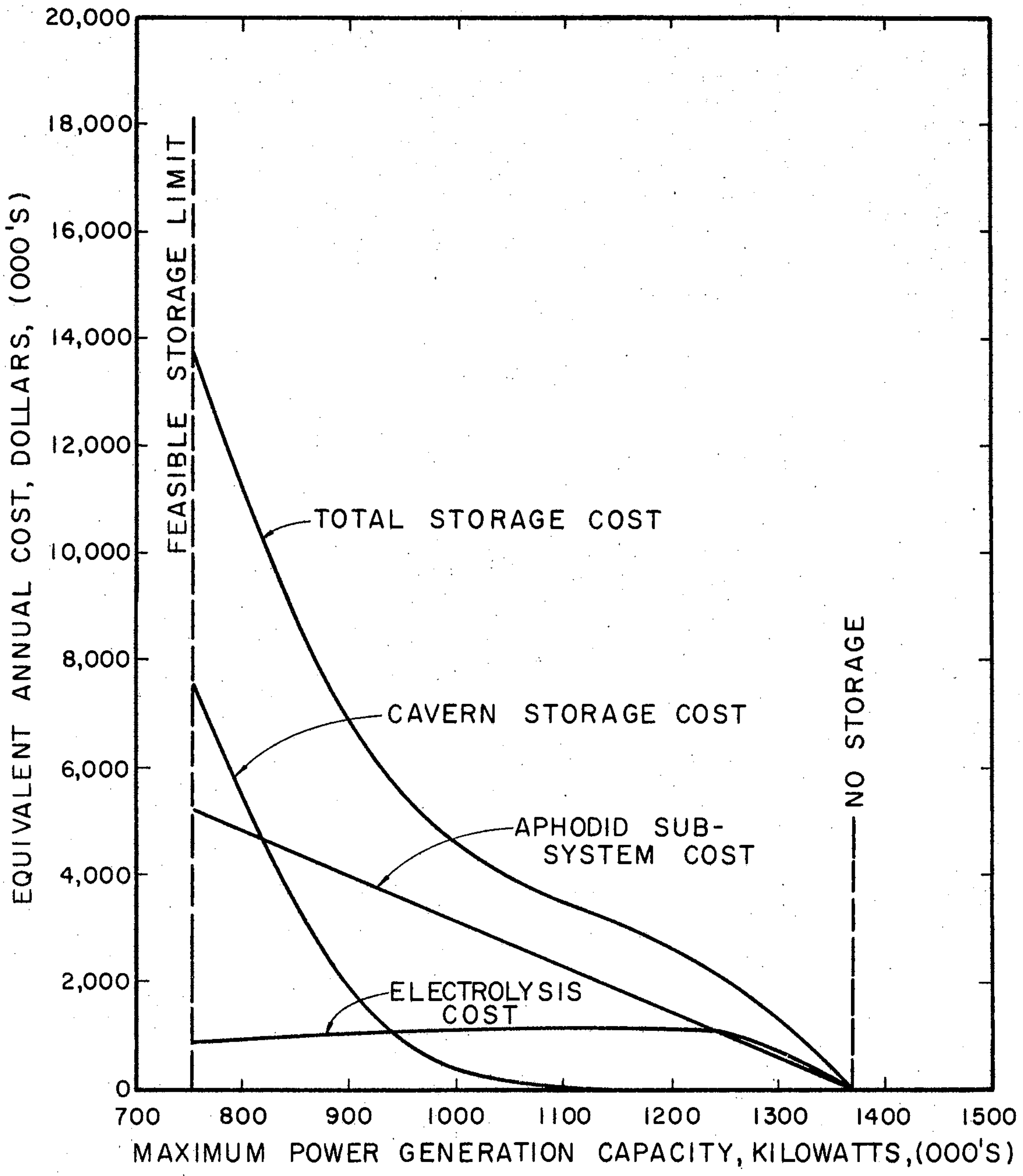


Figure 35. Storage Block Component Costs for Daily Storage Procedure
This data is for the 45 per cent storage block efficiency case.

"1100" and "1400" generation capacity the total system cost is fairly flat and only about five per cent beyond the zero-savings level ("$21,330" on the ordinate scale). The researcher elected to examine an improvement in efficiency at the optimum range level. Table VI shows the next study stage, Step Two.

TABLE VI

PARAMETER REFERENCE TABLE

Parameter	Initial Step	Step Two
Demand Curve	original	same
Power Plant Cost	- same for both -	
Storage Costs	- same for both -	
Efficiencies	0.4585	0.5643
Input	0.9500	0.9500
Cavern	0.9900	0.9900
Output	0.4875	0.6000

The overall results are shown in Figure 36 for the second step. It is observed that the total system cost line is lower than for the step with the lower storage block efficiency, but there are still no savings. The increase in efficiency does not have a proportional increase in savings. The total system cost lines must be below the zero-savings line at some point to obtain savings. The ordinate values between the total system cost lines and the zero-savings line are the annual losses which occur from use of the proposed system with storage. On the other hand the ordinate values between the zero-savings line and the total fuel and power plant cost line are the maximum costs for the total storage system to achieve break-even between storage and no storage systems by generation levels.

In step two the research user evaluated the effects from an increase in storage block efficiency. The system is determined as economically infeasible. The research user can now again increase the efficiency. However, in this case of an aphodid sub-system, the 60.0 per cent figure represents the best efficiency case because of thermal limits to efficiency. The research user's remaining direction for potential feasibility is an examination of the cost parameter which is the third step.

Figures 37 and 38 indicate the storage costs with a breakdown by components. Figure 37 is a graph of storage cost details for the cyclical storage procedure; Figure 38 is for the daily storage procedure. Both graphs are the costs for the second aphodid study. The research user now refers to the "transpositioned fuel and plant cost" line in his evaluation of the cost parameter for feasibility. The fuel and plant cost line is the line of maximum storage costs for economic feasibility. System feasibility in terms of the cost parameter requires that the total storage block costs be below this line of maximum storage costs.

For example, the user refers to Figure 37 at the "1150" point on the abscissa scale. At this point the line of

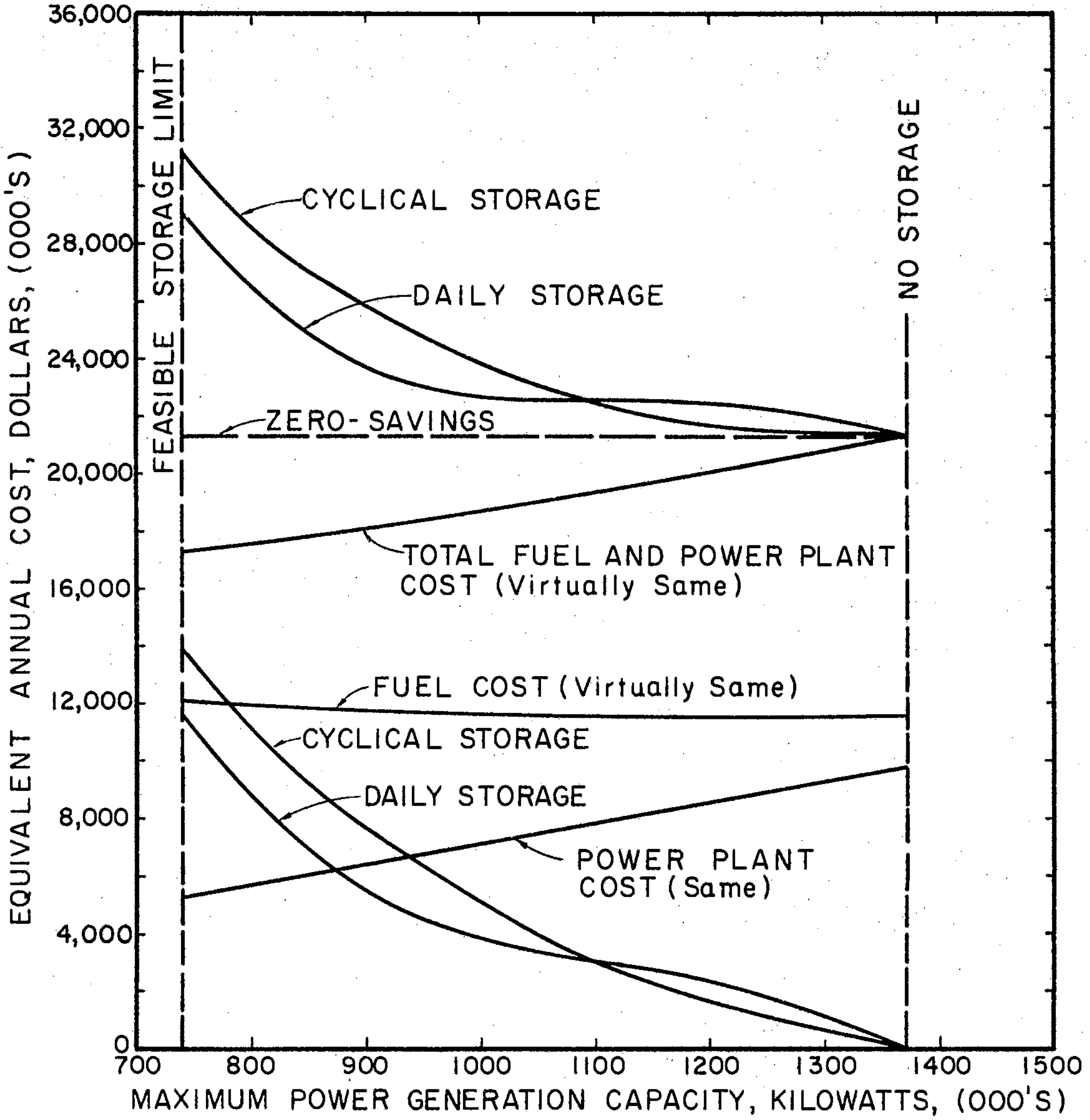


Figure 36. The Effects of Storage Procedures on Total Annual Costs of Energy System This data is for the 56 per cent storage block efficiency case.

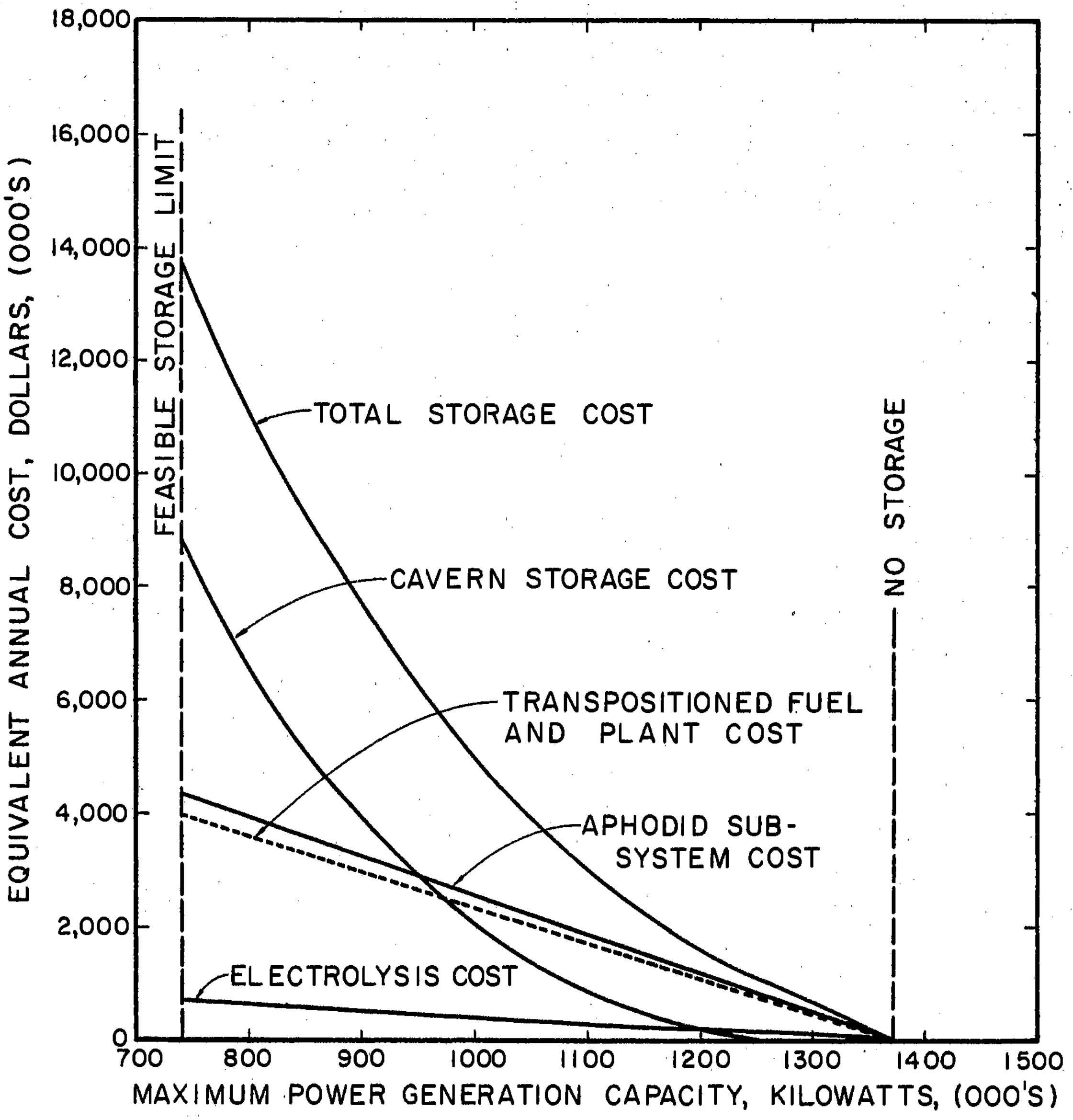


Figure 37. Storage Block Component Costs for Cyclical Storage Procedure
This data is for the 56 per cent storage block efficiency case.

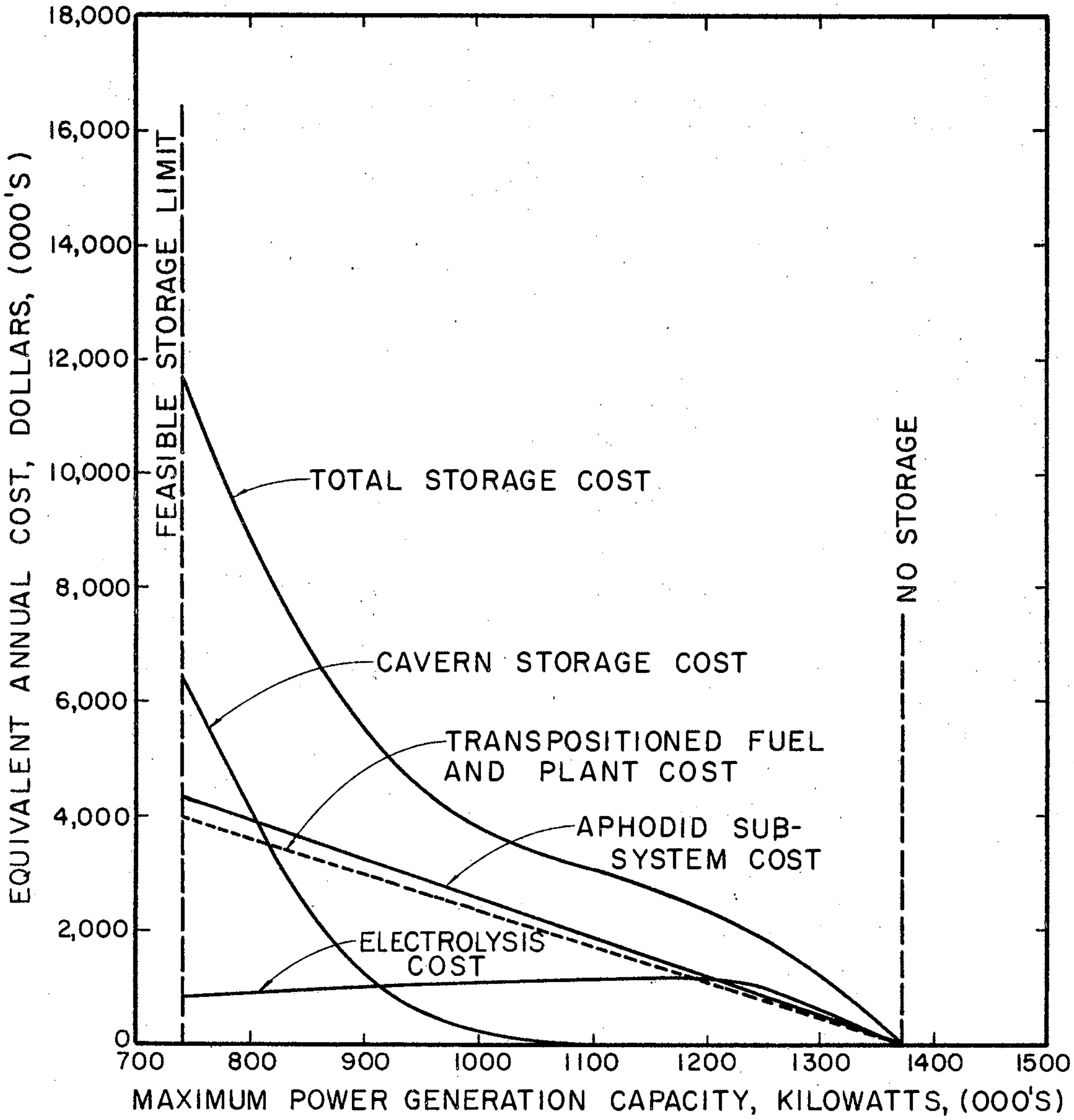


Figure 38. Storage Block Component Costs for Daily Storage Procedure
This data is for the 56 per cent storage block efficiency case.

maximum storage costs is approximately fifty per cent of total storage costs. The user now needs to re-examine the annual costs of unit capacity for possible reduction. For zero savings it is necessary to reduce all component costs fifty per cent, or enough of a component to reduce the total storage cost to the line of maximum costs.

The steps for evaluation of a storage technology's feasibility are demonstrated in this section for the research-and-development engineer. The first step examined, and rejected, system feasibility in terms of all reasonably expected parameters. The second step evaluated, and rejected, system feasibility in terms of the boundaries of the storage efficiency parameter. The study's third step examined the boundaries of the cost parameter (for the high efficiency example). Depending upon which maximum power generation level is appropriate, the average value for required cost reduction is at least fifty per cent. The demand curve, fuel conversion efficiency, and fuel cost are kept constant between the studies. If these last three parameters are representative of the typical application environment, the research user has the current and boundary condition information necessary for a feasibility decision or for a decision about the research emphasis direction.

Application of Uncontrolled Input Model

This study is oriented towards both the research-and-development engineer and the design engineer, whose problem areas concern the feasibility of energy systems with storage which utilize an unconventional energy source. In this case, the storage technology might be commercially available with results needed for evaluation of a proposed method of generation. Or, when practical generators and storage equipment are available, the problem is the economic feasibility for the particular region's power density pattern of the energy source. These results are also used to demonstrate the simulation model design principle of trade-off between over-generation and storage.

For this demonstration study, the original demand curve of Figure 8 is used. The additional parameter for this model is the power density function for the generation block. In this study the power density function is uniform across the year at 0.10 kilowatts per square foot. The study of a conventional plant with a pre-defined generation pattern is a typical example of such a generation pattern. Table VII lists the parameter values for this study. The demonstration costs are ideally low for the purpose of trade-off emphasis. There are no fuel costs.

Figure 39 is the graph which charts the energy system's surplus energy generation. When the line is below the zero ordinate value, the demand curve cannot be satisfied. At zero, the demand curve is satisfied with the least capacity of generation equipment. Above zero, the demand curve is satisfied with more generation equipment than necessary. Surplus energy is available from this "over-satisfied" case.

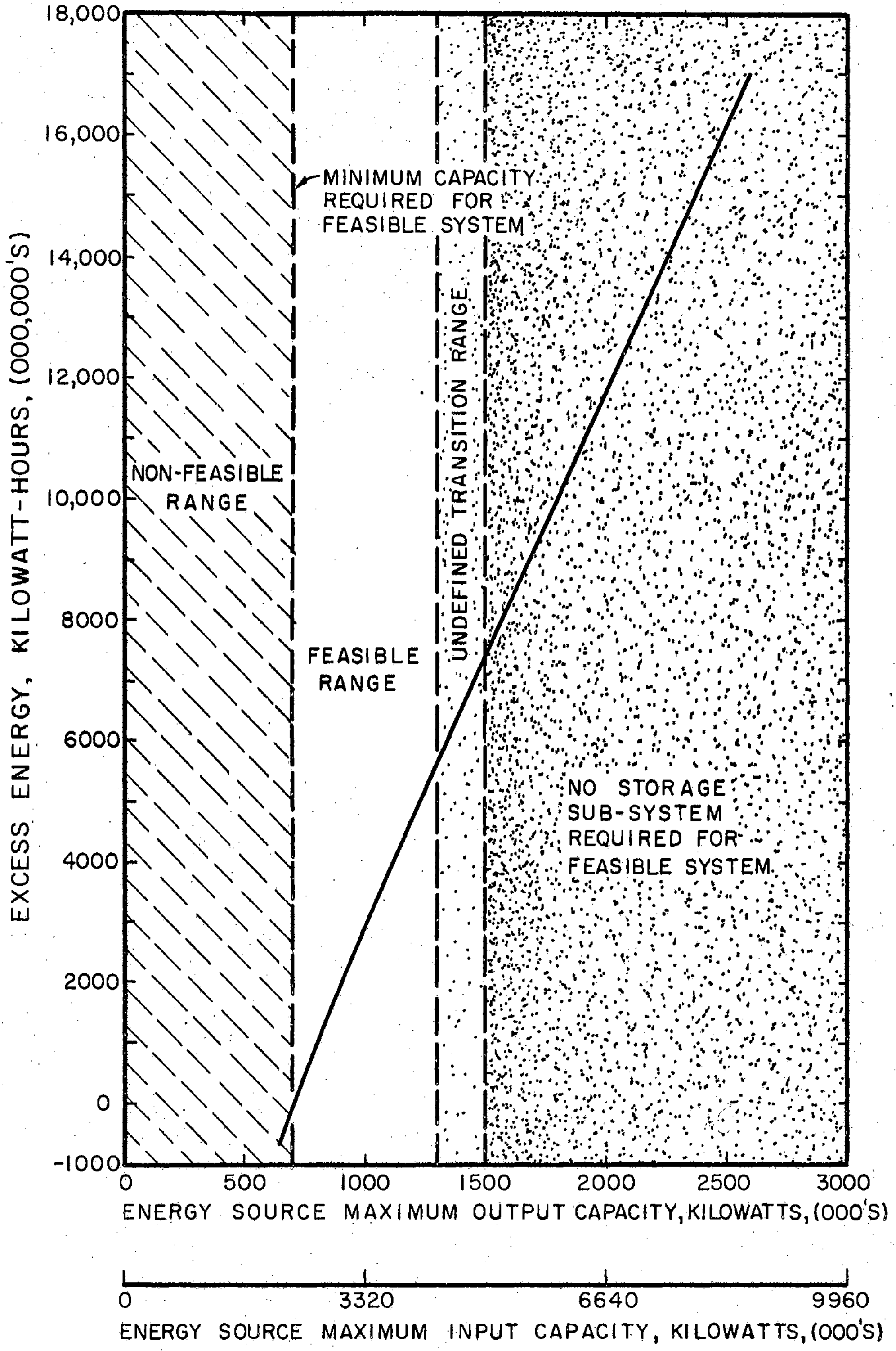


Figure 39. The Effects of Uncontrolled Input Generation Capacity on Energy System Surplus Energy

TABLE VII

PARAMETER REFERENCE TABLE

Parameter	Study Value
Demand Curve	Original
Power Density	Constant
Storage Efficiencies	0.5643
Input	0.9500
Cavern	0.9900
Output	0.6000
Annual Costs/Unit Capacity	
Input	1.0000
Cavern	0.01251
Output	1.0000
Generator	7.1434
Conversion Efficiency	Figure 14

When the line crosses into the "no storage required" area, the system is "super-satisfied" with more generation equipment than is utilizable. The "feasible range" area in this graph is the area for least cost trade-off of generation and storage equipment.

Figures 40 and 41 specify the capacity requirements of the storage components. The lines are economically valid only in the feasible range area. Figure 40 portrays the nature of exchange between fuel cell and electrolysis requirements which is a result of the application of the daily storage procedure for the uncontrolled model.

Figure 42 demonstrates the uncontrolled model's premise of trade-off between storage and generation for the

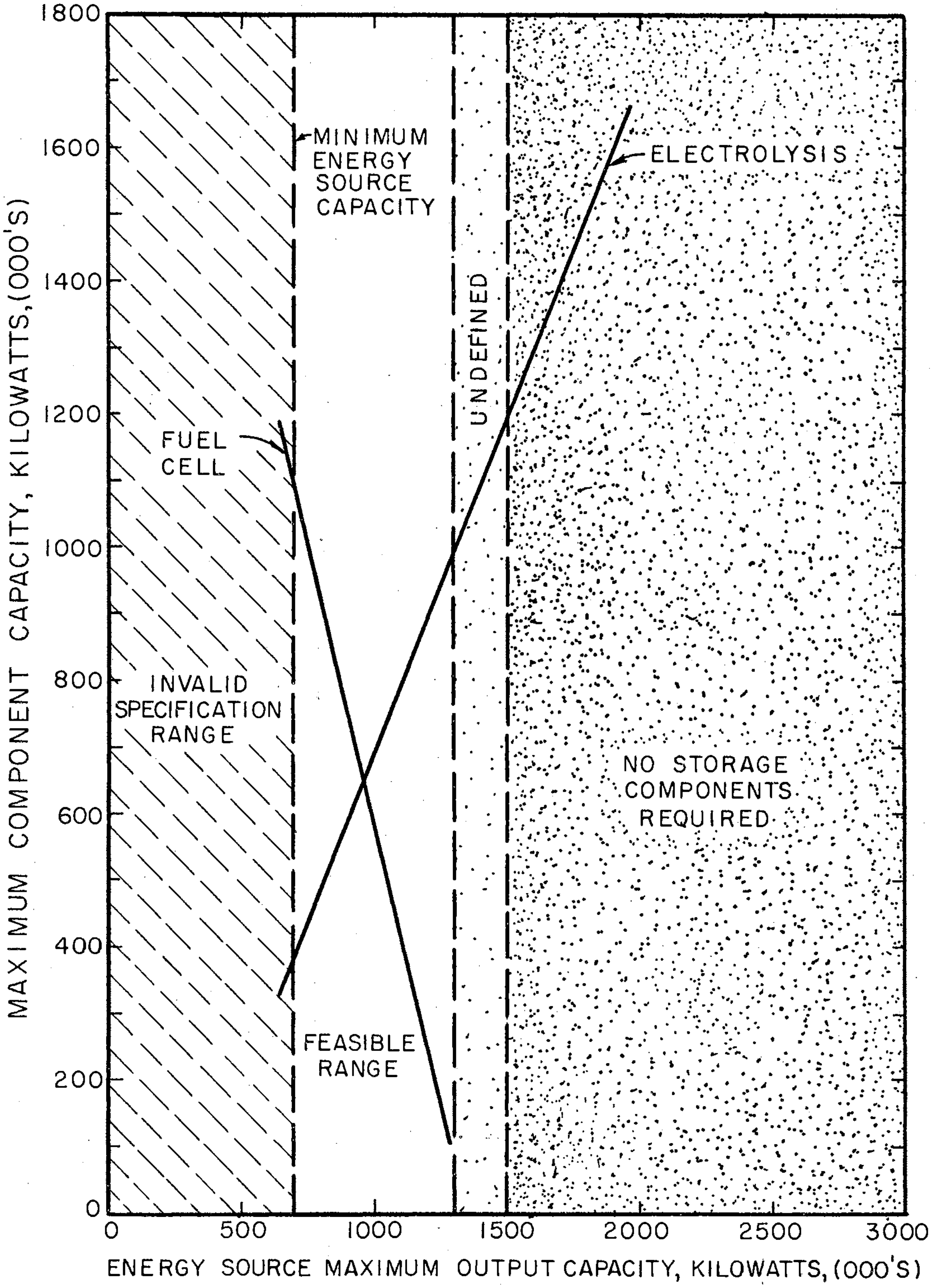


Figure 40. The Effects of Uncontrolled Input Generation Capacity on Fuel Cell and Electrolysis Requirements

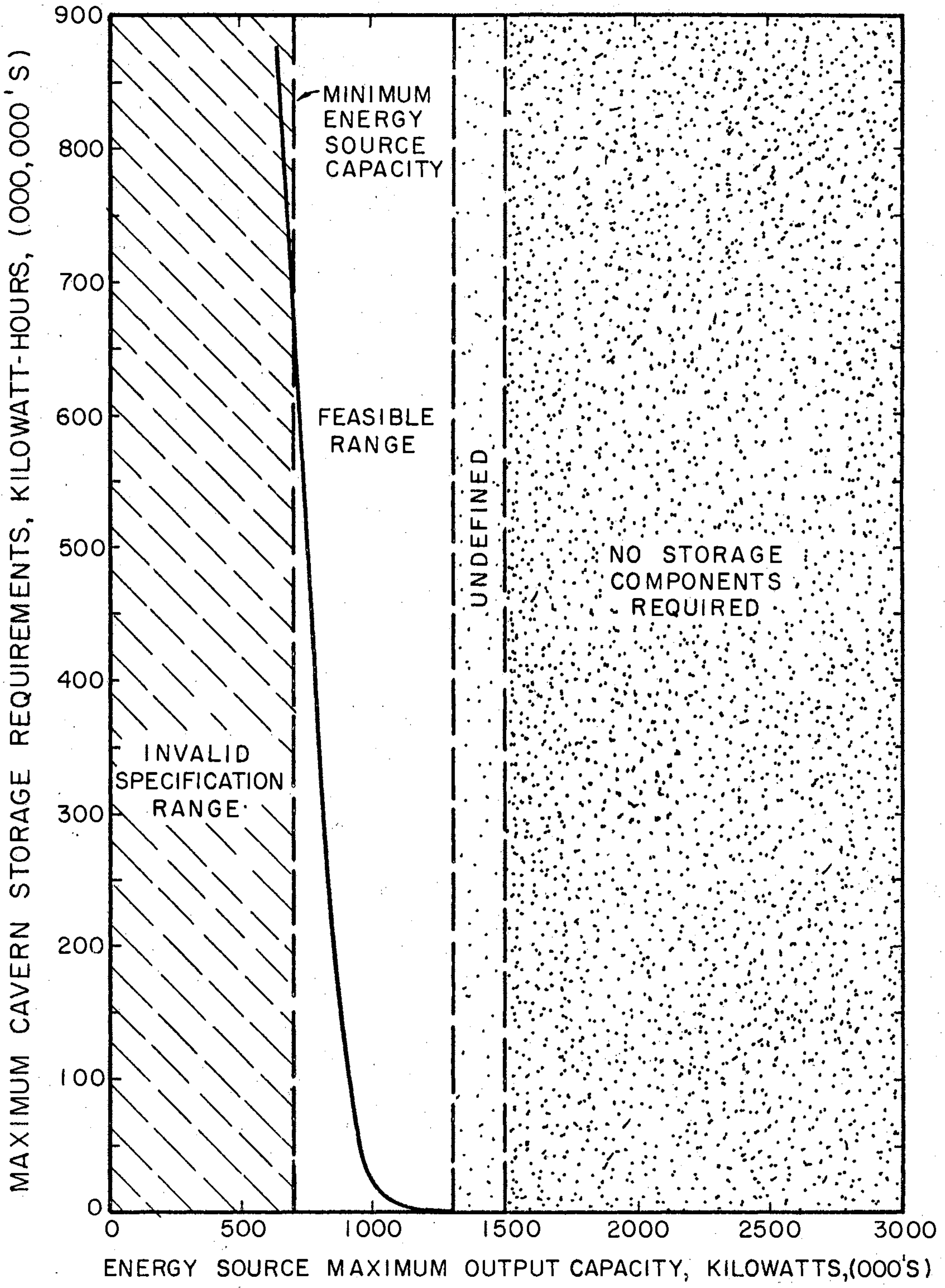


Figure 41. The Effects of Uncontrolled Input Generation Capacity on Cavern Storage Requirements

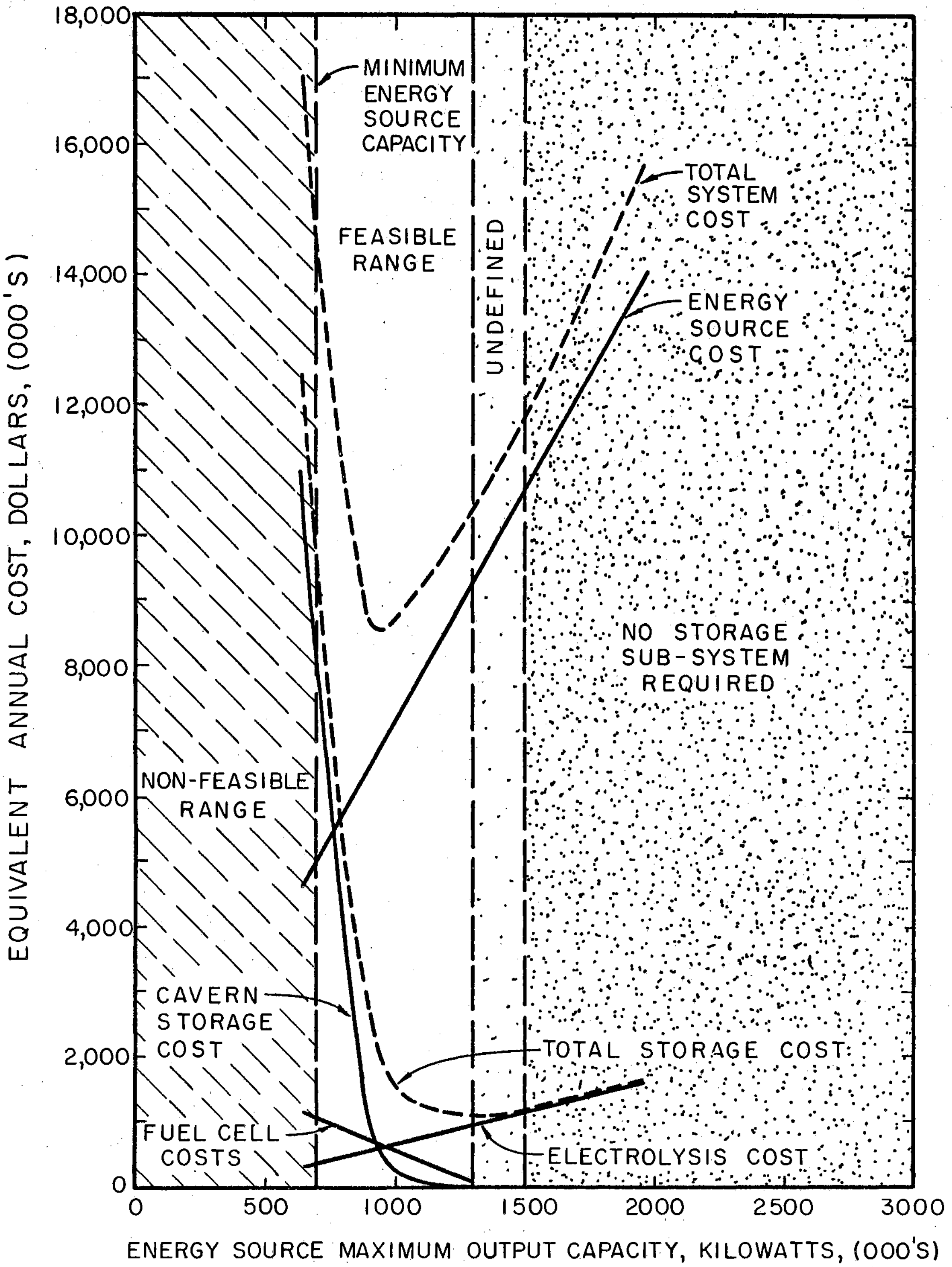


Figure 42. Total Annual Costs for Uncontrolled Input Energy System

uncontrolled model. Even though more than enough energy is generated, over-generation is more economical in terms of total system cost of operation. It is also noticed that there is no cost for fuel. The elimination of this major cost element is the factor which grants the system potential when generation technologies become more commercially available. Fuel cost for a conventional plant is in the range of fifty per cent of annual costs. Thus, the elimination of this cost element "allows" an increase in all equipment costs while economic feasibility is still possible.

Remarks on System Development

This chapter serves for demonstration of the application of these models by research users. The range and nature of possible research applications are shown by examples. These applications also indicate the system simulation design's capabilities in meeting those simulation system design criteria pertinent to the user. The first studies of demand curve and efficiency variations indicate the capabilities of the simulation system to answer design engineer questions.

It is necessary, however, to evaluate the worth of these changes for comparative system aspects as in the third study about an aphodid storage technology. In this third study, with a fixed demand curve, the boundaries for efficiency and for equipment costs determine the limits for an economical energy system. By this approach, the research user can determine his minimum limits of equipment performance for a successful system. The engineer can also reject a technology as either or both physically and economically impractical.

The design or research engineer must first recognize the fact that generalized deductions about energy conversion with storage systems are invalid, as shown by the four actual studies of this chapter. The complex interrelationships of individual storage component efficiencies, demand curve shapes, equipment costs, fuel conversion efficiencies, and fuel cost are such that explicit prediction is impossible. It behooves the engineer to make simulation studies <u>before</u> energy system predictions; the resultant predictions are then relevant only to the set, or closely similar set, of input parameter values involved in the simulation studies.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The conclusions from this research divide into several categories. These categories concern (1) the evaluation of the simulation system, (2) the results of the actual simulation studies, and (3) some general considerations about energy conversion and storage systems. The last sections of this chapter discuss the directions of future research.

Simulation System Conclusion

The design of this simulation system, including the derivations of the system simulation models, successfully achieves the specific goal of this dissertation in Chapter I. In studies of balanced energy conversion and storage systems, the determined results include the interrelationships and effects of parameter: variations in the demand curve; modifications of storage component costs; alternatives in procedures of storing energy; differences in the nature of the energy source; and changes in generation conversion efficiencies and, also, cost of fuel. With these analysis capabilities, different storage technologies can be analyzed for their physical requirements. Storage technologies can be evaluated for economic optimization of the balance between generation and storage capacities on the basis of annual energy demand. Additionally, the simulated system information is available to the research user in suitable dimensions and an easy-to-interpret presentation. The computer costs are moderate for a simulation study.

Limitations of Simulation System

The dispatching of particular generation units on a daily or weekly basis is not within the scope of this model. Therefore, for any given day the decisions about the mix of generation units and use of energy storage is not possible (except in terms of the annual balance of equipment). These short time sub-optimal decisions are made directly on a marginal cost basis. Whenever storage facilities already exist in the energy system, the economic choice of generation versus storage can be examined by use of the simulation models for a demand curve "year" of a day or a week. (This type of economic study requires the use of an appropriate scale for the generation fuel conversion efficiency table in terms of the capacity loading of that season of the year.) In such economic assignments of storage facilities, the utilization of storage equipment is increased; the yearly requirements of storage still exist for the balanced storage system. Dual usage of storage equipment is possible except for the peak capacity generation periods of the year.

Simulation Study Conclusions

All of the conclusions in this section are related to the implications of the actual case studies in Chapter VII. Extrapolation of this data to any energy system application requires consideration of the new conditions of parameter values.

Variation of Demand Curve

On the basis of the results of the actual studies, the inference is that decreased variation in the demand curve requires storage components with lesser capacities. However, this conclusion does not necessarily imply a lower cost energy system since decreased demand curve variation coexists with decreased generation capacity requirements. On an opposite basis, storage and generation equipment capacity relationships increase when demand curve variation increases. An economic feasibility decision is possible only by a cost study for the whole set of conditions of an individual energy system.

Modification of Storage Block Efficiencies

Based on the studies presented in Chapter VII, the inference is that an increase in the overall efficiency of the storage block causes lesser requirements of storage component capacities. However, there is no indication that the gain in total system savings is proportional to the increase in storage block efficiency. An economic decision is possible only by a cost study of the increased cost of the storage block versus the worth in savings in cost of the total system.

Aphodid Case Study

In the first aphodid study step, the economic feasibility is evaluated for a representative demand curve, set of storage efficiencies, and unit-capacity costs. The system is economically rejected for this set of parameter values. The maximum storage efficiency boundaries are examined in the next computer study. For this second step the system is also economically rejected.

By analytical extension, the break-even cost boundaries of the storage equipment are examined in the third step evaluation (at the maximum efficiency boundary). The system is still economically rejected. A reduction in unit costs averaging fifty per cent or more is required for economic feasibility as indicated by this analysis. The other major input variable is the demand curve. No modifications are made for this parameter, since it is representative of this region.

At the optimum boundary values of the major input variables, an aphodid sub-system storage technology does not approach economic feasibility for a controlled input generation with storage power plant. On the basis of present costs, therefore, the conclusion is that an aphodid subsystem storage technology of this configuration offers no potential to economically feasible energy conversion and storage systems which utilize conventional energy sources. This study does demonstrate the simulation system's low cost advantages for examination of the potential of a future research direction.

Fuel Effects

As a result of storage block efficiencies less than one hundred per cent, the total generated kilowatt-hours increase as the capacity of storage operations increase. At the same time the cumulative efficiency of fuel conversion tends to increase as the system load decreases; of course, these considerations are dependent upon the existing generation unit ratings.

Fuel effects from the total energy system are heavily affected by the demand curve, storage block efficiency, generation fuel conversion efficiency, and cost of fuel parameters. The number of present computer studies are insufficient to project generalizations about fuel effects. The current studies indicate relatively uniform fuel costs down to the mid-ranges of the storage and generation balance of capacities. The indications are that total fuel costs are not a major factor in the economic decision even though fuel costs tend to increase as generation capacity is reduced. Tentatively, on the basis of annual demand, fuel effects do not contribute significantly to cost advantages in energy conversion and storage systems. The implications, however, are that savings in fuel costs exist for the daily dispatching of generation within the conversion and storage system that is based on annual demand. More studies are needed over wide ranges of parameter values of hypothetical or actual conditions to examine the effects on fuel consumption and annual fuel costs.

Daily and Cyclical Storage Procedures

The capacity requirements of storage output components are not affected by storage procedures. Cavern storage requirements are greater for the cyclical storage procedure than for the daily storage procedure. Input component capacity requirements are less for the cyclical storage procedure than for the daily storage procedure. These capacity requirements, in physical terms, have little meaning to the economic feasibility of an energy system. Total system cost analysis comparisons of the relative component costs are the basis for the most economic storage procedure determination with regard to any given storage technology.

General Considerations of Storage Procedures

This section is concerned with the broader implications about design and economic feasibility of the selection of a storage procedure for an energy system. Quantified verification is needed for evaluation of some of the relevant factors in a specific installation.

The surface interpretations from actual studies indicate some likely advantage for the daily storage procedure. In an energy system operation, however, there are some less tangible considerations which cause cyclical storage procedure to have favorable advantages. "Cavern storage" is a "non-moving" component and is less likely to be subject to wear, replacement, and varying efficiency levels. The operating reliability of cavern storage is probably higher than other storage components.

Use of a cyclical storage procedure requires the minimum capacities for the input components. With cyclical storage the input capacities increase with the decrease in generation capacity, and the input components are also less erratic in capacity range movements over time. More important, a cyclical storage procedure enables better operating practices of generation equipment assignments and fuel economy. The capacity level of base load is increased and the proportion of the year at base load is increased. A greater percentage of the total kilowatt-hours is generated at a lower system load percentage than the percentage for a daily storage procedure. Improvement in base-loading is especially relevant to nuclear generation plant aspects.

The handicap, of course, is the need for low cost cavern storage. That is, low cost in proportional terms of the total storage block cost. Additionally, an "universal" cavern storage technology is desirable to overcome kilowatt-hour capacity limitations like the acre-feet restrictions of pumped storage. The qualified conclusion is that "cavern storage" often acts as a barrier to new concept storage technologies. The constraint of "how to hold economically the potential energy" can limit the visualization of new approaches to input and output component research. Research is recommended in "cavern storage" concepts. More research is needed about the efficiency of storage where hydrogen is the contained energy.

Recommendations for Future Research

The directions of future research concern two general areas of effort. The first area includes modifications and developments of the simulation system and its supporting models. The second area indicates a number of potential study applications of the simulation system in energy conversion and storage problems.

Simulation System Research

The simulation models specify the worst case capacity values of the input and output components by levels of reduced generation capacity. The specification of the capacity values by hour across the year would provide useful information to the equipment design engineer. This level of detail would require at least an extra hour of computer-printout time. The programming approach would be the recording of these values on a chronologically-oriented auxiliary tape during each hourly computation within the main program.

There is an alternative approach which requires less computer time; this approach offers less information to the design engineer. The approach still offers useful economic information for the practical operation of the power plant. This modification would list the ten or twenty highest values of input components and output components. Direct examination of these capacities would indicate whether or not the component requirements are significantly increased relative to the higher requirement range for only a few hours of the year. If so, a practical adjustment in power plant operations in the storage of energy would reduce storage component requirements with negligible change in other aspects of the energy system.

An extension of the simulation models is desirable for treatment of the sub-optimization problems of daily dispatching of generation units and possible use of storage energy. This extension would be a major research modification probably requiring large changes in the computational algorithms of the system simulation models. A complete new research design would include the annual economic balance of generation and storage equipment combined with the sub-balance assignment of energy production by generation or storage block for daily energy needs. Such a research extension would need to include the determination of capacities of storage block components, where necessary, on a daily basis for any incremental increases to the annual requirements.

The last area of simulation system research is improvements of the demand curve's parameter-curve program. After a number of research studies in different regions, changes in this program might be indicated. The changes might include new definitions of the demand curve parameters for a larger acceptance by the power industry. The changes might include the addition of new parameters for definition of the demand curve where research studies indicate pertinent effects on the design of storage facilities.

Simulation System Applications

This section outlines a number of areas for future research of an applied nature. The capabilities of the simulation system enable this exploration of varied storage technology concepts for economic feasibility. Some of these areas are of current concern as potential energy systems. These potential systems require economic analysis support for examination of fruitful directions of research.

The problem area of "universal" cavern storage is important especially in the design of uncontrolled input generation systems. Ideally efficient locations for unconventional energy source-generation are not always located where storage sites are economically available, or where the need exists in isolated locations. One such technology might be the design of a flexible plastic container for hydrogen which is held at a fixed level below a water surface. Investigations are being made in Europe for a storage system which pumps air-holds air-releases air through an air turbine for peaking generation [14]. Extensions of this design can include the use of water-filling the cavern for maintenance of pressure.

Wind generation is a well-developed technology. Feasibility studies might be made for wind generation and pumped hydro system combinations. Secondary level examinations of such systems could examine the feasibility of transmitting only the hydroelectric power to overcome the variation effects of wind.

Economic studies of wind generation and storage combined with conventional generation might be made. In this case, the demand curve would be divided into two segments for simulation studies. The upper capacity requirements of the peaking power supply of energy demand could be met by wind generation and storage. The bulk of the demand curve would be met by conventional generation.

Many of the problems of underdeveloped nations concern a high-value energy need which does not require a pattern similar to a typical demand curve in this country. Food preservation, irrigation, and pumping water from saturated areas are some examples. Studies of uncontrolled generation for uniquely shaped demand curves need to be made to evaluate system costs.

In the area of nuclear generation there is now an active need for a broad range of studies. The current and future growth in nuclear generation could be made more economically feasible with a suitable storage technology; for a discussion of this problem refer to "Current Research Studies in Nuclear Generation" in Chapter I. This range of studies could include a number of storage technologies and demand curve characteristics for economic feasibility at different locations.

On a broader conceptual basis, boundary studies of a national scale of energy storage could project the advantages and requirements for the future in electrical transmission research. In these studies the first input and last output components would be designated as long-range transmission lines with a suitable efficiency. By this method the simulation system could then evaluate the costs and equipment specifications for conceptual transmission and storage plans where large dam sites remote from the population centers would be used for peaking generation.

In the above paragraphs, a number of applied studies are suggested which utilize the simulation system of this dissertation. Some of the suggested studies have current need and some are problems of a longer-range view. This section chiefly serves to describe the usefulness of this simulation system for economic studies of energy storage systems. Obviously, there are a large number of other problem areas where the simulation system can prove useful to feasibility studies.

Recommendations of a Professional Nature

An underlying tenet of this dissertation is its role in the research function. By demonstration, an implied dissertation resultant is an expository enlargement of the potential role of industrial engineering for contribution to the initial stages of "hardware" research-and-development engineering projects. This demonstration of a research contribution in the nature of a production system is considered to be a desirable and significant goal for the industrial engineering profession in expansion of its interdisciplinary contributions to engineering accomplishments for the benefit of mankind.

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APPENDIX A

INFORMATION ABOUT COMPUTER PROGRAMS

Program listings and other information about the four computer programs may be obtained from:

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School of Electrical Engineering
Oklahoma State University
Stillwater, Oklahoma, 74074

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APPENDIX B

CONTROL AND DATA CARDS FOR COMPUTER PROGRAMS

This appendix lists and defines the control and data cards for each of the four computer programs. The system monitor cards and the computer program cards (source or object) precede the control and data cards. <u>Warning</u>: Punch nothing on any "ENDCRD" except "b9999.E+34"; see page 209.

Parameter-Curve Model ("PCURVE" Computer Program)

These cards immediately follow the "$ENTRY" system card in the numerical order as stated.

Note: "b" equals blank; the first symbol or number is column one of the 80-column card.

Sequence	Name and Definition	Format	Sample Value
1.	"NMPASS" — The number of modifications of the demand curve; a zero value is for analysis only of the original demand curve.	I10	bbbbbbbbb2
2.	"ADT" — The time interval in hours between demand curve values.	F10.6	bbb1bbbbbb
3.	"NDLPTS" — The number of demand values per day.	I10	bbbbbbbb24
4.	**"Demand Data Cards"** — The chronologically-ordered cards of demand curve values	6F10.2	bbbbb88822bbbbb99911bbbbb77733bbbbb66644bbbbb88822bbb1878744 (888.22 megawatts)

	in megawatts; the first card is the earliest time; the maximum number of cards is 8760; these values compose "DMDTBL" (Demand Table).		
5.	"ENDCRD" — End-of-data card.	E10.0(or 4PE10.0) ("F10.2")	b9999.E+34
6A.	"OPTDLY" — The operator parameter value for the day option;—5.5 for mean case;—11.1 for option bypass.	F10.5	bbbbb50bbb (50 per cent; decreases variation)
7A.	"OPTWEK" — The operator parameter value for the week option;—5.5 for mean case;—11.1 for option bypass.	F10.5	bbbb100bbb (100 per cent; variation same)
8A.	"KOPTPK" — The operator parameter value for the peakedness option; less than or equal to 50; greater than or equal to 1;—11 for option bypass.	I5	bbb11 (11 weeks)
9A.	"OPTBLK" — The operator parameter value for the bulkedness option;—5.5 for mean case;—11.1 for option bypass.	F10.5	bbbb150bbb (150 per cent; increases variation)

Note: The number of sets of 6, 7, 8 and 9 cards must equal the "NMPASS" number. In this case where "NMPASS" equals two, one more set of 6 through 9 cards is required. When "NMPASS" equals zero, there are no cards for 6, 7, 8 and 9.

6B.	
7B.	
8B.	
9B.	
10.	"$IBSYS"— A computer center system card; it is the last card.

Controlled Input Generation Under A Cyclical Storage Procedure System Simulation Model ("CYCOGE" Computer Program)

These cards immediately follow the "$ENTRY" system card in the numerical order as stated.

Note: "b" equals blank; the first symbol or number is column one of the 80-column card.

Sequence	Name and Definition	Format	Sample Value
1.	"B1PCT" — Percentage efficiency for "B1" storage component.	F8.4	bbbb4875 (48.75 per cent)
2.	"B2PCT" — Percentage efficiency for "B2".	F8.4	bbb1bbbb (100.0 per cent)
3.	"B3PCT" — Percentage efficiency for "B3".	F8.4	bbbb9900
4.	"STRPCT" — Percentage efficiency for "cavern storage".	F8.4	bbbb990b
5.	"A1PCT" — Percentage efficiency for "A1".	F8.4	bbbb99bb
6.	"A2PCT" — Percentage efficiency for "A2".	F8.4	bbbb99bb
7.	"A3PCT" — Percentage efficiency for "A3".	F8.4	bbbb99bb
8.	"ADT" — The time interval in hours between demand curve values.	F10.6	bbb1bbbbbb (1.0 hours)
9.	"DLRKWH" — Cost of purchased fuel per kilowatt hour.	F15.10	$$$$$¢¢¢¢¢¢¢¢¢¢
10.	"B1DLR" — Equivalent Annual Cost per kilowatt of capacity for "B1" storage component.	F12.6	$$$$$$¢¢¢¢¢¢
11.	"B2DLR" — "B2" cost (see number 10).	F12.6	$$$$$$¢¢¢¢¢¢
12.	"B3DLR" — "B3" cost (see number 10).	F12.6	$$$$$$¢¢¢¢¢¢

13.	"STRDLR" — Equivalent Annual Cost per kilowatt-hour of capacity for "cavern storage" component in storage block.	F12.6	$$$$$$¢¢¢¢¢¢
14.	"A1DLR" — "A1" cost (see number 10).	F12.6	$$$$$$¢¢¢¢¢¢
15.	"A2DLR" — "A2" cost (see number 10).	F12.6	$$$$$$¢¢¢¢¢¢
16.	"A3DLR" — "A3" cost (see number 10).	F12.6	$$$$$$¢¢¢¢¢¢
17.	"GENDLR" — Equivalent Annual Cost per kilowatt of capacity for the conventional power plant generation system.	F12.6	$$$$$$¢¢¢¢¢¢
18.	"GASTBL" — Table for generation fuel conversion efficiency; the first card is efficiency percentage at zero per cent system load, etc.; there must be 101 cards.	F10.6	bbbb3300bb (33 per cent)
19.	"ENDCRD" — High number value	E10.0 (or 4PE10.0)	b9999.E+34
20.	"Demand Data Cards" — The chronologically-ordered cards of demand curve values in megawatts; the first card is the earliest time; the maximum number of cards is 8760; these values compose "DMDTBL" (Demand Table).	6F10.2	bbbbb88822bbbbb99911bbbbb77733bbbbb66644bbbbb88822bbb1878744 (888.22 megawatts)
21.	"ENDCRD" — End-of-data card.	E10.0 ("F10.2")	b9999.E+34
22.	"$IBSYS" — A computer center system card; it is the last card.		

Controlled Input Generation Under A Daily Storage Procedure System Simulation Model ("DLYOGE" Computer Program)

The instructions for control and data cards are identical to the instruction for the Controlled Input Model under a cyclical storage procedure.

Uncontrolled Input Generation System Simulation Model ("UNCTRL" Computer Program)

These cards immediately follow the "$ENTRY" system card in the numerical order as stated.

Note: "b" equals blank; the first symbol or number is column one of the 80-column card.

Sequence	Name and Definition	Format	Sample Value
1.	"B1PCT" — Percentage efficiency for "B1" storage component.	F8.4	bbbb4875 (48.75 per cent)
2.	"B2PCT" — Percentage efficiency for "B2".	F8.4	bbb1bbbb (100.0 per cent)
3.	"B3PCT" — Percentage efficiency for "B3".	F8.4	bbbb9900
4.	"STRPCT" — Percentage efficiency for "cavern storage".	F8.4	bbbb990b
5.	"A1PCT" — Percentage efficiency for "A1".	F8.4	bbbb99bb
6.	"A2PCT" — Percentage efficiency for "A2".	F8.4	bbbb99bb
7.	"A3PCT" — Percentage efficiency for "A3".	F8.4	bbbb99bb
8.	"B1DLR" — Equivalent Annual Cost per kilowatt of capacity for "B1" storage component.	F12.6	$$$$$$¢¢¢¢¢¢

9.	"B2DLR" — "B2" cost (see number 8).	F12.6	$$$$$$¢¢¢¢¢¢
10.	"B3DLR" — "B3" cost (see number 8).	F12.6	$$$$$$¢¢¢¢¢¢
11.	"STRDLR" — Equivalent Annual Cost per kilowatt-hour of capacity for "cavern storage" component in storage block.	F12.6	$$$$$$¢¢¢¢¢¢
12.	"A1DLR" — "A1" cost (see number 8).	F12.6	$$$$$$¢¢¢¢¢¢
13.	"A2DLR" — "A2" cost (see number 8).	F12.6	$$$$$$¢¢¢¢¢¢
14.	"A3DLR" — "A3" cost (see number 8).	F12.6	$$$$$$¢¢¢¢¢¢
15.	"GENDLR" — Equivalent Annual Cost per kilowatt of capacity for the conventional power plant generation system.	F12.6	$$$$$$¢¢¢¢¢¢
16.	"PCTTBL" — Table for generation conversion efficiency of unconventional energy source; the first card is efficiency at zero per cent system load, etc.; there must be 101 cards.	F10.6	bbbb3300bb (33 per cent)
17.	"ADT" — The time interval in hours between demand curve values; greater than or equal to two hours.	F10.6	bbb2000000 (2.0 hours)
18.	"ENDCRD" — High number value.	E10.0(or 4PE10.0)	b9999.E+34
19.	"Demand Data Cards" — The chronologically-ordered cards of demand curve values in megawatts; the first card is the earliest time; the maximum number of cards is 4380; these values compose "DMDTBL" (Demand Table).	6F10.2	bbbbb88822bbbbb99911bbbbb77733bbbbb66644bbbbb88822bbb1878744 (888.22 megawatts)
20.	"ENDCRD" — End-of-data card.	E10.0 ("F10.2")	b9999.E+34

21. "Power Density Data Cards" —6F.10.4

bbb8882222bbb9991111bbb7773333bbb6664444bbb9991111bbb8882222

(888.2222 kilowatts per square foot)

The chronologically-ordered cards of power density values *in kilowatts per square foot* of the *potential* energy of the unconventional energy source received at generation system; the first card is the earliest time; the maximum number of cards is 4380; these values compose "PRDTBL"; the number of cards should equal "DMDTBL"; the chronological order must be identical to "DMDTBL".

22. "ENDCRD" — End-of-data card. E10.0 ("F10.4") b9999.E+34

23. "$IBSYS" — A computer center system card; it is the last card.

General Information About Deck Arrangement

This section is applicable to all four computer programs. All six fields of Demand Data and Power Density Data cards must be utilized regardless of the "ADT" interval. This does not apply to the respective, last data card when the number of values are not an even multiple of six.

Whenever the last data card of the Demand Data (or the Power Density Data) does not use all six, ten-column fields, the "ENDCRD" value *must* be entered in the first-available blank field of the data card. The value entered within the field is "b9999.E+34" ("b" equals blank). In this situation the subsequent end-of-data "ENDCRD" card must *not* be used; this does not affect the high-number value "ENDCRD" cards.

APPENDIX C

RUNNING TIMES FOR COMPUTER PROGRAMS

The running times tend to vary somewhat because of handling time. The "PCURVE" running time is additionally affected by the number of modified demand curve decks, the number of selected options, and the choice of options.

The compilation time is necessary for program source decks; preparation of object decks save this machine time. The following listing indicates sample running times for maximum size decks of demand curve data.

Program	Demand Curve (number of values)	Compilation Time (hours)	Load and Execution Time (hours)
1. CYCOGE	8760	0.16	0.44
2. CYCOGE	8760	0.12	0.46
3. DLYOGE	8760	0.08	0.10
4. DLYOGE	8760	0.08	0.10
5. UNCTRL	4380	0.09	0.08
6. UNCTRL	4380	0.10	0.08
7. PCURVE	8760	0.06	0.22
(1 modification deck, 3 affecting parameter options)			
8. PCURVE	8760	0.06	0.21
(1 modification deck, 1 affecting parameter option)			
9. PCURVE	8760	0.06	0.35
(2 modification decks, each with 1 affecting parameter option)			
10. PCURVE	8760	0.06	0.28
(1 modification deck, 4 affecting parameter options)			

APPENDIX D

ERROR MESSAGES AND OPERATIONAL WARNINGS

This appendix discusses the computer program error messages and general warnings about operational preparation. Most errors are prevented by following carefully the preparation instructions for the computer control and data cards in Appendix B.

General Warnings

This information applies to all four computer programs. Each program lists a series of internal test messages before the computer output pages as described in Chapters IV and VI. On the last output page of each program is the phrase, "THATSALLSHEWROTE"; the computer center's time analysis follows this page as the last printed page.

The demand curve data must be in megawatts and in time-increasing chronological order. Original source demand data may require conversion to a suitable scale and format. The order of these cards can be numbered in the right-hand card columns. These preparation steps are necessary prior to input use for any of the four computer programs.

Unless otherwise specified, input data follows the conventional right-adjusted fields.

If difficulties arise or changes are desired, reference should be made to the listings of computer program instructions. These listings include many comment cards at various points in the program in order to clarify the logical steps.

Whenever any program is used for demand curve durations less or more than a year, the research user must adjust his interpretations of the computer output and heading definitions. All input card values must be appropriate to the demand curve deck and duration. No special efforts are necessary except that (1) extra consideration is needed for Equivalent Annual Costs of equipment, if most accurate costing is desired, and (2) the fuel conversion efficiency table is suitably adjusted for the scale-of-plant.

PCURVE Computer Program

The demand curve data cards generated by this program are numbered for chronological sequence in the right-hand six columns of the punched card.

Whenever an operator parameter modifies any demand curve value so that the demand value is less than ten kilowatts, an error message occurs. This situation can arise when the variation of a demand curve is being increased. The purpose is to prevent negative demand curve values since they are logically invalid and unacceptable to the simulation models. After printing this error message, the program aborts the current modification of the demand curve, and proceeds to the next modification set of demand curve operator parameters, if any. For example, if the original value for NMPASS were two under this situation, then the resulting number of modified demand curves would be one.

The algorithms of this program require <u>complete</u> sets of daily demand values, i.e. the ADT ("hourly") values making up each day. However, demand values for a day, week, or more can be missing and the program will still operate as if the <u>end</u> of the "year" were missing data for days or weeks. The research user should prepare with care a complete demand curve deck for the duration of demand suitable to his investigation.

CYCOGE Computer Program

A listing of the generated BLLVL (below-level) table is printed before the computer output pages in Chapter VI. The last two values of this print-out are not relevant.

The generation fuel conversion efficiency table must have 101 values. Cost of fuel is in dollars per kilowatt-hour relative to the understood decimal point of the input card. Equipment costs are based on Equivalent Annual Costs per unit of capacity at some rate of return on investment. For approximate purposes, the rate of return can be zero per cent. Storage component efficiencies are decimal percentages relative to the understood decimal point.

DLYOGE Computer Program

The warnings here are similar to those for the CYCOGE program except that there is no BLLVL table.

UNCTRL Computer Program

The research user needs to take care in preparation of the demand curve deck and the power density deck. They should be equal in length; they must be in the same chronological order. An error message occurs when the number of points are not equal. The program then selects the smaller number and continues operation. If the difference is only a few points, it is not likely that the error is significant.

The demand curve values are in megawatts. The power density curve values are in kilowatts per square foot.

An error message can occur when the first-row value of XTRKWH is not negative. This is a hypothetical situation.

An error message occurs when the generated kilowatt-hour output times five cannot satisfy the demand curve because of too low storage block component efficiencies. This error message overrides the caption for the interpolated line of the just-feasible energy system; it supersedes any computed results.

VITA

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