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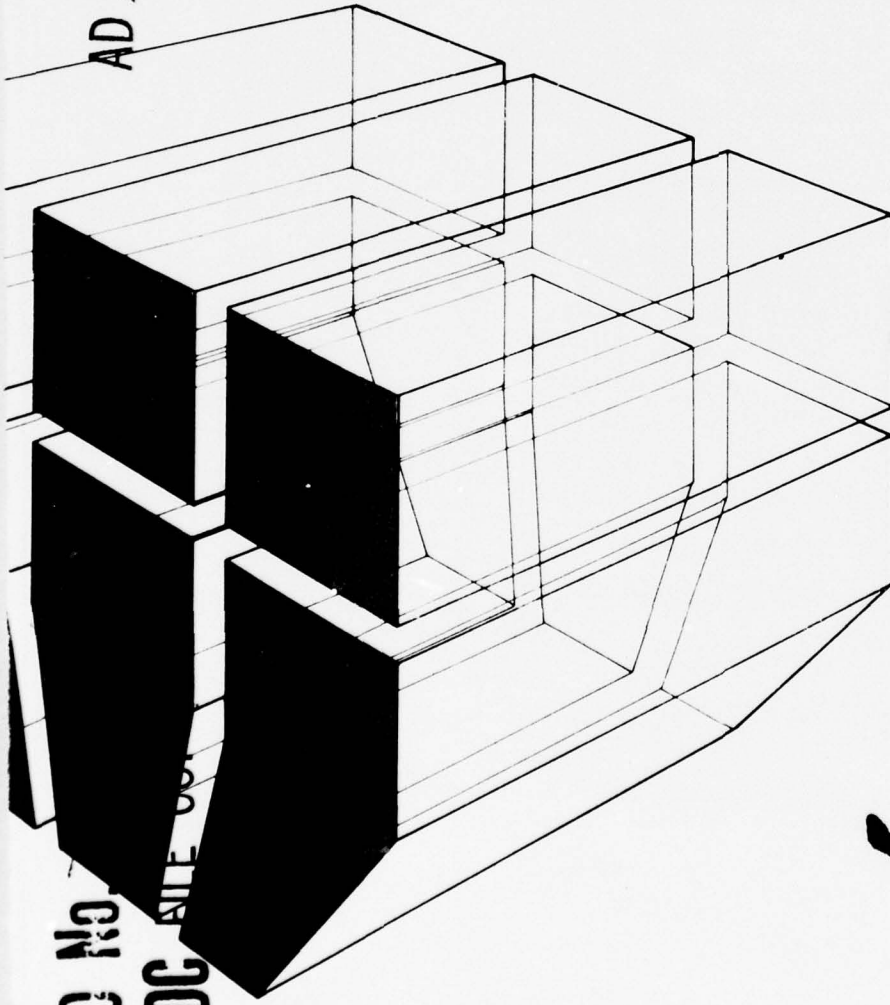
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June 1977
Development of Total Energy and Total Utility Systems
for Military Facilities

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USE OF THE BUILDING LOADS ANALYSIS AND
SYSTEM THERMODYNAMICS PROGRAM TO
PERFORM TOTAL ENERGY SYSTEM ANALYSIS

by
Douglas C. Hittle



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes a systematic procedure for applying the Building Loads Analysis and System Thermodynamics (BLAST) computer program to perform energy and life-cycle cost analyses of conventional, total energy, and selective energy systems as they might be applied to meet the energy demands of buildings or groups of buildings. The iterative application of this computer tool to permit the selection of nearly optimal candidate systems is described, and use of the program to estimate the performance of specific components during final plant design is outlined. The BLAST program and methods for its effective use are designed to support the engineering efforts required to implement guid- <i>→ OVER</i>		

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ance issued by the Office of the Chief of Engineers (*Engineering Instructions for Preparation of Feasibility Studies for Total Energy, Selective Energy, and Heat Pump Systems*, 1 July 1975). In addition to the prediction of space energy demand and the simulation of various air distribution systems, the BLAST program can simulate the performance of central energy supply systems consisting of any or all of the following components: diesel engine generators, gas turbine generators, steam turbine generators, centrifugal or reciprocator chillers, absorption chillers, double-bundle chillers (heat pumps), boilers, solar collectors, hot thermal energy storage, cold thermal energy storage, and utility company power.



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FOREWORD

This work was performed for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under Project 4A762719AT41, "Design, Construction, and Operations and Maintenance Technology for Military Facilities"; Task T6, "Energy Systems"; Work Unit 012, "Development of Total Energy and Total Utility Systems for Military Facilities." The applicable QCR number is 1.05.005. Mr. H. Maschke was the OCE Technical Monitor.

The study was performed by the Energy Branch (EPE), Energy and Power Division (EP), U. S. Army Construction Engineering Research Laboratory (CERL). Dr. D. J. Levenenz is Chief of EPE and Mr. R. G. Donaghy is Chief of EP.

Appreciation is expressed to Dr. George Shih, mechanical engineer of CERL, for his efforts in developing engine part-load performance models, and the consultant Computation Bureau of San Francisco, CA, for their major contribution to the development of the central plant simulation program.

COL J. E. Hays is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director.

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USE OF THE BUILDING LOADS ANALYSIS AND SYSTEM THERMODYNAMICS PROGRAM TO PERFORM TOTAL ENERGY SYSTEM ANALYSIS

1 INTRODUCTION

Background

Recognizing that total energy systems offer the potential for more efficient use of scarce fuel resources, the Department of Defense (DoD) in 1974 issued a document¹ that required careful study of the feasibility of total energy, selective energy, and built-up heat pump systems for major new construction and rehabilitation projects. Following DoD's action, the Office of the Chief of Engineers (OCE) issued instructions² (hereinafter referred to as "OCE Instructions") to supplement the directive and provide additional guidance for preparing feasibility studies.

Implicit in the predictions of energy savings and the requirement to study total energy, selective energy, and built-up heat pump systems is the assumption that the potential performance of these systems can be predicted accurately and that such systems can be designed to operate at peak efficiency. In the past, the approach to designing energy systems was to satisfy peak demand without regard to part-load performance or variations in load profiles. Although peak demands must usually be satisfied, the use of peak demand alone is particularly unsatisfactory when considering total energy systems. Both load variations and part-load performance greatly affect total energy system efficiency, and thus must be considered in the design and performance analysis. The criteria for system evaluation must be based on annual energy consumption and not the ability to meet peak demand. Since the analysis must be made on an hourly basis, manual calculation of load profiles, equipment performance, and economics is too difficult and tedious to be practical.

The use of a computer program for performing these hourly performance calculations is the only feasi-

ble approach. However, there are several difficulties in this approach: (1) existing computer programs for making these calculations are not directly available to Corps of Engineers designers; (2) the proprietary programs available are difficult and expensive to use, cannot be directly used by Corps Districts, and are often inaccurate in one or more of the calculation modes; and (3) there is no methodology for applying computer programs to a total energy study.

Objective

The objective of this research was to develop energy and life-cycle cost-analysis tools and a computer-aided design method for District Engineer personnel and their architect/engineers to use in assessing the performance of candidate total energy systems, and for optimizing total energy system performance in the design phase in accordance with requirements of DoD Manual 4270.1-M and OCE's supplemental instructions.

Approach

The first step is meeting the research objective was to develop a user-oriented, fast-running computer simulation program for total energy systems. Existing computer programs were evaluated and the best available program was procured and modified to conform with the modeling requirements, including the requirement that the program interface with building load predictions and air distribution models developed under separate Army- and Air Force-funded work units. This simulation program is described in detail in a two-volume U. S. Army Construction Engineering Research Laboratory (CERL) draft report entitled *The Building Loads Analysis and System Thermodynamics Program (BLAST) Program*; Volume I is the User Instructions, and Volume II is the Program Reference Manual.³

The second step was to study several good total energy studies and develop a methodology for systematically analyzing candidate total energy systems so that the optimum system configuration could be established.

Finally, this report was prepared in order to describe systematically the methodology for using the BLAST program so that the optimum total energy configuration can be determined and energy and life-cycle

¹Modification of DoD Construction Criteria Manual 4270.1-M (Department of Defense, 13 September 1974).

²Engineering Instructions for Preparation of Feasibility Studies for Total Energy, Selective Energy, and Heat Pump Systems (Office of the Chief of Engineers, 1 July 1975).

³D. C. Hittle, *The Building Loads Analysis and System Thermodynamics (BLAST) Program*, Volume I: User Instructions and Volume II: Program Reference Manual, Draft Technical Report (U. S. Army Construction Engineering Research Laboratory, 1977).

costs can be compared with those of a conventional system.

Chapter 2 briefly describes the features of the BLAST program, Chapter 3 provides guidelines for using the program during the performance of feasibility studies, and Chapter 4 outlines methods of using it for detailed equipment and system performance evaluations necessary for final design.

Scope

This report provides guidelines for using the BLAST program to perform total energy, selective energy, and heat pump studies, and final design calculations. The report does not provide detailed instructions for preparing inputs for the program; these are presented in the BLAST User Instructions. Instead, this report focuses on the selection of candidate systems and the interpretation of program output, with the aim of optimizing the systems used for comparative study and the system finally selected for field implementation.

The methods described herein provide in part the necessary tools for complying with the OCE Instructions.

2 THE BLAST PROGRAM

General Description

The BLAST program is a comprehensive computer program for estimating hourly space heating and cooling requirements, hourly performance of fan systems, and the hourly performance of a central plant, total energy plant, and/or solar energy system. Figure 1 illustrates the general program flow. Apart from its comprehensiveness, this program differs in four key respects from similar programs that have been used for total energy studies.

1. The BLAST program uses extremely rigorous and detailed algorithms to compute both building loads and system performance. Many of the methods used are based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) algorithms,^{4, 5} however, many new algorithms, which

⁴*Procedure for Determining Heating and Cooling Loads for Computerized Energy Calculations* (ASHRAE, February 1975).

⁵*Procedures for Simulating the Performance of Components and Systems for Energy Calculations*, W. F. Stoecker, ed., 3rd ed. (ASHRAE, 1974).

represent improvements in the ASHRAE methods, have been included.

2. The program employs its own input language, which permits rapid input preparation in a completely unformatted English-like style. This language contains a library of all materials, wall and roof sections, and their properties found in the *ASHRAE Handbook of Fundamentals*.⁶ The user, by referring to these building components by name, is freed from the tedious task of inputting scores of numbers for each space or building. Similarly, the use of default equipment performance parameters permits the user to investigate generic systems easily and rapidly.

3. The program execution time is extremely brief, making the study of many alternative concepts relatively inexpensive.

4. The program is not proprietary and is therefore open to inspection by its users and those who are to rely on the results generated.

Simulation Capabilities

The BLAST program requires the general type of input data described in Sections 6 through 9 of the OCE Instructions, i.e., occupancy, lighting, and equipment usage schedules, description of the building(s), system design variables, hourly climatological data, etc. Detailed descriptions of data requirements and input preparation are presented in the BLAST User Instructions. The simulation methods are outlined in the User Instructions and documented in detail in the Program Reference Manual.

In addition to calculating the space loads and simulating a range of air-handling systems, the BLAST program is capable of simulating any thermodynamically feasible system consisting of any or all of the following central plant components:

1. Diesel engine generators
2. Gas turbine generators
3. Steam turbine generators
4. Centrifugal or reciprocating chillers
5. Absorption chillers (both one- and two-stage)

⁶*Handbook of Fundamentals* (ASHRAE, 1972).

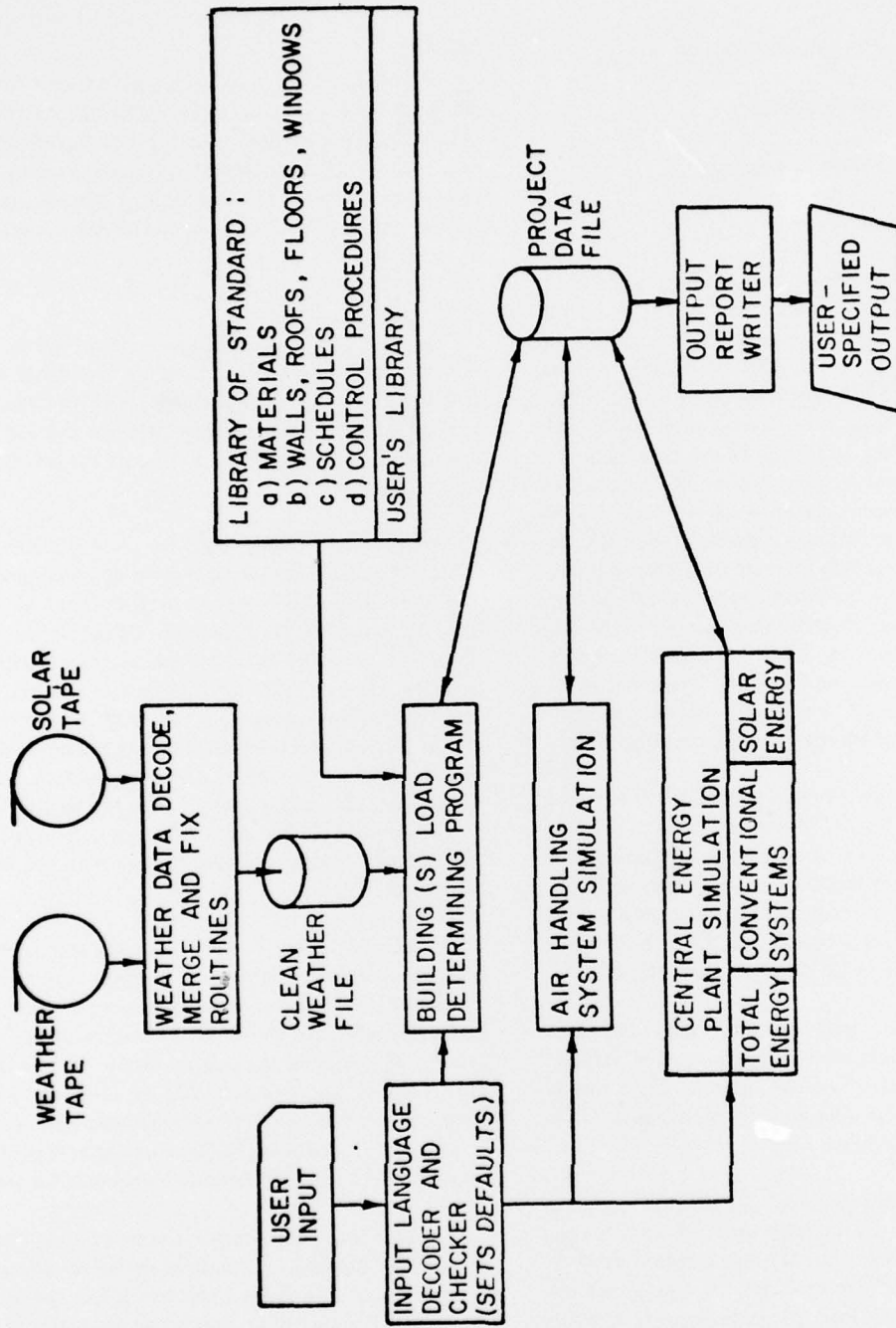


Figure 1. Flow diagram for the BLAST program.

6. Double-bundle chillers (heat pumps)
7. Boilers
8. Solar collector and storage tank systems
9. Hot thermal energy storage
10. Cold thermal energy storage
11. Utility company power

Thus, with the exception of engine-driven heat pumps and heat pumps using waste engine heat, the program user can configure all of the systems described in the OCE Instructions. Later versions of BLAST will include the required additional heat pump system simulation capability. Note that generic models for each component (based on data from several manufacturers) are present in the model, but the user may vary one or more sets of equipment performance parameters to allow the rigorous simulation of a particular manufacturer's product. This permits the user to study generic total energy plant configuration (diesel vs. gas turbine, for example) during the preliminary phases of the project without developing detailed equipment performance parameters. During the final design phase, detailed data can be used to assess any performance variations that may exist among different manufacturers.

In addition to performance analysis of variously configured central energy plants, the BLAST program computes life-cycle costs of each system option selected on the basis of user-supplied or default capital cost, maintenance cost, operating cost, and utility rate schedules. The BLAST program uses the OCE life-cycle costing method outlined in the OCE Instructions.

Default cost data have been provided only as a convenience for users who wish to become familiar with the economics of various options. *Users should not assume that these data are or will remain valid* for their particular application.

The principal outputs from the BLAST program (see Chapter 3) are (1) monthly totals of pertinent energy demands, (2) fuel or utility consumptions (always converted to source energy), and (3) equipment use statistics (average part-load ratio and number of hours of operation per year for each plant component) and life-cycle cost summaries.

3 USING THE BLAST PROGRAM FOR CENTRAL ENERGY PLANT STUDIES

Procedure

As with any complicated engineering problem, the study of central energy plants requires engineering judgment. The procedures described below illustrate a step-by-step approach for coupling engineering judgment with computer calculations that has been successfully applied to the study of central energy plants.

Step 1: Obtain Required Input Data for Predicting Building(s) Load Profiles

The first step in performing a central energy plant analysis is to determine the energy demanded in the building zones or spaces. The BLAST program uses weather data, user-supplied use profiles, and the user's description of the building to compute the hourly zone energy demands.

Hourly climatological data for an ASHRAE "Test Reference Year" are available from the National Oceanic and Atmospheric Administration (NOAA), Asheville, NC, for some 60 sites in the United States. Additional sites and years are also available from NOAA and from the Air Force Air Weather Service. Federal agencies and persons engaged in federally funded studies should contact CERL for assistance in obtaining the required weather data. The BLAST program requires that the weather data be computerized in the NOAA "1440 Series" format. Hourly solar radiation data in NOAA's "280 Series" format can also be used with the hourly weather data.

In addition to the weather data, user-supplied use profiles of space occupancy, lighting, miscellaneous equipment, and infiltration must also be provided. Note that these schedules do not include energy required for heating and cooling (i.e., fans, pump, chillers, etc.), since these energy demands will be computed by the program. Section 6 of the OCE Instructions outlines procedures for obtaining building use data. If available, measured data from similar buildings should be used.

The user must also supply a zone-by-zone description of the building or buildings under consideration. This description includes basic data about the properties of the building walls, roofs, windows, floors, etc., and a definition of the internal loads and temperature control in each space. Note that this input is consider-

ably simplified by the availability of predefined walls, roofs, floors, windows, materials, etc., in the program library. The building plans and the ASHRAE *Handbook of Fundamentals* are the major sources of information used in inputting a building description.

Step 2: Use BLAST to Obtain Space Loads

When the required data have been assembled and correctly formatted, the BLAST program should be used to obtain the space loads. The user can run the program in the design-day mode to simulate a series of days with extreme (design) weather conditions. The output from these runs will determine the sizing of heating and cooling equipment. The design-day runs should be followed by a 1-year simulation to prepare for systems simulation runs and to provide information about the distribution and magnitude of space energy demands. The output from the program should be carefully inspected to determine the type or types of air distribution systems and system zoning which will meet the space demands most efficiently.

In many cases, buildings being studied as total energy/selective energy (TE/SE) candidates have not yet been constructed. The BLAST program can be particularly useful in these cases, since it permits study of the effects of building architecture on space energy demands. Users should take advantage of this feature by examining design options such as building orientation, glass area, wall and roof construction, space usage and temperature control, and the use of shading overhangs to minimize the space energy demands. Frequently, the increased costs, if any, of energy-conservative building design can be offset by reduced costs of smaller heating and cooling systems. Even in the case of existing buildings, retrofit options such as adding insulation, installing storm windows and shading devices, reducing infiltration, or modifying lighting loads and space temperature control should be examined as methods for minimizing the space energy demand.

Step 3: Simulate Air Distribution Systems

When the peak and hourly space energy demands have been determined, air-handling systems for the building should be simulated to determine energy demands on the central energy plant. If the buildings are still under design, several different air-handling systems should be examined to determine which systems will meet the space demands most efficiently. In many applications, variable air volume systems produce the best results, since they reduce fan energy consumption and minimize ventilation air heating and cooling requirements. In the case of existing buildings, relatively inex-

pensive control or fan system modifications can often significantly reduce energy consumption.

Step 4: Simulate a Conventional Central Energy Plant

All TE/SE studies require investigation of a conventional central heating and cooling plant as a basis for comparing cost and energy use of TE/SE systems. By simulating conventional systems first, valuable information can be obtained for identifying candidate TE/SE systems.

Conventional systems usually consist of one or more boilers and chillers. The chillers are driven with purchased electricity, and the boilers are powered by purchased fossil fuels. Double-bundle chillers (heat pumps) may also be part of a conventional system.

The output from the simulation of the selected air distribution systems provides the hourly demand for hot water or steam, chilled water, and electricity for lights and miscellaneous equipment. This output should be reviewed before selecting the components and sizes for a conventional plant simulation. Equipment use statistics are particularly useful for establishing component size. By examining the distribution of the air systems' energy demands, the proper number and size of boilers and chillers can be selected to insure efficient part-load performance of the central energy plant. For most large energy plants, the selection of a single large boiler or chiller will usually result in poor efficiency because of reduced component efficiency under part load.

Given that several smaller boilers and chillers are selected, how optimal the chosen central energy plant configuration is can be established by reviewing the output of a BLAST simulation of the plant. Again, equipment use statistics provide valuable information for configuring a more efficient central energy plant. For example, if the simulation output indicates that peak demand is much lower than the sum of the component capacities, then smaller or fewer components should be selected. If the peak demand matches the capacity but the average part-load ratio is small, then large components should be replaced with several smaller components. Alternately, thermal energy storage (hot or cold) can be used to reduce peak demand and permit the selection of smaller components.

Several iterations through the central energy plant simulation process may be required to arrive at a near-optimal configuration. This is an important step, since comparisons between conventional and TE/SE plants will be valid only if the conventional plant is properly configured.

Step 5: Simulate a Diesel Engine Generator Total Energy Plant

A diesel engine generator total energy plant will almost always be the most efficient type available for consideration and is one that must be simulated according to the OCE Instructions. The procedure for determining the best diesel plant configuration is similar to that described above for conventional systems. The major new factors which must now be considered are the number and size of diesel engine generators to be used and the appropriate mix of absorption and electrical chiller capacities.

To begin the definition of a candidate diesel system, the electrical and thermal energy demand summaries from the conventional system simulation should be reviewed. If there is a continuously high thermal energy requirement for purposes other than cooling (as in a hospital, for example), then absorption cooling may not be desirable. The first candidate system would therefore consist of several diesel engine generators (with heat recovery) and the same mix of various boiler and chiller sizes as in the near-optimal conventional system.

Selection of the smallest increment of diesel generator capacity is a matter of judgment and includes consideration of reliability as well as part-load plant performance. As a first estimate, the conventional plant energy consumption data may be reviewed and the mean demand of the month with the lowest electrical consumption may be used as the smallest size increment. It may be advantageous from an operation and maintenance standpoint to select several identical diesel engine generators. The number of generators can thus be established by referring to the peak electrical demand given as output from the conventional plant simulation.

When the number and sizes of components for this first candidate system have been selected, the plant should be simulated. Again, better configurations can be selected by reviewing energy consumption and equipment use statistics from the simulation. The number and sizes of diesel generators can be adjusted to achieve optimal average part-load operating ratios as was done for chillers in the conventional system. If the output from the first candidate system simulation shows high quantities of unrecovered waste heat, particularly in months where cooling demands occur, then a new plant should be configured which includes a mix of absorption and electrically driven chillers. A first estimate of a desirable ratio of absorption to electrical chiller

capacities may be obtained by considering the respective chiller coefficients of performance and the ratio of power production to available waste heat for the diesel engine.

Step 6: Simulate a Gas Turbine Generator Total Energy Plant

Although less efficient, gas turbine generators may have certain cost advantages over diesel engine generators and must, therefore, be considered in a TE/SE study. The procedure for selecting a good gas turbine generator plant follows exactly that which was outlined for a diesel plant. Thus, the results of the diesel plant simulations can provide a good point of departure for simulating a gas turbine system.

Step 7: Simulate Steam Turbine Systems

While steam turbine generating plants are generally more efficient than gas turbine plants, they have limited small-scale applicability due to high capital and maintenance costs and limited equipment availability. In marginal cases, one simulation of a steam turbine generator plant will usually be sufficient to indicate whether such plants deserve detailed study. If the results are positive from an energy or economic viewpoint, the optimum configuration can be established as previously described.

Step 8: Simulate Selective Energy and Total Energy Systems With Two or More Engine Types

The study of selective energy systems and total energy systems with two or more engine generator types (a mix of gas and steam turbine generators, for example) introduces many new design variables and vastly enlarges the number of possible plant configurations. Thus, the systematic determination of "optimal" systems becomes much more difficult.

Selective energy systems are usually configured in one of two ways: (1) by base loading the selective energy plant and meeting peak electrical loads with purchased utilities, or (2) by meeting all or part of the base electrical load with purchased power and meeting peak load with the selective energy plant. The first option will produce the most efficient selective energy plant operation but may be unacceptable to the local utility. Several simulations of this configuration should be performed using smaller or fewer diesel, gas turbine, or steam generators than were used previously in simulating total energy plants. When these simulations are performed, the total chilling capacity will not change, but the ratio of absorption to electrical chilling capacity will be reduced.

Peaking* with a selective energy plant should generally be considered only when utility demand charges are high, and only if thermal demands are sufficiently high during peak electrical demand periods to permit the plant to operate efficiently. A peaking plant should also be configured to meet at least a small fraction of the base load to avoid operational problems. Peaking plants require substantial capital investment for relatively small fuel savings, since the equipment will be fully used during only a fraction of the building's operating life.

The criterion for equipment selection and system definition for total energy systems with two or more engine types is usually economics rather than plant efficiency (diesel plants are almost always the most efficient). Total energy systems with two or more engine types are frequently considered when existing equipment (e.g., emergency generators) can be incorporated into a new total energy plant configuration.

Although the specific guidelines provided for total energy plants cannot be rigorously applied to selective energy and total energy plants with two or more engine types, the BLAST program is sufficiently inexpensive and easy to use to permit the simulation of many candidate systems. This enumerative approach will permit the user to establish life-cycle cost trends for various selective energy and total energy systems having two or more engine types and thus arrive at a near-optimum configuration. Rigorous computer optimization methods are currently under development but, in the near term, intuition and engineering judgment take on added importance in the study of selective energy and total energy central systems having two or more engine types.

Step 9: Use the Simulation Results to Rank Candidate Systems

Recalling that life-cycle cost computation is part of each BLAST simulation, it is now possible to rank each candidate system according to its overall efficiency and separately according to its life-cycle cost (compared in both cases to the conventional system). This ranking will facilitate the application of feasibility criteria and permit selection of the system to be used for final design.

Suggestions for Effectively Using BLAST

As the previously described procedure indicates, the BLAST program is extremely user-oriented. Two im-

*Meeting peak demands.

portant suggestions to assist in developing sound user habits are outlined below:

1. Perform as many simulations as the job requires. When building loads and air distribution system performance have been determined, 1-year central plant simulations will cost approximately \$3 to \$15 each, depending on computer charge rates. This cost is inconsequential when compared to the overall cost of feasibility studies and the design and construction of central energy plants.

2. Be practical in configuring candidate systems. Even though a component of any size can be simulated by BLAST, there is little point in simulating systems that cannot be built. It would be useless, for example, to simulate a total energy plant which included several 1860-kW steam turbine generators unless generators of that size were being manufactured.

4 USING THE BLAST PROGRAM FOR DESIGN CALCULATIONS

After choosing the best candidate total energy or selective energy system and deciding to proceed with design, the design engineer can use the BLAST program to perform many of the necessary calculations required in the final design process. The principal difference in applying the program for design calculations rather than for feasibility studies is that specific, rather than generic, components will be studied.

Most of the design variables for TE/SE systems have been roughly established during the study of system feasibility. Thus, the size, number, and type of generators and other components should not be changed radically during the final design phase. The equipment performance parameters should be modified, however, to simulate more accurately the differences among components manufactured by different companies.

The equations used in simulating the performance of components in BLAST are usually expressed as products of quadratics or polynomials of a single variable; therefore, the equipment performance coefficients can be determined by simple one-dimensional curve fittings. This is particularly convenient, since most manufacturers present the data on component performance as one-dimensional curves or tables where all variables except one are fixed. In the case of a diesel engine, for example, the following equations are used:

electric energy output/fuel energy input =

$$A_1 + A_2 \times \text{PLR} + A_3 \times \text{PLR}^2 \quad [\text{Eq 1}]$$

where PLR is part-load ratio, and A_1 , A_2 , and A_3 are equipment performance parameters.

recoverable jacket heat/fuel energy input =

$$B_1 + B_2 \times \text{PLR} + B_3 \times \text{PLR}^2 \quad [\text{Eq 2}]$$

where B_1 , B_2 , and B_3 are equipment performance parameters.

recoverable lube oil heat/fuel energy input =

$$C_1 + C_2 \times \text{PLR} + C_3 \times \text{PLR}^2 \quad [\text{Eq 3}]$$

where C_1 , C_2 , and C_3 are equipment performance parameters.

total exhaust heat/fuel energy input =

$$D_1 + D_2 \times \text{PLR} + D_3 \times \text{PLR}^2 \quad [\text{Eq 4}]$$

where D_1 , D_2 , and D_3 are equipment performance parameters.

exhaust gas temperature/fuel energy input =

$$E_1 + E_2 \times \text{PLR} + E_3 \times \text{PLR}^2 \quad [\text{Eq 5}]$$

where E_1 , E_2 , and E_3 are equipment performance parameters.

The diesel generator model uses the input electrical load and engine generator size to compute part-load ratio (PLR). Eq 1 is then used to compute fuel energy input. Eqs 2 and 3 are used to compute recoverable jacket and lube oil heat. Finally, Eqs 4 and 5 are used with the U-factor-area product for the exhaust gas heat exchanger to compute the recoverable exhaust heat. The left sides of the equations indicate the manufacturers' curves or tables that must be obtained for diesel engine generators to derive the equipment performance parameters. Note that simple transformations in the form of the manufacturers' curves may be required. For example, the data required to determine A_1 , A_2 , and A_3 for Eq 1 might be presented in the form of fuel consumption versus kilowatt electrical load. In this case, the transformation required is:

$$\frac{(\text{electrical load}) (K)}{(\text{fuel consumption})(\text{heat content of fuel})} = \frac{\text{electrical energy output}}{\text{fuel energy input}}$$

where K is a constant to convert the ratio to consistent units, and

$$\frac{\text{electrical load}}{\text{generator capacity}} = \text{part-load ratio}$$

The following example illustrates the procedure for generating equipment performance coefficients for a specific diesel engine generator.

Example*:

The data for a 630-kW ebullient diesel engine generator presented in Table 1 were obtained from the manufacturer.

Also from the manufacturer:

lube heat (Btu/min) = 8.4 × horsepower

fuel consumption (Btu/min) = 1.1 (exhaust heat + jacket heat + lube heat + aux heat + work)

The first step in determining the equipment performance coefficients is usually to determine A_1 , A_2 , and A_3 of Eq 1. However, because of the way these data are presented, fuel consumption cannot be determined directly, and the several calculations required will provide data for computing the other coefficients first.

Step 1. Determine exhaust gas temperature. Although the exhaust gas temperature is not given, it can be determined from the following equations:

total exhaust gas heat at 90°F = $\dot{m} c_p (T_E - 90)$

recoverable exhaust gas heat of 300°F = $\dot{m} c_p (T_E - 300)$

where m is the exhaust gas mass flow rate, c_p is the exhaust gas specific heat, and T_E is the exhaust gas temperature in °F.

After dividing one equation by the other and rearranging

$$T_E = \frac{90 (\text{recoverable exhaust gas heat at } 300^\circ\text{F})}{\text{recoverable exhaust heat at } 300^\circ\text{F}} - \frac{300 (\text{total exhaust gas heat at } 90^\circ\text{F})}{\text{total exhaust gas heat at } 90^\circ\text{F}}$$

At 100 percent load, for example

$$T_E = \frac{90 (17650) - 300 (31960)}{17650 - 31960} = 559^\circ\text{F}$$

*To prevent confusion, SI equivalents are not given for units in this example. The applicable conversion factors are: 1 Btu = 1.055 kJ; (°F - 32) 5/9 = °C.

Repeating the process using manufacturer's data for other part-load ratios gives the results presented in Table 2.

Step 2. Determine exhaust gas heat. Note that the exhaust gas heat is not equal to the total rejected heat at 90°F. The number required is the total number of Btu's leaving the engine in the exhaust gas per minute (since ratios will ultimately be used, it does not matter whether Btu/min or Btu/hr are used as long as the same units are used consistently). This number equals $\dot{m} c_p (T_E - 32)$ since 32°F is the base temperature for enthalpy calculations. Since T_E is known, only $\dot{m} c_p$ must be found in order to compute exhaust gas heat. The manufacturer's data can be used to do this by noting that:

$$\text{total exhaust gas heat at } 90^\circ\text{F} = \dot{m} c_p (T_E - 90)$$

For 100 percent load,

$$\dot{m} c_p (559 - 90) = 31,960$$

or

$$\dot{m} c_p = \frac{31,960}{559 - 90} = 68.14 \text{ Btu/min } ^\circ\text{F}$$

Thus, the total heat content of the exhaust gas at 100 percent load is

$$68.14 (559 - 32) = 35,912 \text{ Btu/min}$$

Repeating the process for other part-load ratios gives the results in Table 3.

Step 3. Determine lube oil heat. The manufacturer indicates that lube heat is a linear function of load on the engine:

$$\text{lube heat (Btu/min)} = 8.4 \cdot \text{kW} \cdot 1.34 \text{ HP/kW}$$

For the 630-kW generator set, this percent results in the figures in Table 4.

Step 4. Determine jacket heat. The jacket heat is determined by subtracting the lube heat from column 4 of the manufacturer's data. Table 5 gives the results.

Table 1
Example Manufacturer's Data

1 Percent Load	2 Total Exhaust Gas Heat Rejected at 90°F (Btu/min)	3 Recoverable Exhaust Gas Heat at 300°F (Btu/min)	4 Jacket & Lube Heat (Btu/min)	5 Work (Btu/min)	6 Aux Heat (Pumps, Fans, etc.) (Btu/min)
100	31,960	17,650	25,400	35,820	11,128
75	24,380	12,910	18,900	26,870	8,520
50	17,040	8,070	12,300	17,910	6,760
25	10,820	4,020	5,900	8,960	4,470

Table 2
Exhaust Gas Temperature for Various Part-Load Ratios

Percent Load	Part-Load Ratio	Exhaust Gas Temperature	
100	1.0	559°F	1019°R
75	.75	536°F	996°R
50	.50	489°F	949°R
25	.25	424°F	884°R

$$(^{\circ}\text{R} = ^{\circ}\text{F} + 460)$$

Table 3
Exhaust Gas Heat for Various Part-Load Ratios

Percent Load	Part-Load Ratio	Exhaust Gas Heat (Btu/min)
100	1.0	35,912
75	.75	34,345
50	.50	31,142
25	.25	26,712

Table 4
Lube Heat for Various Part-Load Ratios

Percent Load	Part-Load Ratio	kW Load	Lube Heat (Btu/min)
100	1.0	630	3992
75	.75	472	2991
50	.50	315	1996
25	.25	157	995

Table 5
Jacket Heat for Various Part-Load Ratios

Percent Load	Part-Load Ratio	Jacket Heat (Btu/min)
100	1.0	21408
75	.75	15909
50	.50	10307
25	.25	7905

Step 5. Determine fuel consumption. Having computed the exhaust heat, jacket heat, and lube heat and using the auxiliary energy and work energy given by the manufacturer, the fuel consumption can be computed on the basis of the formula provided by the manufacturer:

$$\text{fuel consumption} = 1.1 (\text{exhaust heat} + \text{jacket heat} + \text{lube heat} + \text{aux heat} + \text{work})$$

Table 6 presents the fuel consumed for various part-load ratios.

Step 6. Normalize results. The various heat rates (jacket heat, lube heat, exhaust heat, electrical power) must be divided by the fuel input rate to get data into form for curve fitting. Table 7 shows the results.

$$\text{electrical power} = \text{kW} \times 3412 \text{ Btu/kW-hr} \frac{1 \text{ hr}}{60 \text{ min}}$$

Step 7. Fit data to obtain equipment performance coefficients. Five parabolic equations are needed to simulate diesel engines. These equations are of the form $y = a_0 + a_1x + a_2x^2$. In fitting an equation to the various data sets, the x's are always part-load ratios and

Table 6
Fuel Consumption for Various Part-Load Ratios

Percent Load	Part-Load Ratio	Fuel Energy (Btu/min)
100	1.0	119,086
75	.75	97,798
50	.50	74,923
25	.25	50,646

the y's are the numbers in columns 2, 4, 5, 6, and 7 of Table 7. Many programmable calculators and almost all computer centers have program packages for doing this simple curve fit. The formula for parabolic curve fitting can be found in any good statistics text, such as that by Mood and Graybill.⁷ Tables 8 through 12 show the results of the regressions for the sample data and the coefficients for Eqs 1 through 5.

The BLAST user's manual presents details of the procedures required for curve-fitting manufacturers' data to obtain equipment performance parameters for each type of component and describes how to input these coefficients to override the default values.

From the example, it can be seen that considerable number manipulation may be necessary. This problem can be simplified by asking the equipment manufacturers to provide the performance coefficients, or, as a minimum, by asking that the data be provided in the proper form to permit direct parabolic curve fitting.

In addition to the equipment performance parameters, other design variables such as chilled water temperature, condenser water temperature, and temperature of the exhaust gas leaving heat recovery equipment, can be varied to determine optimum design conditions.

The simulation of specific components during the design phase should reveal the magnitude of any effects on annual energy consumption caused by different brands of equipment and should permit specification of the most efficient or cost-effective components.

⁷A. M. Mood and F. A. Graybill, *Introduction to the Theory of Statistics* (McGraw-Hill, 1963).

Table 7
Normalized Data

1	2	3	4	5	6	7
Part-Load Ratio	Exhaust Gas Temperature °R	Electric Power (Btu/min)	Electric Power Fuel Input Rate	Exhaust Heat Rate Fuel Input Rate	Jacket Heat Rate Fuel Input Rate	Lube Heat Rate Fuel Input Rate
1.0	1019	35,820	.301	.302	.180	.034
.75	996	25,870	.265	.352	.163	.031
.50	949	17,910	.239	.416	.138	.027
.25	884	8,960	.177	.527	.097	.020

Table 8
Electrical Power/Fuel Input Rate Vs. Part-Load Ratio

Part-Load Ratio	Actual $\frac{\text{Electrical Power}}{\text{Fuel Input Rate}}$	Predicted $\frac{\text{Electrical Power}}{\text{Fuel Input}}$
1.0	.301	.299
.75	.265	.272
.5	.239	.232
.25	.177	.179

Coefficients: $A_1 = .144$, $A_2 = .289$, $A_3 = .104$

Table 9
Jacket Heat Rate/Fuel Input Rate Vs. Part-Load Ratio

Part-Load Ratio	Actual $\frac{\text{Jacket Heat Rate}}{\text{Fuel Input Rate}}$	Predicted $\frac{\text{Jacket Heat Rate}}{\text{Fuel Input Rate}}$
1.0	.180	.180
.75	.163	.164
.50	.138	.137
.25	.097	.097

Coefficients: $B_1 = .046$, $B_2 = .230$, $B_3 = 0.096$

Table 10
Lube Heat Rate/Fuel Input Rate Vs. Part-Load Ratio

Part-Load Ratio	Actual	$\frac{\text{Lube Heat Rate}}{\text{Fuel Input Rate}}$	Predicted	$\frac{\text{Lube Heat Rate}}{\text{Fuel Input Rate}}$
1.0		.034		.034
.75		.031		.031
.5		.027		.027
.25		.020		.020

Coefficients: $C_1 = .012, C_2 = .038, C_3 = -.016$

Table 11
Exhaust Heat Rate/Fuel Input Rate Vs. Part-Load Ratio

Part-Load Ratio	Actual	$\frac{\text{Exhaust Heat Rate}}{\text{Fuel Input Rate}}$	Predicted	$\frac{\text{Exhaust Heat Rate}}{\text{Fuel Input Rate}}$
1.0		.302		.304
.75		.352		.347
.5		.416		.421
.25		.527		.525

Coefficients: $D_1 = .660, D_2 = -.601, D_3 = .244$

Table 12
Exhaust Gas Temperature Vs. Part-Load Ratio

Part-Load Ratio	Actual Exhaust Gas Temperature	Predicted Exhaust Gas Temperature
1.0	1019 °R	1019
.75	996 °R	995
.5	949 °R	950
.25	884 °R	884

Coefficients: $E_1 = 796, E_2 = 390, E_3 = -168$

Unless the results of systems simulations using specific component data differ substantially from the generic simulations previously performed, previous simulations need not be repeated for selecting optimum component sizes. If simulations using specific component data indicate a considerably higher energy consumption than generic simulations, this probably indicates that the actual components simulated are not well suited to the particular central energy system. In any case, if large differences exist, the procedure outlined in Chapter 3 should be repeated to optimize final design.

5 CONCLUSIONS

A fast, easy-to-use, computer-aided method for predicting the performance of total energy and selective energy systems has been developed. This method has been integrated with an overall building energy analysis computer program which permits the energy and life-cycle cost analysis of conventional, total energy/selective energy, and solar energy systems, as well as the analysis of impact of building design on energy consumption.

Applications of this method, which incorporates the BLAST program, will provide the Corps of Engineers with the capability of designing energy-conservative facilities and assessing the potential savings of total energy systems and other energy conservation options in terms of both dollars and fuel.

Results of this work will provide a means of complying with the DoD-issued *Modification of DoD Construction Criteria Manual 4270.1-M*.

6 FUTURE PLANS

The computer-aided methodology described in this report will be field-tested during FY77. Concurrently,

the BLAST program will be applied to an ongoing total energy study by an OCE-designated District Office. The results of user response to the ease with which the program can be applied will be compiled, and a report of these results will be prepared. Included in the report will be a plan for both the widespread implementation of the BLAST program and the development of the necessary training and user support activities.

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