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THE ROLE OF OPERATIONS RESEARCH IN THE ANALYSIS OF COMPLEX MANAGEMENT PROBLEMS IN A LARGE ELECTRIC UTILITY

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Note: This text is subject to editorial revision.

CONTENTS

1. Introduction

The efficient management of business enterprises is steadily becoming more difficult as their size and complexity increases. Because of this trend, managers have encouraged the formation of specialist staff groups to provide independent and detailed advice in specific fields of interest to the company. In line with this development, a new type of staff group has recently emerged, with a field of activity known as "operations research".1/

2. Operations research in Ontario Hydro

The Hydro-Electric Power Commission of Ontario is the official name for the publicly-owned electric utility which provides 90 per cent of the electric power requirements of the Province of Ontario. Ontario Hydro as it is more generally called, serves a territory of some 250,000 square miles with direct and indirect customers numbering over 1,800,000. Its assets total 2,500 million dollars, and its staff consists of some 16,000 people. In operation are 66 hydroelectric generating stations and two major coal-fired thermal stations. Under construction are three additional hydro stations, two coal-fired thermal stations and two nuclear thermal stations. In 1959, 32,300 million kWh were generated with a peak demand of 5.6 million kWh and 213 million dollars received from the sale of this energy.

Ontario Hydro has been making use of operations research for more than five years, although some work of an operations research character was done before that. The Operations Research Group now consists of a mechanical engineer, a mathematician, and an electrical engineer. Originally, the group comprised an engineer, a mathematician and a physicist. For most studies, the permanent group has been augmented by other staff and line personnel including an industrial engineer, an economist, a supply expert, an electronic engineer, and a computer programmer. The largest team has consisted of five people and the longest study twelve months. The Group, although located in the Research Division, works in close collaboration with the manager for whom the study is being made.

In the Group's studies, extensive use has been made of punched-card and electronic computers (IBM 650, Univac II) to facilitate the work. Without such machines, the scope of the work would have been considerably restricted because extensive computation has generally been required both in the solution of mathematical models and for data processing. Occasionally,

1/ See annex for the definition of "Operations research".

/hand computation

hand computation using a desk calculator has been found to be more convenient and less expensive than machine computation.

To date eleven operations research studies have been undertaken by the Group ranging from the prediction of lake levels to the economic scheduling of Ontario Hydro's Southern Ontario System. A brief description of three of the studies will be given in the hope that they will provide a more specific understanding of the principles and practice of operations research.

3. Optimum scheduling of the Beck Complex

The extensive generating facilities installed by Ontario Hydro at Niagara Falls are well known. The total capacity of the Niagara plants is well over 2 million kW, supplying over one-half of Ontario Hydro's generation. Translated into money, the annual output is worth over $65 million. Translated into human ability, the output is equivalent to the muscular energy of 100 million men. There can thus be no doubt of the importance of these power sources and no doubt of the importance of ensuring that they are operated efficiently. A striking feature of the installation is the use of pumped storage as a means of storing energy at night when the demand is low and supplying energy in the day-time when the demand is high. The arrangement and complex structure of the pumped-storage facilities are reproduced in figure I.

(a) Physical model

In the foreground of the photograph can be seen two large generating stations, known as the Sir Adam Beck Generating Stations No. 1 and No. 2. To the right, is the pumped-storage reservoir with its pumping-generating station. At the upper left is the intake from the upper Niagara River, from which water is led through a canal and tunnels to the common forebay of the two Beck stations. Water in the forebay can be pumped by the pumping-generating station into the reservoir, or alternatively water may be discharged through the pumping-generating station into the forebay. All of these facilities are conveniently referred to as the "Beck Complex".

In figure II, some of the "model-making" activities of the operations research team can be seen. This diagram is a simplified but quite realistic model of the Beck Complex for use in developing a mathematical model. The

/graphical model

graphical model is more revealing than the photograph (figure I). It is apparent from the diagram that the flow through the conduit depends on the difference in level between the river and the forebay, and that there is an upper limit to the flow. The forebay level can be varied by increasing or decreasing discharge through the Beck plants or by pumping or discharging water at the pumping-generating station. Water pumped into storage reduces the discharge through the Beck stations and the resulting power output from the Beck stations. Water discharged from storage through the pumping-generating plant is also discharged through the Beck stations so the water is utilized two fold. Also, it should be noted that the efficiency of the various stations varies with discharge and water levels. A variety of operating combinations are possible. All in all, the name Beck Complex is well deserved.

(b) Worth of power

Consider now a typical daily power demand curve for the Southern Ontario System (figure III). As would be expected, the demand at night is low, rises sharply in the early morning, remains high until noon then declines somewhat, gradually resuming its increase with a high about 5 p.m. when the lighting, heating, cooking and transportation loads reach a maximum. As the evening wears on, the demand decreases.

The cost of producing power follows a somewhat similar pattern, as shown in figure IV. The values for worth of power shown in this figure are assumed and do not represent Ontario Hydro costs, but the trend shown is a reasonable one. At night water-power resources are adequate to meet the demand, and the cost of generating power is low. During periods of heavier demand, it is necessary to utilize thermal-electric units. For peak demands, it is sometimes more economic although more expensive per kilowatt-hour to buy some power from other interconnected power companies rather than start up thermal-electric units for a short period.

(c) Dynamic programming solution

With these two items at hand, a model of the Beck Complex and an assumed worth of power, how does one go about deciding the best way to operate the stations? "Dynamic programming" is the answer. Space is not available here for a review of the theory of dynamic programming, but

/essentially it

essentially it is a form of mathematical decision-making that indicates the best decisions to make in sequence over a period of time when faced with the choice of many alternative courses of action.

In the case of the Beck Complex, the plants are scheduled hour-by-hour each day so there are twenty-four decision points when the discharges through the stations must be decided. The number of operating possibilities for each hour is easily in excess of fifty. Thus the number of ways of scheduling plant operations over a day exceeds a billion billion billion possibilities. The solution to this tremendous problem, obtainable only by dynamic programming, is given in figures V to VII.

Figure V shows the discharges through the pumping-generating station and through the Beck stations for each hour of the day. The rate of pumping or generating is affected by the worth of power so pumping occurs during the low-worth period and generating takes place during intervals when the worth of power is high. Note also that diverting water to storage reduces discharge through the Beck stations.

Figure VI shows the effect of the previous discharges on levels in the reservoir and in the forebay. The reservoir is filled completely during the low-worth period and is emptied at various rates during high-worth periods. Note particularly the fluctuations in forebay level. The forebay behaves as a storage facility, transferring energy from one worth interval into a higher worth interval. Thus the forebay level rises during the transition from a one-mill period to a two-mill period, and from a two-mill to a four-mill period. The third fluctuation occurs when the Beck stations are not able to discharge from the forebay all the water being discharged from the reservoir into the forebay at the maximum possible rate during the highest worth period. The level of the forebay rises storing the additional water and increasing the head on the Beck plants.

Figure VII shows the resulting power outputs from the three stations and their combined output. During pumping, the pumping-generating station absorbs power from the Beck stations so the combined output is low. As would be expected, maximum power output from the stations occurs during the peak worth of power.

The solution shown on the three figures provides the optimum mode of operation for the Beck Complex with the particular values of worth of power assumed. Work is now continuing on methods of hydro-thermal scheduling which will provide accurate values of worth of power and thus make possible the most effective economic use of the Beck Complex.

4. Inventory management

Ontario Hydro is a large consumer of materials and goods ranging from pencils to steam shovels. As part of its supply system, a large central warehouse known as Central Stores is maintained in Toronto, and more than a hundred smaller area warehouses are located strategically throughout the Province. In the main, both types of warehouse carry stocks of standard items used in substantial quantities. Inventories of standard items approximate $5 million at Central Stores and $3 million in the area warehouses. Shipments out of Central Stores are in the order of $15 million per year.

An operations research team was assigned the task of studying all phases in the distribution of standard supplies to determine whether substantial improvements could be made in a system that was already meeting Ontario Hydro'd needs with reasonable effectiveness and economy. The team began by studying elements of the supply system - purchasing procedures, warehouse operations, accounting requirements, information flow, inventory theory. Measurements were made of lead times (the times from preparation of a purchase order until delivery of goods to Central Stores), frequency of orders on Central Stores, purchasing costs, warehouse costs, number of unfilled orders, stock levels at Central Stores and at the area warehouses, transportation delays, and a host of other significant items. Two kinds of orders were involved in the study: (1) orders received by Central Stores from area warehouses, which are filled from Central Stores' stocks; and (2) purchase orders placed with manufacturers by the Purchasing Department on behalf of Central Stores. The information collected was studied, cross-checked, analyzed, discussed, re-analyzed and so on. Finally, a report of some 400 pages was prepared summarizing the data collected, outlining analyses, and submitting recommendations, thirty-one in number. With few exceptions, the recommendations of the report were accepted by Management

/after the

after the report had been thoroughly reviewed and discussed.

(a) Scientific inventory control

Among the major recommendations was a proposal that certain scientific methods for inventory control be adopted. This particular aspect of the study may be of interest because it illustrates two approaches characteristic of operations research. First, the solution to a problem in the physical sciences was transferred to a problem in business. Second, "simulation analysis" proved useful in predicting the effectiveness of the solution.

Consider for a moment the fluctuations of inventory level for one item in an ideal warehouse operation (see figure VIII). Starting at a point where a new shipment of goods is received at the warehouse, the stock gradually decreases as orders are filled. When the stock level reaches zero, a shipment of goods previously ordered arrives. The cycle of usage and replenishment then repeats. Since in a perfect system, neither the rate of usage nor the lead time vary from cycle to cycle, this is a straightforward operation. Is there room for cost reduction? Evidently warehousing costs could be reduced by keeping inventories smaller. Interest charges would be lower and a smaller warehouse would result in reduced rental costs. But purchase orders would have to be placed more often, so purchasing costs would rise.

Turn now from this business problem to an analogous engineering problem illustrated graphically in figure IX. What is the most economical thickness of insulation to use on a steam pipe? The thicker the insulation, the higher the installation cost but the lower the heat loss. The most economical thickness as given by the upper curve in figure IX is that thickness which results in the minimum combined annual costs of insulation and heat loss.

Similarly, there is an economic order quantity which minimizes the combined annual cost of purchasing and warehousing. Purchasing cost as used here includes the costs of placing purchase orders, inspection and unloading. Warehousing cost includes building expense, interest on capital tied up in inventory, losses resulting from obsolescence, and similar expenses. As figure X shows, annual purchasing costs go down as the size of the order increases. The annual cost of warehousing increases because

/the average

the average stock level is higher. The economic order quantity, shown by the vertical line, is that order quantity for which the combined annual cost of purchasing and warehousing is a minimum.

A formula for calculating the economic order quantity, which gives the correct quantity directly, is as follows:

$$\text{Economic order quantity} = \sqrt{\frac{2YP}{H}},$$

in which

Y = annual usage of item, in dollars

P = procurement cost per purchase order, in dollars

H = yearly holding cost as a fraction of average inventory value.

The influence of this formula on economic order quantities can be shown in a hypothetical case. For example, with an annual usage of $320,000, a purchase cost of $15 per order, and a holding cost of 15 per cent of the average inventory value, the economic order quantity is $8000. For an annual usage of $3200, the economic order quantity is $800; that is, for 1/100th the usage, the order quantity is reduced to 1/10th.

Consider a more realistic chart of stock-level fluctuation as shown in figure XI. The size of order is equal to the economic order quantity, but the rate of usage is no longer constant and the lead time varies. The important thing to remember here is that consideration must be given to the fact that lead times and usage rates are both variable. These variations can be taken care of by choosing the right times to place order so that replenishment goods will arrive before stocks are exhausted.

An item should be re-ordered as soon as the potential stock (actual amount of stock on hand together with the amount already on order with the manufacturers, less unfilled orders from area warehouses) is equal to the re-order level as given by the equation:

$$\text{Re-order level} = (L + S + I)W,$$

in which

L = average lead time in weeks

S = safety stock in weeks

/I -

I = information delay in weeks

W = average weekly usage.

L x W is the anticipated usage during the period of awaiting delivery from the manufacturer; S x W is the quantity equivalent to several weeks' usage necessary to take care of variations in lead time and usage; and I x W is the quantity required to look after usage from the time that the stock level reaches the critical level until the stock clerk finds out about it. The re-order level is not constant, but instead varies with changes in usage, lead time, safety stock level and information lag.

The correct level of safety stock is important since its magnitude will have a considerable influence on the occurrence of shortages. By using probability theory, it is possible to determine a reasonable relation between the magnitude of safety stock for any particular item and the resulting frequency of shortages.

As for information delay, consideration must be given to the fact that about 10,000 different kinds of items are stocked at Central Stores. A report on stock levels of these items is prepared weekly. Consequently, a stock clerk checking the report may obtain data on stock levels as much as a week late. The information delay in this case can thus be taken as one week.

(b) Simulation analysis

The rules for economic order quantity and re-order level just described form the basis for the recommended scientific ordering system at Central Stores. A reasonable question at this stage would be: How well do the results of applying these new rules compare with the results obtained under the former system? The new procedures have been in use only a short time, so today's results cannot be compared with yesterday's results. Besides, conditions change so that usage rates are different, and lead times longer or shorter than before. The answer to the above question was found by using "simulation analysis".

In applying simulation analysis, the inventory histories of a number of typical standard items were studied. Their stock levels for each week over a three-year period were recorded, requisitions for the items for each

/week of

week of the three years were noted, and lead times for each purchase order were found. In carrying out the simulation, the proposed ordering rules were then applied to each of these items. The actual stock levels at the beginning of the three-year period were taken as the starting points. It was assumed that the same orders were received at Central Stores and that lead times were the same as in the past. The only difference between what actually happened in the past and what happened in the simulation resulted from application of the new ordering rules. In the simulation, whenever potential stock levels fell to the re-order level, a purchase order was placed for the economic order quantity. The economic order quantity was not constant in these calculations, but was instead a variable computed from price levels, usage rates, purchasing costs and warehousing costs. All of these factors fluctuated during the three-year period. Furthermore, the effects of two weeks', four weeks' and six weeks' supply of safety stock were investigated. A valid comparison was thus obtained between actual stock levels during the three-year period and what these levels would have been if the new ordering rules had been followed. Figure XII is a reproduction of typical computer output data depicting the simulated inventory behaviour of a single item over one year of the three-year period.

Figure XIII represents a comparison of actual and simulated stock levels for one of the items studied, a specific kind of copper wire. As can be seen, the average stock level is lower in the simulation based on six weeks' safety stock, and the weeks of shortage are fewer. The actual average stock level was 124,000 pounds as compared with an average stock level of 100,000 pounds in the simulation, and 17 weeks' actually out of stock compared with 5 weeks' out of stock. In fairness to Ontario Hydro supply staff, it should be noted that a strike at one of the major suppliers was responsible for the copper shortage.

(c) <u>Ordering rules for area warehouses</u>

On the basis of the results obtained with the simulation analysis and other forms of analysis, the operations research team demonstrated that substantial savings could be achieved through the use of the proposed ordering rules. For the smaller area warehouses, a simpler procedure was developed. The ordering rules proposed for the area stores are as follows:

/Re-order level

Re-order level: orders are to be placed when the stock level falls to 1/13 of the past year's usage, that is, four weeks' average usage.

Economic order quantity: the order quantities are shown in the following table:

Past year's usage (Value in dollars)	Order quantity (Weeks' usage)
0 to 100	52
101 to 1,000	18
1,001 to 10,000	6
10,001 and over	2

For the area warehouses, lead times are short and relatively constant, since orders are placed on Central Stores. Also, the information delay time is negligible. Hence area stock can be permitted to become fairly low, with dependence on Central Stores for prompt replenishment. In the proposed procedure, stock levels drop to four weeks' usage before orders on Central Stores are placed, and the order quantity depends on the previous year's usage. Where the previous year's usage was less than $100, a single order for a complete year's supply is prepared. Where the past year's usage was high, over $10,000, orders are for two weeks' usage. Appropriate order quantities are specified for in-between annual usages.

(d) Centralized data-processing

In the operation of both systems of inventory control, up-to-date and accurate figures are required on stock levels, usage and lead times for all items at all locations. Improved centralized data-processing facilities and procedures have therefore been established to ensure effective implementation of the ordering rules. Information on the flow of inventories in the areas is punched on paper tape and the tape is then mailed to the Tabulating Section at Central Stores. More than five thousand material issues are handled each day, with inventory reports prepared at frequent intervals for regional and head-office use.

(e) Special management reports

A major element in the new system of inventory control is the preparation of special reports for all levels of management concerned with the supply

/operation up

operation up to and including the General Manager. These reports provide concise and up-to-date information on stock levels, usage, change in stock levels, target stock levels and potential stock reductions for major categories of items.

Figure XIV, Inventory Management Report, is a sample of one such report. The top half of this report gives numerical data on inventories for the past month, while the lower half contains a chart. On this chart is plotted every month the inventory control ratio. The ratio is obtained from the following expression:

$$\text{Ratio} = \frac{\text{Actual stock level} - \text{economic inventory level}}{\text{Actual stock level}} \times 100\ \%$$

$$= \frac{\text{Potential stock reduction}}{\text{Actual stock level}} \times 100\%$$

It will be evident that when the actual stock becomes equal to the calculated economic inventory level, the inventory control ratio becomes zero.

An allowance for reasonable fluctuations in usage and stock levels is made, by incorporating in the chart control limits of plus and minus 25 per cent. When the inventory control ratio falls within these limits, the store may be considered to have attained economic controlled performance. When the ratio falls outside these limits, a check is required to determine what action is required to bring the store's operations within the controlled performance zone.

The effectiveness of the entire inventory management programme is well illustrated by the Economic Inventory Chart in figure XV. While the actual figures have been deleted for purposes of public presentation, the strong and continuing reduction in inventories, accomplished without any sacrifice in quality of service speaks for itself.

5. Vehicle replacement policy

When should a vehicle be replaced? This problem is important for Ontario Hydro whose fleet consists of some 2,500 vehicles of many types, operating under diverse conditions. Although many proposed solutions of this central problem in fleet operations have been published, few survive a logical analysis. Also, a policy which has been found to be satisfactory

/for another

for another fleet will almost certainly not be the best for a publicly-owned organization such as Ontario Hydro, with different financial objectives, tax rates, interest rates and availability of capital.

The problem of developing a scientific method which would enable the Commission to establish the optimum vehicle replacement policy was assigned to an operations research team. The team, specially formed, consisted of a physicist, a mathematician, and a mechancial engineer, all with research backgrounds. The initial step in the investigation of this problem was a meeting with the fleet management staff. The nature of the problem was discussed, and tentative objectives and conditions were established.

(a) Data collection

In order that a suitable vehicle replacement policy could be developed, basic information was needed on such factors as the existing method of fleet operation, the types of performance records maintained, the system of cost accounting for vehicles, and the level and adequacy of repairs. To obtain this information, the team went and talked with central garage staff, the accountant of a typical region, some of the field mechanics, vehicle users, the cost accountants, the vehicle purchasing agent, and many others involved in the complex task of handling a large operation. All sources of data relevant to the study were located and the validity of the available information was examined. At this stage, nothing was taken for granted and all information was cross-checked wherever possible.

As might be expected, this survey of fleet operations disclosed many aspects which were secondary to the main question of vehicle replacement, but on which information was welcomed by fleet management. Although these side benefits will not be described, they are mentioned because almost any serious operations-research study, in solving the main problem, is bound to produce valuable information on other issues.

(b) Analysis of vehicle costs

After the data and observations obtained from the survey had been consolidated and reviewed, the following criterion for the solution was defined: "For the typical vehicle in each group of similar vehicles with similar usage, the cumulative average cost up to the optimum replacement age should be less than the cumulative average cost up to any other

/possible replacement

possible replacement age." This criterion was subject to the limitation that used vehicles would not be purchased as replacements. In determining the total cost of vehicle operation there are many factors which must be considered, both direct and indirect. It would be extremely difficult from an operational and accounting standpoint to obtain good data for all of these. Fortunately, it can be shown that cost factors which change directly with time or which vary directly with mileage need not be considered, since they will be essentially the same for new and old vehicles in similar service. Many costs such as those for licences and insurance are directly proportional to time, while tyre wear and gasoline and oil consumption are directly proportional to mileage. In the absence of specific data, accidents were presumed to be random in nature, with no bias relative to new or to old vehicles.

Eventually, the following factors were selected as being the most important in establishing the optimum replacement age: capital wastage, interest, repairs and unserviceability. Obsolescence was included in the analysis by the extent to which it was reflected in capital wastage values. The costs associated with the factor of unserviceability were considered to be those incurred whenever a vehicle is unavailable for service because of breakdown. Among the indirect costs of breakdown are the adverse effect on customer good will, loss of power sales because of service delays, and idle man- and machine-hours. These are difficult to express quantitatively but their importance was recognized by inclusion of the unserviceability factor.

(c) Optimum replacement interval

In applying the various factors mentioned above, it is necessary to consider a hypothetical vehicle whose costs are the average for similar vehicles in a fleet. A bar chart may be drawn (figure XVI) which shows capital wastage, interest and repair costs during each year of the vehicle's life; for the moment, consideration of the very real costs arising from vehicle unserviceability is omitted. It will be noticed that capital wastage (derived from market figures) and interest decrease with age, whereas repair costs tend to increase. With the same cost data as a basis, points may be plotted on the chart, representing the cumulative average

/cost up

cost up to each year of vehicle age. It will be realized that the correct replacement age is given by the age which results in the lowest cumulative average cost.

In this diagram, based on purely arbitrary figures, the optimum replacement age is six years, although the hypothetical vehicle had its lowest annual cost in the fourth year. For a complete solution, the chart must be re-drawn, with unserviceability costs added. The optimum replacement age can then be established under the four factors considered. This has been done in figure XVII, where unserviceability costs in each year of the hypothetical vehicle's life have been added to the other significant costs - capital wastage, interest and repairs. The optimum replacement age is found here to be five years, since the cumulative average cost is a minimum for this replacement policy.

(d) <u>Dynamic replacement policy</u>

This system of determining the optimum replacement age has one major drawback in that it requires data extending back over several years. With the rapid changes that have characterized our economy, former salvage values and repair costs are unreliable as a basis for predicting future costs. Fortunately, it is possible by a dynamic method to circumvent these difficulties and to obtain a solution which exhibits both current capital wastage and current repair costs. The basis for the method is as follows:

1. For each group of similar vehicles with relatively equal mileages, the costs of capital wastage, interest, repairs and unserviceability are obtained for the past year only.
2. The optimum replacement age for this group is then determined as already outlined, except that the following assumption is made: costs expected for each future year of a vehicle's life are best represented by the corresponding costs incurred in the previous year for similar vehicles of equivalent age. For example, the average repair cost last year for trucks then in their third year of service is used to predict future costs in the third year of truck life.

It is then possible to plot graphs showing optimum replacement age. The parameters are vehicle age and average mileage per year. The curves

/will all

will all be based on the most recent data, less than one year old, and provide fleet management with a clear-cut basis for replacement policy.

Another feature of the analytical system lies in the form of the data on repair costs. This has been organized for the detection of significant changes in repair costs. By the use of appropriate statistical techniques, it is possible to assert whether repair costs are attributable to changes in garage operations, or are merely due to sampling error. Also, the control system permits the detection of "lemons", that is, vehicles whose repair costs greatly exceed the average.

(e) Implementation

The vehicle replacement policy outlined was adopted some years back, but its implementation required extensive changes in the existing methods both of collecting and of analyzing data on fleet operations. Effective utilization of the new policy has now been achieved, and present indications point conclusively to the realization of substantial savings in the cost of operating Ontario Hydro's fleet.

Figure XVIII shows some actual results obtained in 1958 for two classes of vehicles in the fleet. The usefulness of the analysis in helping fleet management decide on the most satisfactory replacement age is clearly evident. The decision in these two cases was five years and eight years respectively as the optimum replacement ages. The ten-year figure as indicated by the analysis was not used because there were relatively few vehicles in the older age groups; cost data for these years were therefore somewhat imprecise for use in forecasting future costs.

Practical experience with the policy has emphasized the need to eliminate costs in excess of those at the economic replacement point which applies where there are a fixed number of staff and facilities. In this situation a realistic evaluation of the costs associated with the economic replacement point, relative to predetermined standard costs, may well indicate that the cumulative average curve should be lower for the entire life of the class of vehicle represented.

6. Conclusion

The three studies described above are typical examples of the way

/operations research

operations research has assisted Ontario Hydro management in solving complex operational problems. Electric power companies are often faced with a need for objective and comprehensive analyses to facilitate important decisions and for scientific procedures to optimize specific major operations. In such cases, management should give serious consideration to the advisability of employing operations research as an alternative to other methods of study such as departmental assignments or committee panels.

/ANNEX

ANNEX

Definition of operation research

Operations research is a fairly new field which requires definition. It must be realized that the definition of broad scientific fields is not easy; for example, adequate definitions of "physics" or "chemistry" are not readily obtainable. The oldest and most widely-accepted definition of operations research is by C. Kittel, an early practitioner, who states that, "Operations research is a scientific method for providing executive departments with a quantitative basis for decisions."

The following more pragmatic definitions has been proposed by E. O. Boshell, Chairman of Westinghouse Air Brake:

> "The process of analyzing and probing into business and its environment is a form of research. When this process involves the use of recognized scientific methods, it satisfies my understanding of operations research."

As these two definitions may suggest, the essential diference between operations research and other scientific research is in the phenomena being studied.

Instead of studing nuclear reactions or electronic emission or plant hormones, the scientist is concerned with the behaviour of men and machines at work, with a business activity, with a pattern of industrial production.

Typical operations research projects

One way of providing an insight into the fields of operations research activity is to examine the titles of some recent papers in operations research:

"Purchasing Raw Material on a Fluctuating Market"
"Linear Programming Solves Gasoline Refining and Blending Problems"
"On the Determination of Optimum Reserve Generating Capacity in an Electric Utility Service"

/"Shock Waves

"Shock Waves on the Highway"
"The Travelling Salesman Problem"

This title refers to a situation in which a salesman or travelling exhibit must visit a number of cities in the course of an assignment. The problem is to find the route which minimizes the total distance travelled.

"On the Optimal Allocation of Limited Resources"
"System Reliability as a Function of System Age: Effects of Intermittent Component Usage and Periodic Maintenance"
"Queueing with Impatient Customers and Indifferent Clerks"

This study deals with a common problem - a queue which will repel prospective customers if it gets beyond a certain length and clerks who pay no attention to the order in which customers arrive.

"Research in Financial Planning and Control"
"Application of Servomechanism Theory in the Study of Production Control"
"The Effect of Promotional Effort on Sales"
"A Model for the Allocation of Raw Materials to Blast Furnace Plants"
"Criteria for the Selection of Water-Resource Projects"

Characteristics of operations research

The above titles can of course only give a glimpse into the wide range of military and business activities which form the subjects of operations research studies. What else is there, besides the subject, that characterizes operations research?

(a) Staff

One characteristic will be the type of person who finds himself in this field. He will almost inevitably have a scientific background in engineering, physics, biology, mathematics, chemistry, or some other technical field. Occasionally, an economist, psychologist, or accountant will be found here. These scientists will be well qualified. Their academic training will generally extend well beyond the bachelor's degree. They will have spent several years with government or industry on research and development projects. Thus, before becoming involved in operations research projects, they will have demonstrated their ability to handle difficult problems in their particular scientific fields. Furthermore, they will have deeply imbedded in them the characteristics of any first-class scientist or engineer, a sense of curiosity, a respect for measurement, and a passion for objectivity.

/(b) Organization

(b) Organization

The form of organization for operations research is another essential aspect. Operations research is almost always carried out on a team basis, with members of different scientific backgrounds devoting full time to the project. The diversity of talents enables the team to survey a problem from many view-points, ensures that all the skills required to solve the problem are available, and encourages critical analysis of possible solutions before submission to management. Often, the team is enlarged and made more effective by the addition of a line man familiar with the actual operation being studied. In any event, close liaison with the manager in charge of the operation is always essential to ensure that the team's terms of reference are precise and adequate, and to provide management guidance on matters of policy. There must always be mutual respect and confidence between manager and team. Once the problem is formulated, the team must be given freedom to obtain all necessary information anywhere in the organization and time enough to digest and analyze the data.

(c) Techniques

The third element characteristic of operations research lies in the techniques employed in the solution of business problems. Any or all of the mathematical and experimental procedures that might be employed in a purely physical problem are available. The technique usually found necessary first in any study is the statistical collection and analysis of data. The data will include both financial and operating aspects. Sampling and probability theory are often useful at this stage in enabling useful results to be obtained from limited information. Later on, "model-building" will be used in developing a physical or mathematical analogue of the business system under study. Although models are frequently used in scientific and engineering work, the term "model" is rarely used; instead we refer to such familiar items as equations, Ohm's law, valve diagrams and flow charts without thinking of them as models.

Another technique quite recently developed is known as "linear programming." This is a mathematical procedure for finding the best solution to certain linear problems. One typical problem involves finding the lowest-cost acceptable mix of several different raw materials with different purchase costs and different compositions. There is the reverse problem of which

/components to

components to produce in a refinery from given batches of petroleum so as to obtain the highest profit from the refined products.

A fairly old technique, but one in which considerable advances have been made recently is "queueing theory". This form of analysis first proved useful in the design of telephone switchboard equipment which would be adequate to meet anticipated customer demand. Queues are a frequent occurrence throughout society - in restaurants, at airports, in factories, on the highway, everywhere. Queueing theory will help in deciding how many clerks to hire, how many runways to build, how many maintenance men to hire, and so forth. A very recent and powerful addition to queueing theory is the "Monte Carlo" method. Almost any variety of queueing problem can now be solved at reasonable cost, by combining the "Monte Carlo" method with high-speed electronic computers.

The "transport method" is another techique that is being widely accepted because of its direct usefulness. This method will provide the most economic arrangement of shipments from factories to warehouses, or from warehouses to customers, or from oil fields to unloading ports. Required data include the amount of material available at each originating point, the amount required at each destination and the freight or shipping costs between each origin and destination.

There are other techniques available such as "dynamic programming", "simulation analysis", but as already mentioned, an operations research team will make use of any mathematical or physical process applicable to the problem at hand. In fact, teams have been known to successfully use nothing more complicated than ordinary arithmetic when faced with highly complex problems.

The use of mathematics should not be considered as a revolutionary means of solving business problems, but rather as one way in which the team may prefer to express a problem so as to better understand and solve it. As a result of their scientific training and research background, the members of the team will inevitably analyze any problem in an objective and flexible way. They will search, in a free and unfettered interchange of ideas and analysis, for that element of "truth" which will enable them to arrive at a sound recommendation.

/To the

To the maximum extent possible, recommendations will be based on a quantitative assessment of the situation and a quantitative estimate of the results to be derived from implementation of the recommendation. The manager then synthesizes the team's analysis with truly intangible factors - politics, morale, tradition - to arrive at his final decision.

/Bibliography

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3. B. Bernholtz, W. Shelson, and O. Kesner, "A Method of Scheduling Optimum Operation of Ontario Hydro's Sir Adam Beck-Niagara Generating Station", Power Apparatus and Systems, December 1958, ,ages 981-991.

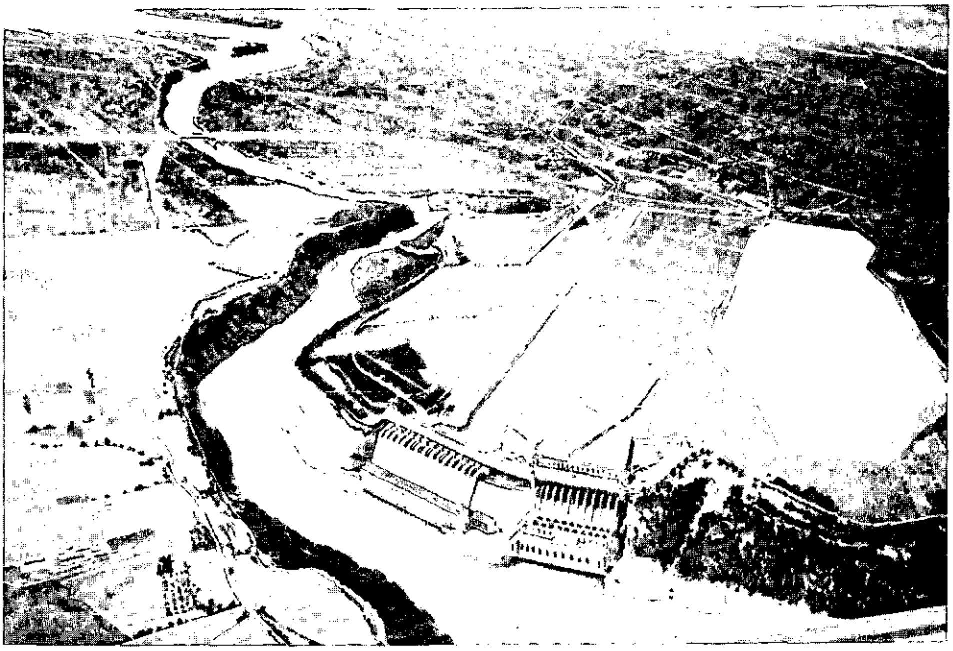

FIGURE 1

SIR ADAM BECK—NIAGARA GENERATING STATIONS

106852—RD.

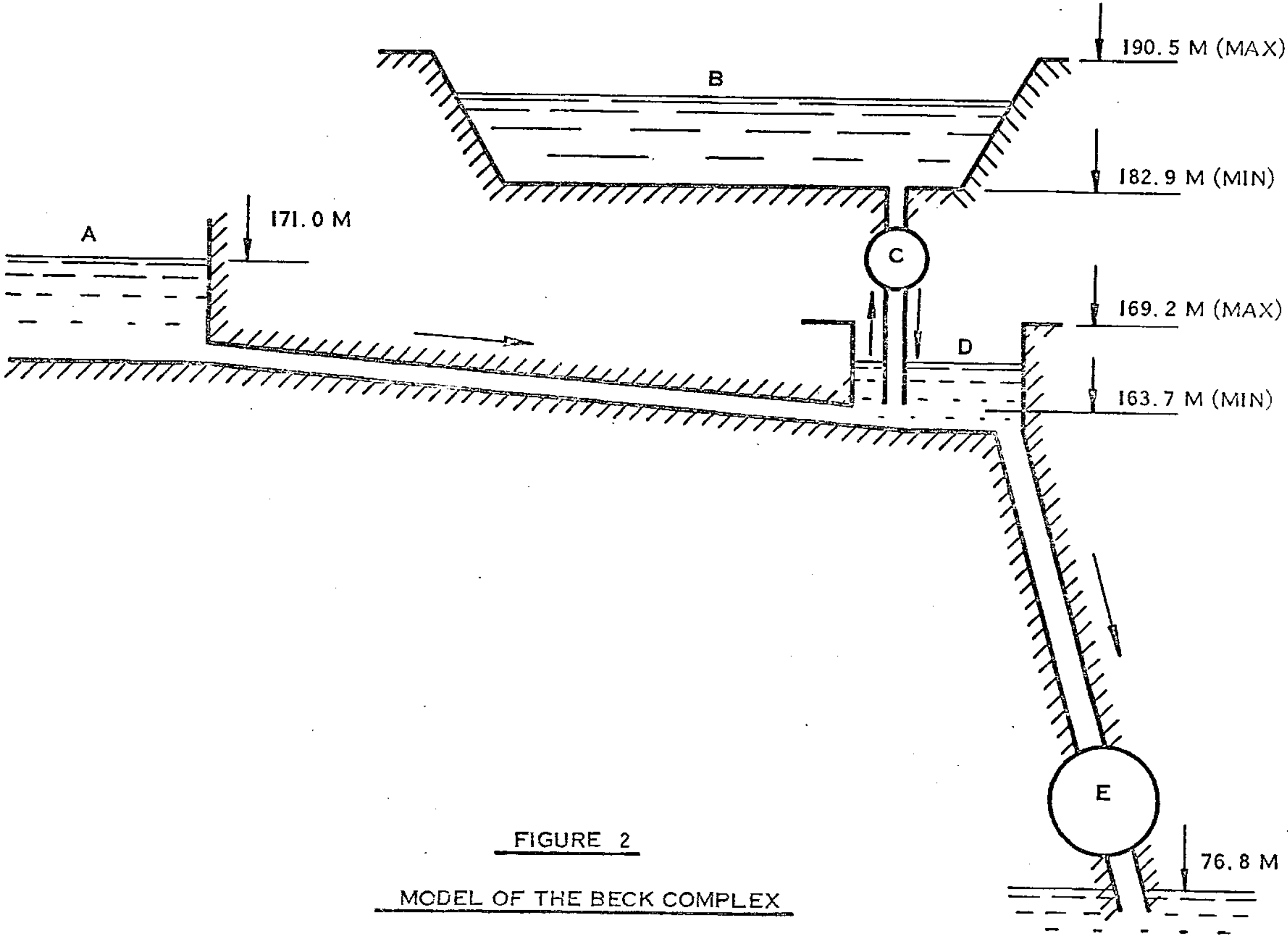

FIGURE 2

MODEL OF THE BECK COMPLEX

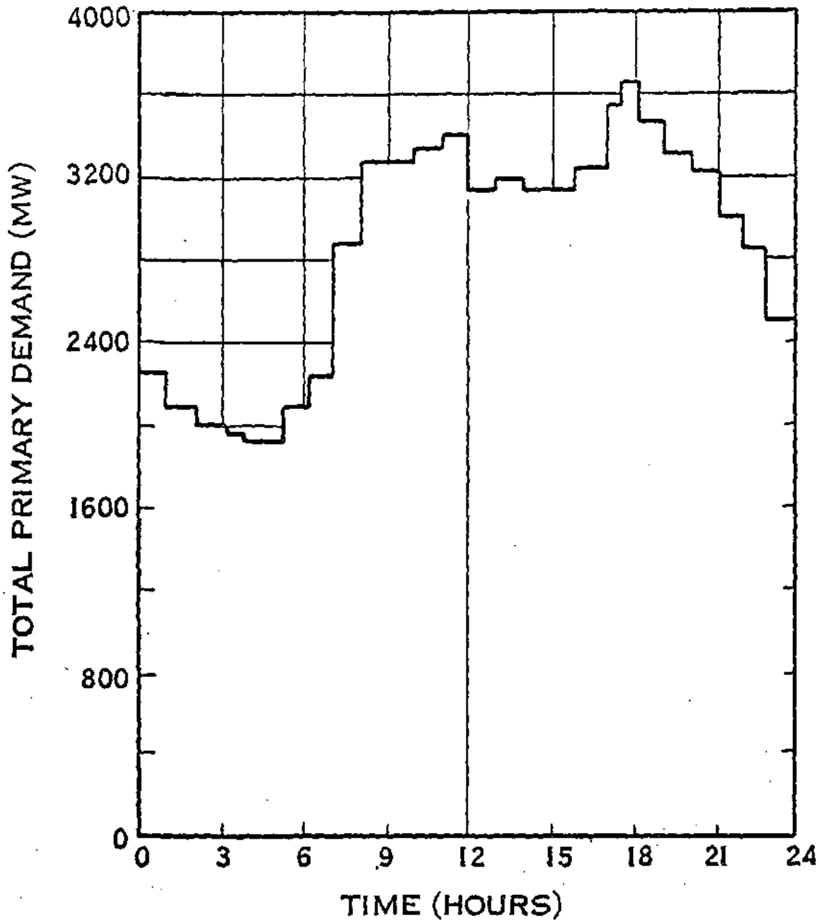

FIGURE 3

POWER DEMAND OVER A DAY

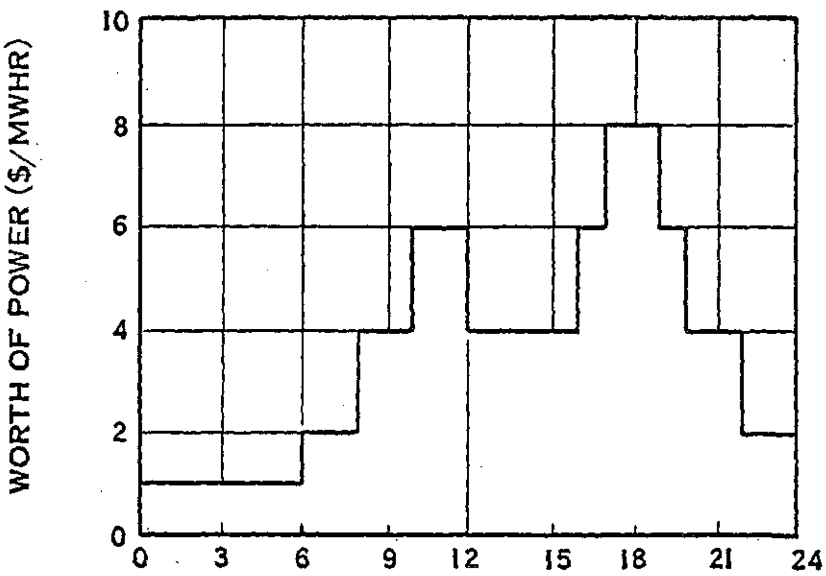

FIGURE 4

ASSUMED WORTH OF POWER

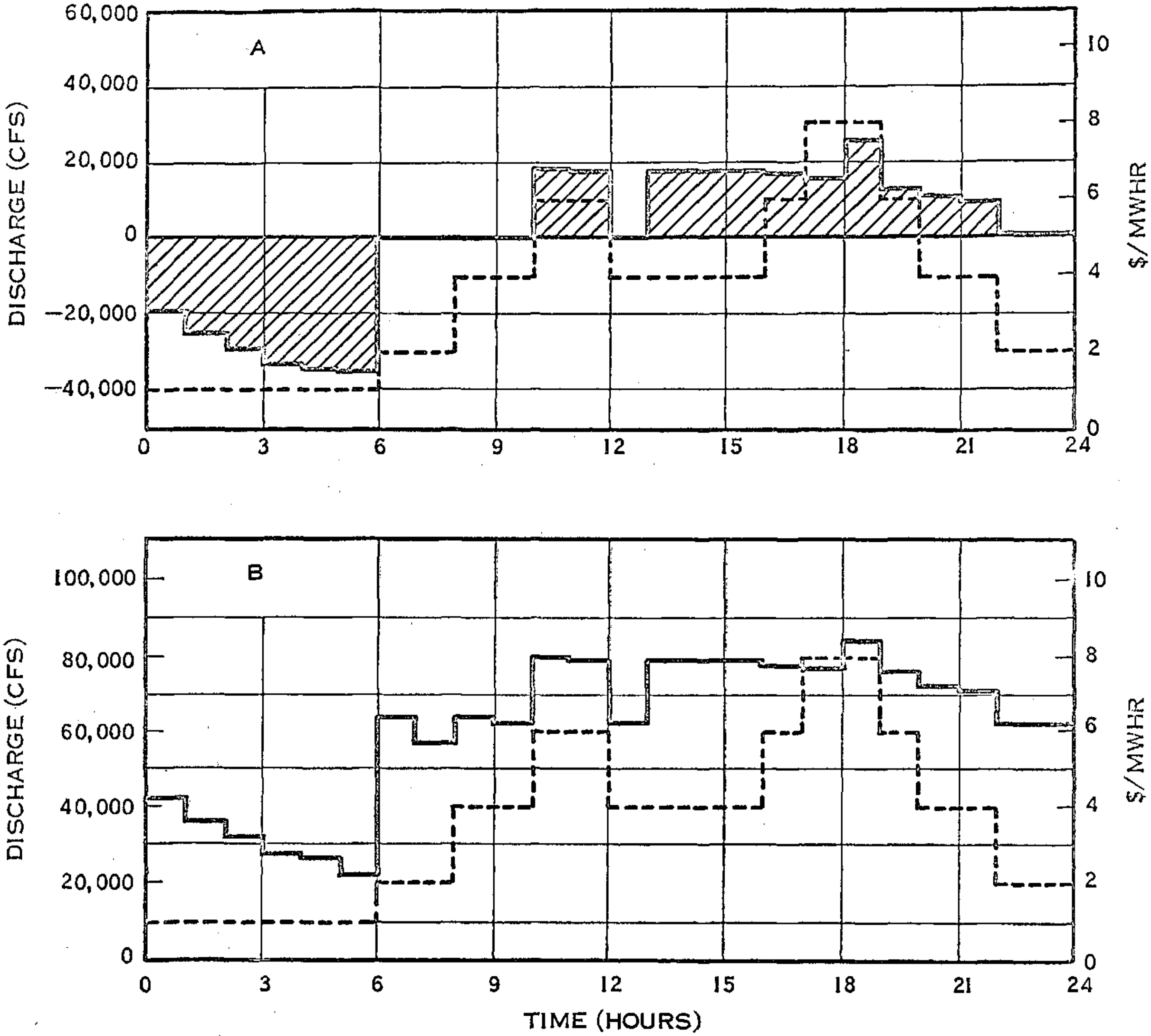

FIGURE 5

OPTIMUM SCHEDULE OF DISCHARGES

1 CFS = 0.02832 M^3/SEC

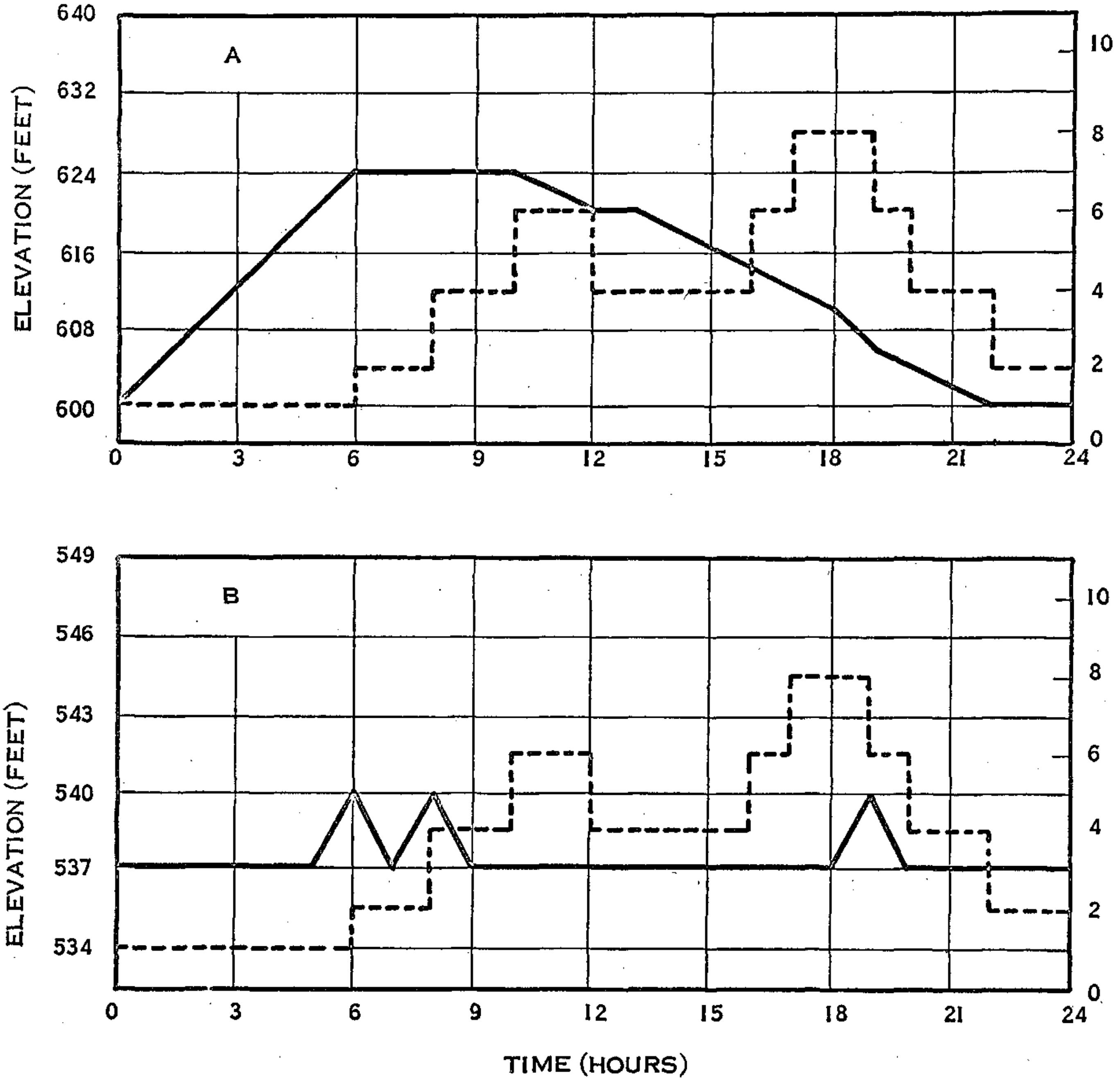

FIGURE 6

OPTIMUM SCHEDULE OF WATER LEVELS

FT = 0.3048 M

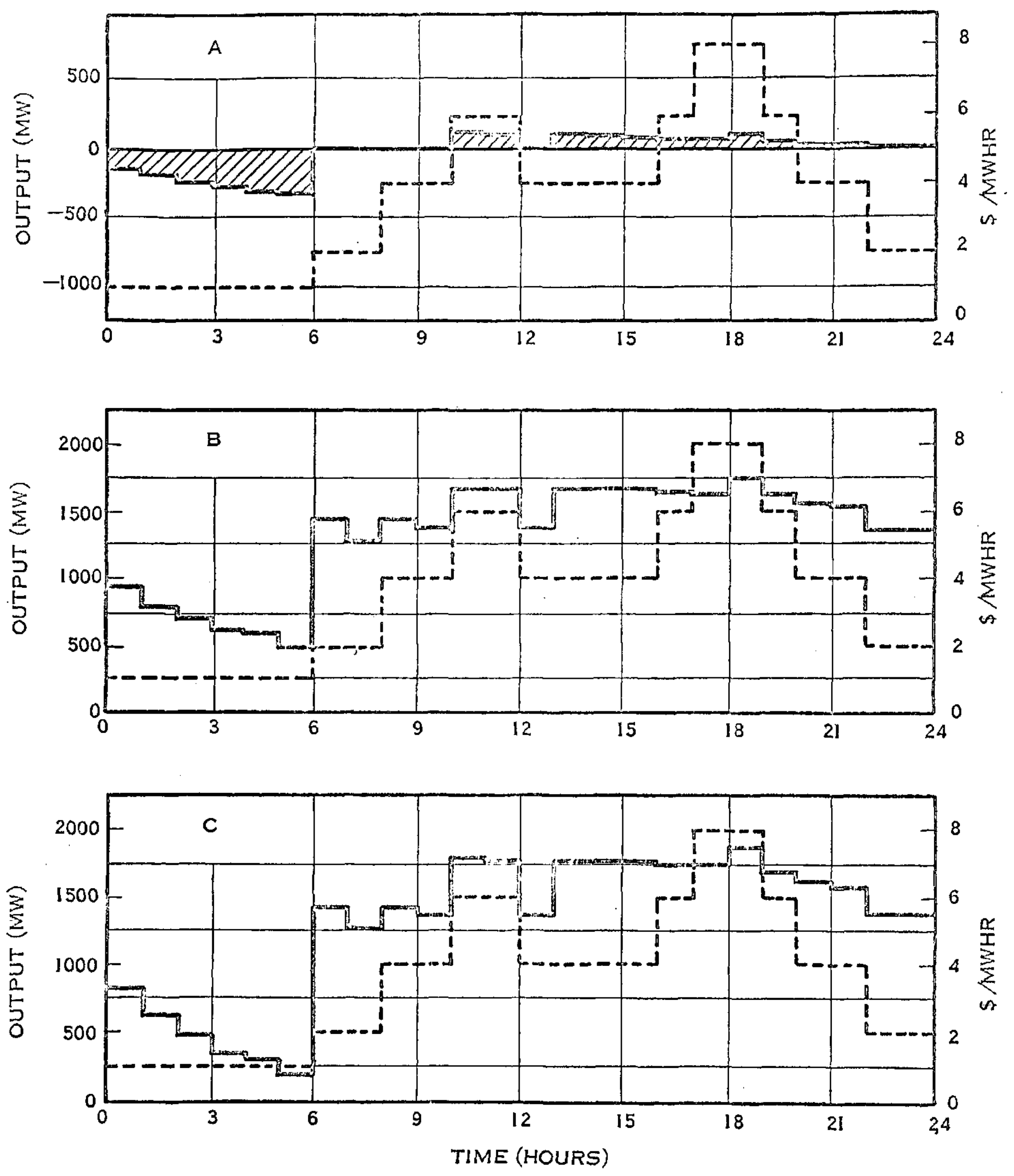

FIGURE 7

OPTIMUM SCHEDULE OF ELECTRICAL GENERATION

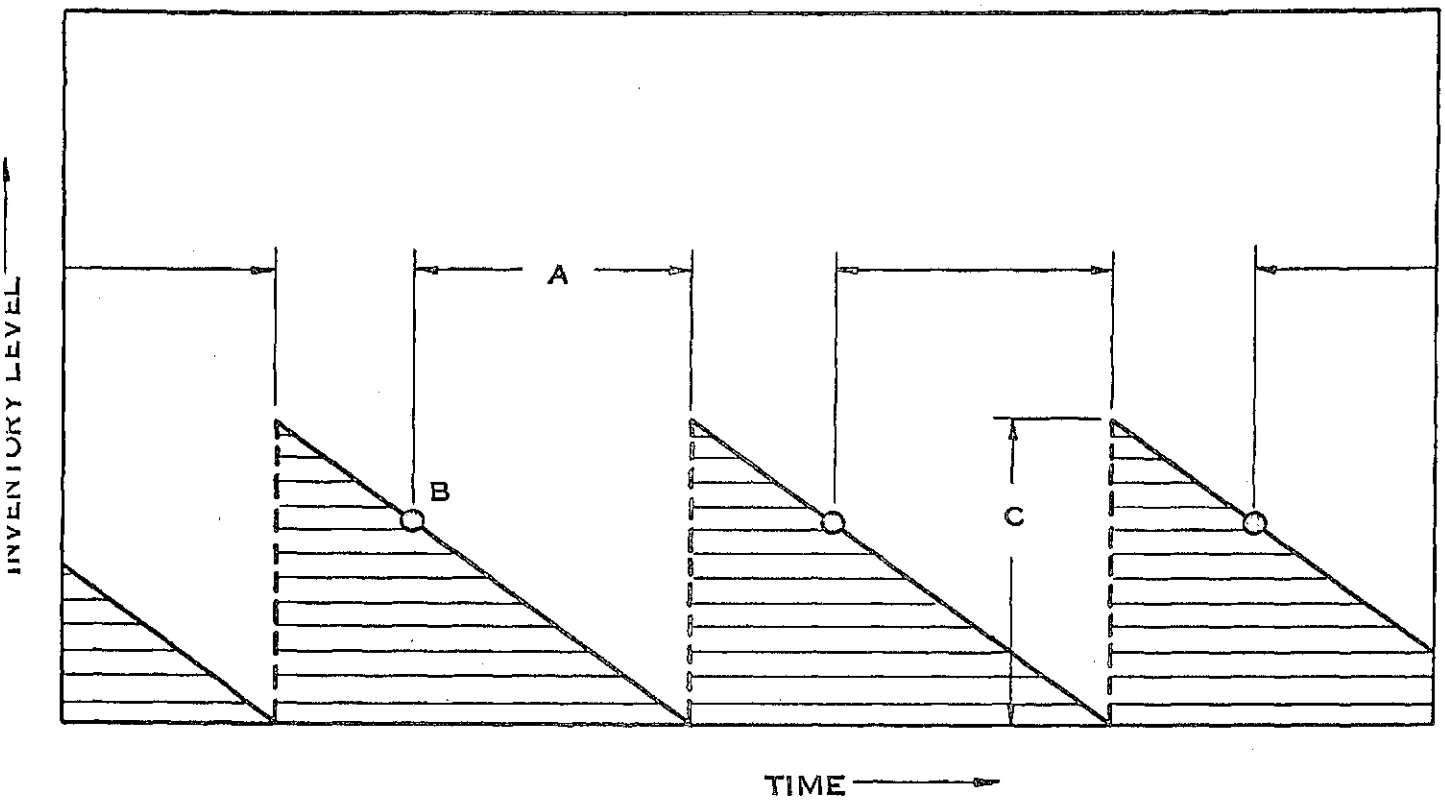

FIGURE 8

MODEL OF IDEAL INVENTORY BEHAVIOUR

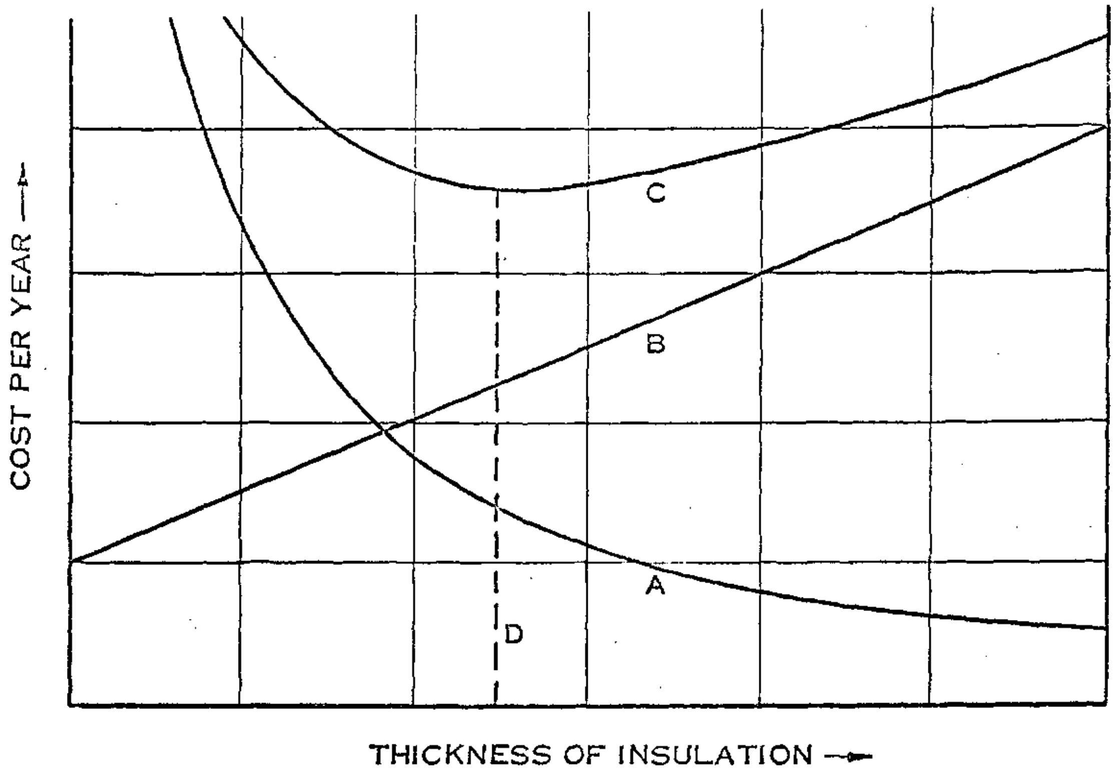

FIGURE 9

OPTIMUM THICKNESS OF THERMAL INSULATION

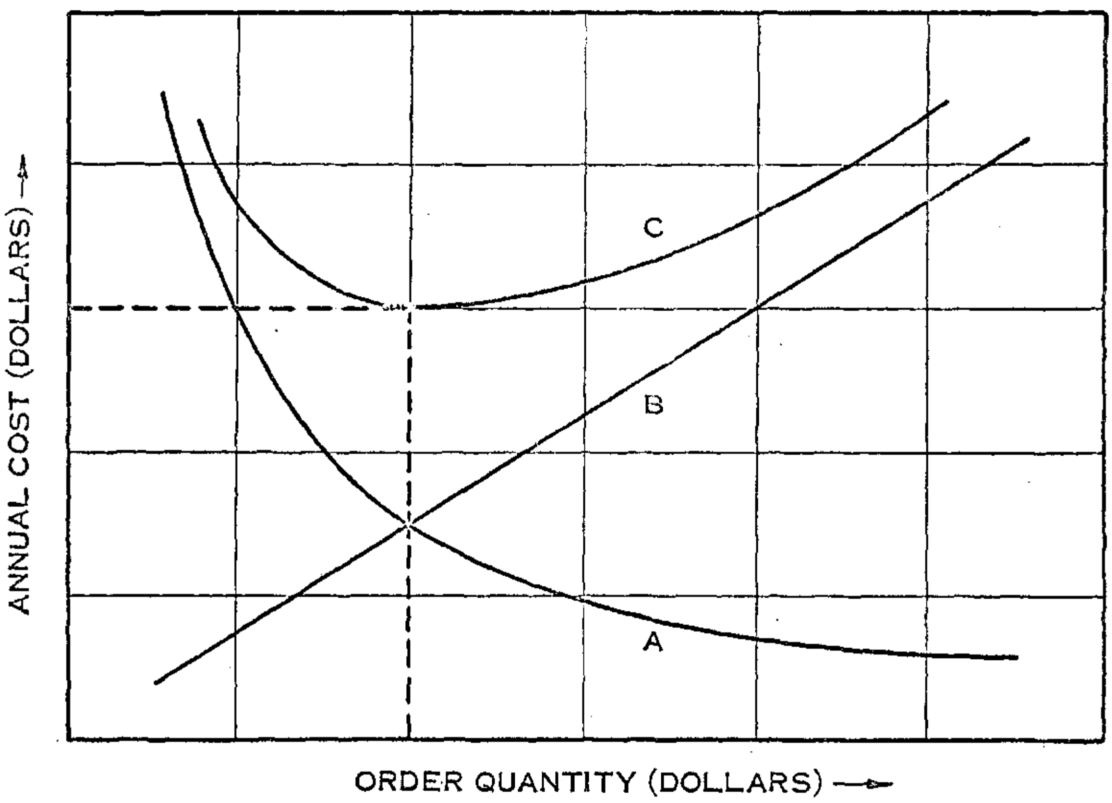

FIGURE 10

GRAPHICAL ILLUSTRATION OF ECONOMIC ORDER QUANTITY

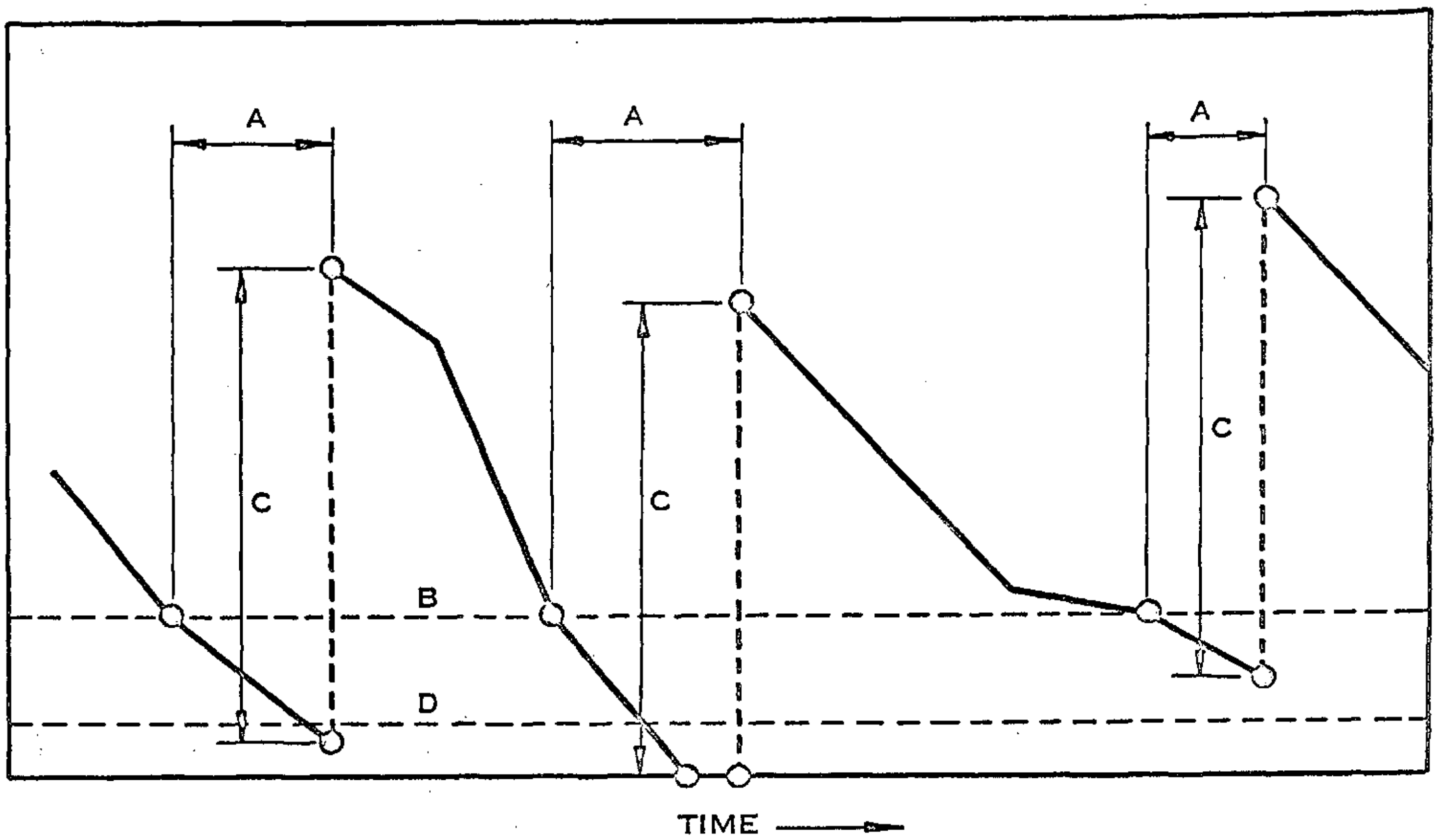

FIGURE II

TYPICAL INVENTORY SYSTEM WITH VARIABLE USAGE AND VARIABLE LEAD TIMES

YEAR : 1955 MATERIAL : COPPER WIRE SAFETY STOCK : 6 WEEKS

A	B	C	D	E	F	G	H	I	J	K	L
JAN 1	10689	10689		96718	228718	216029	18800	33	22000	27	22000
										28	22000
										29	44000
JAN 2	10347	10347		130371	218371	216029	18800				
JAN 3	4399	4399		125972	213972	216029	18800				
JAN 4	9803	9803		116169	222969	216029	18800	34	18800		
JAN 5	6590	6590		109579	216379	216029	18800				
FEB 1	8234	8234		101345	208145	216029	18800				
FEB 2	12264	12264		133081	214681	216029	18800	35	18800	30	22000
										31	22000
FEB 3	7616	7616		125465	225865	216029	18800	36	18800		
FEB 4	7486	7486		139979	218379	216029	18800			32	22000
MAR 1	2003	2003		137976	216376	216029	18800				
MAR 2	6643	6643		131333	209733	216029	18800				
MAR 3	9681	9681		121652	218852	216029	18800	37	18800		
MAR 4	5318	5318		157134	213534	216029	18800			33	22000
										34	18800
APR 1	5598	5598		151536	226736	221746	19000	38	18800		
APR 2	8378	8378		143158	218358	221746	19000				
APR 3	5835	5835		137323	231523	221746	19000	39	19000		
APR 4	6489	6489		149634	225034	221746	19000			36	18800
APR 5	12321	12321		156113	212713	221746	19000			35	18800
MAY 1	15063	15063		141050	216650	221746	19000	40	19000		
MAY 2	13742	13742		127308	221908	221746	19000	41	19000		
MAY 3	10886	10886		116422	211022	221746	19000				
MAY 4	10055	10055		106367	219967	221746	19000	42	19000		
JUN 1	11430	11430		94937	227537	221746	19000	43	19000		
JUN 2	22527	22527		110010	205010	221746	19000			37	18800
										38	18800
JUN 3	27650	27650		101360	196360	221746	19000	44	19000	39	19000
JUN 4	18224	18224		83136	216136	221746	19000	45	38000		
JUL 1	13091	13091		70045	222045	230100	19400	46	19000		
JUL 2	30052	30052		39993	211393	230100	19400	47	19400		
JUL 3	14581	14581		25412	216212	230100	19400	48	19400		
JUL 4	23656	23656		20756	211956	230100	19400	49	19400	43	19000
JUL 5	22215	20756	1459		209141	230100	19400	50	19400		
AUG 1	19200	20659		17341	228741	230100	19400	51	38800	45	38000
AUG 2	18131	17341	790		230010	230100	19400	52	19400		
AUG 3	17650	18440		560	231760	230100	19400	53	19400	44	19000
AUG 4	13950	13950		5610	217810	230100	19400			42	19000
SEP 1	16050	16050		8560	221160	230100	19400	54	19400	41	19000
SEP 2	35748	8560	27186		204812	230100	19400	55	19400		
SEP 3	24736	19000	32924		218876	230100	19400	56	38800	40	19000
SEP 4	15000	38800	9124		223276	230100	19400	57	19400	47	19400
										52	19400
OCT 1	13150	22274		16526	229526	246862	17800	58	19400	51	38800
OCT 2	10100	10100		25826	237226	246862	17800	59	17800	48	19400
OCT 3	10529	10529		15297	244497	246862	17800	60	17800		
OCT 4	19600	19600		15097	242697	246862	17800	61	17800	50	19400
OCT 5	16755	16755		17342	243742	246862	17800	62	17800	46	19000
NOV 1	5610	5610		69932	255932	246862	17800	63	17800	49	19400
										53	19400
										54	19400
NOV 2	25413	25413		44519	230519	246862	17800				
NOV 3	10307	10307		34212	238012	246862	17800	64	17800		
NOV 4	5038	5038		48574	250774	246862	17800	65	17800	55	19400
DEC 1	18119	18119		88655	232655	246862	17800			56	38800
										57	19400
DEC 2	19691	19691		86764	230764	246862	17800	66	17800	62	17800
DEC 3	4250	4250		119714	244314	246862	17800	67	17800	58	19400
										59	17800
DEC 4	7861	7861		129653	254253	246862	17800	68	17800	63	17800
				79721							

FIGURE 12

COMPUTER OUTPUT DATA OBTAINED FROM SIMULATION ANALYSIS

SHOWING THE EFFECT OF NEW ORDERING RULES ON INVENTORY BEHAVIOUR

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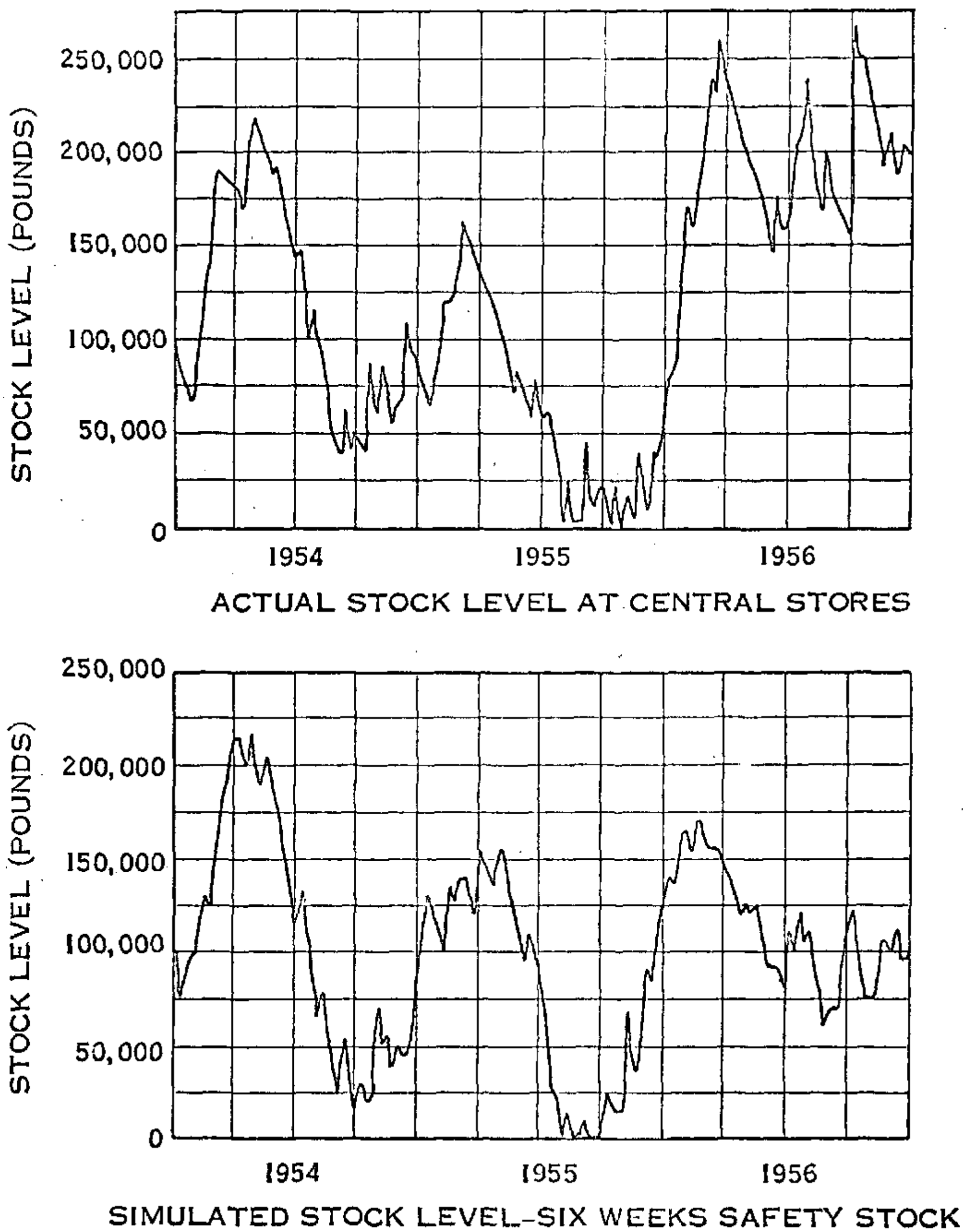

FIGURE 13

COMPARISON OF SIMULATED AND ACTUAL STOCK LEVELS OF COPPER WIRE

1 POUND = 0.4536 KG

ONTARIO HYDRO

INVENTORY MANAGEMENT REPORT

FROM THE OFFICE OF MANAGER SUPPLY CONTROL

LOCATION

MONTH July 1960

TYPE OF MATERIAL		MONTH'S USAGE	MONTH'S CHANGE IN STOCK	STOCK LEVEL	ECONOMIC INVENTORY LEVEL	POTENTIAL STOCK REDUCTION	INVENTORY CONTROL RATIO
		$	$	$	$	$	%
GENERAL MATERIAL		67,138	-7,907	137,619	135,100	2,519	2
POLES	QUANTITY	333		950			
	VALUE	11,904	-3,466	34,216	28,300	5,916	17
TRANSFORMERS	QUANTITY	79		382			
	VALUE	15,926	2,174	86,239	49,500	36,739	43
TOTAL	$	94,968	-9,199	258,074	212,900	45,174	17

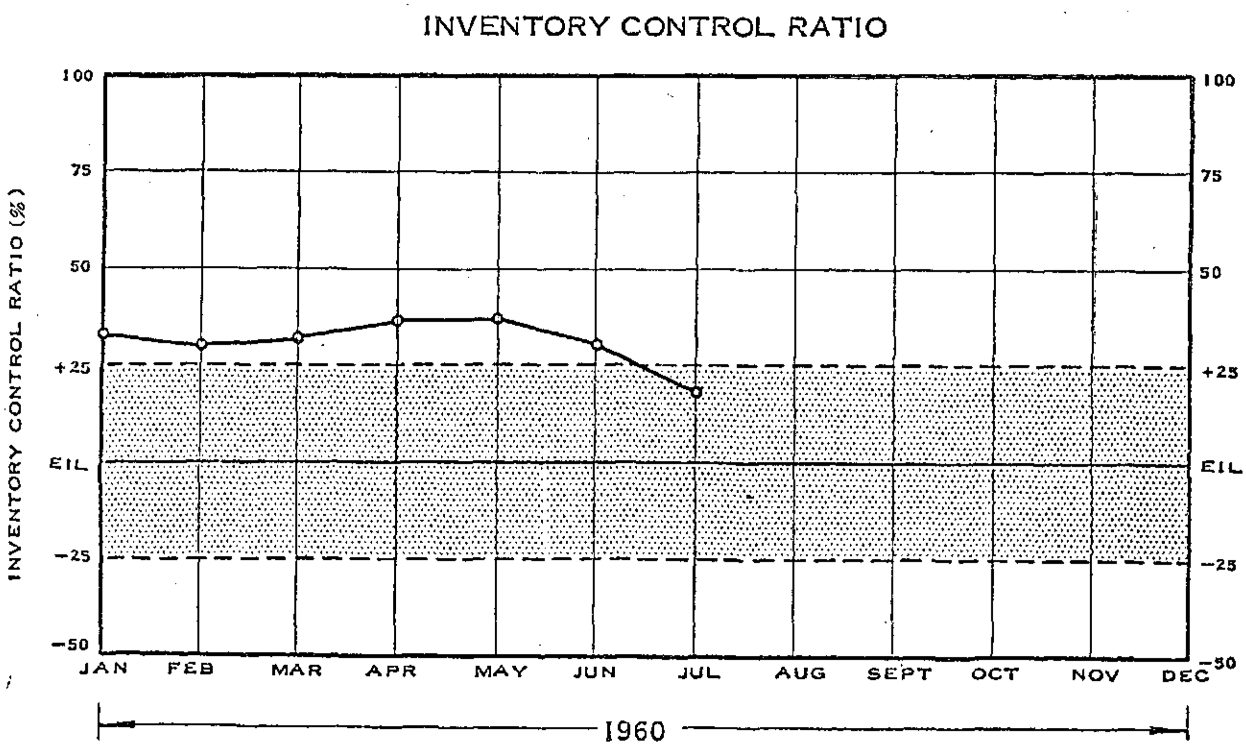

FIGURE 14 INVENTORY MANAGEMENT REPORT

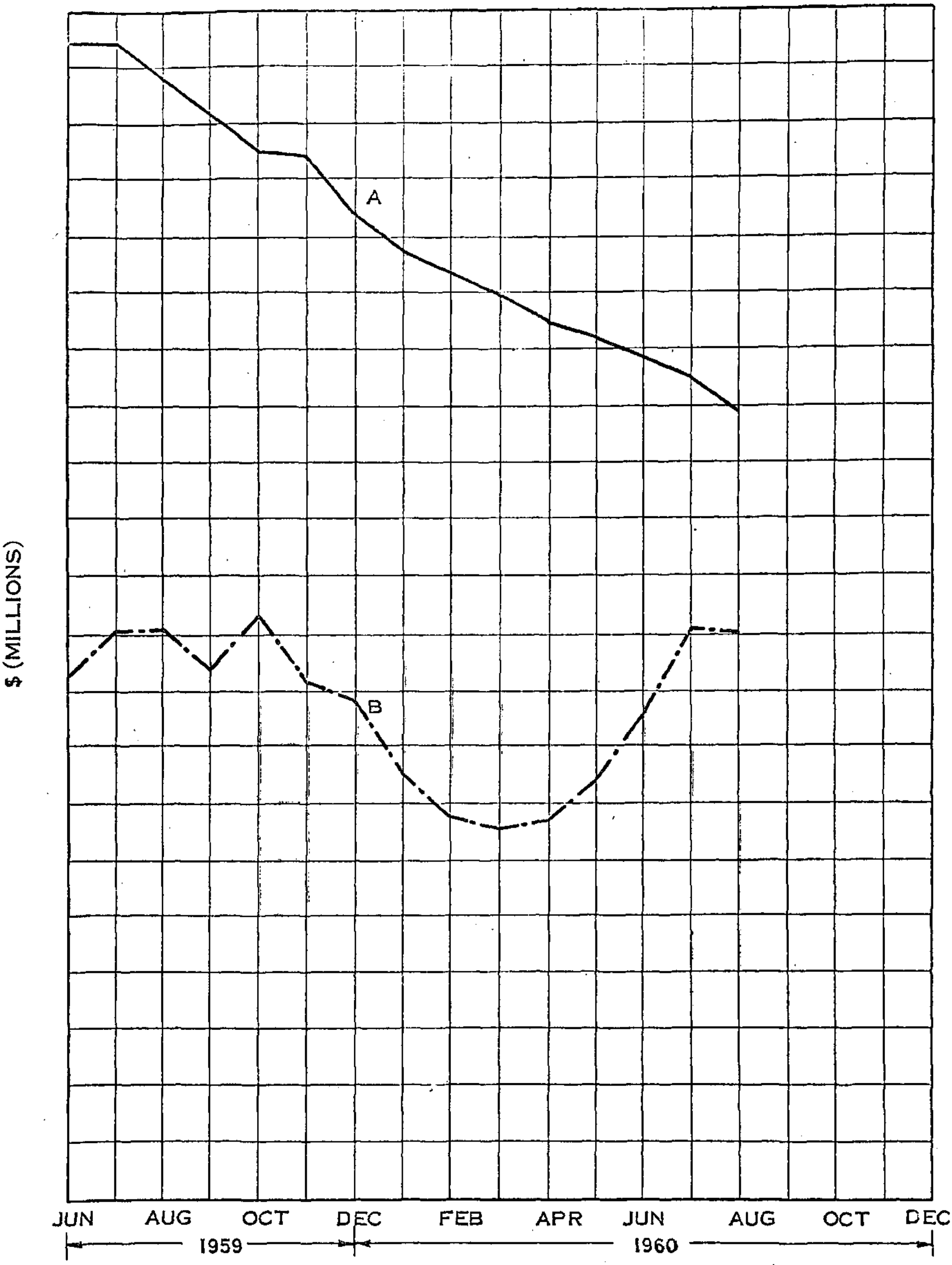

FIGURE 15

ECONOMIC INVENTORY CHART ALL REGIONS COMBINED

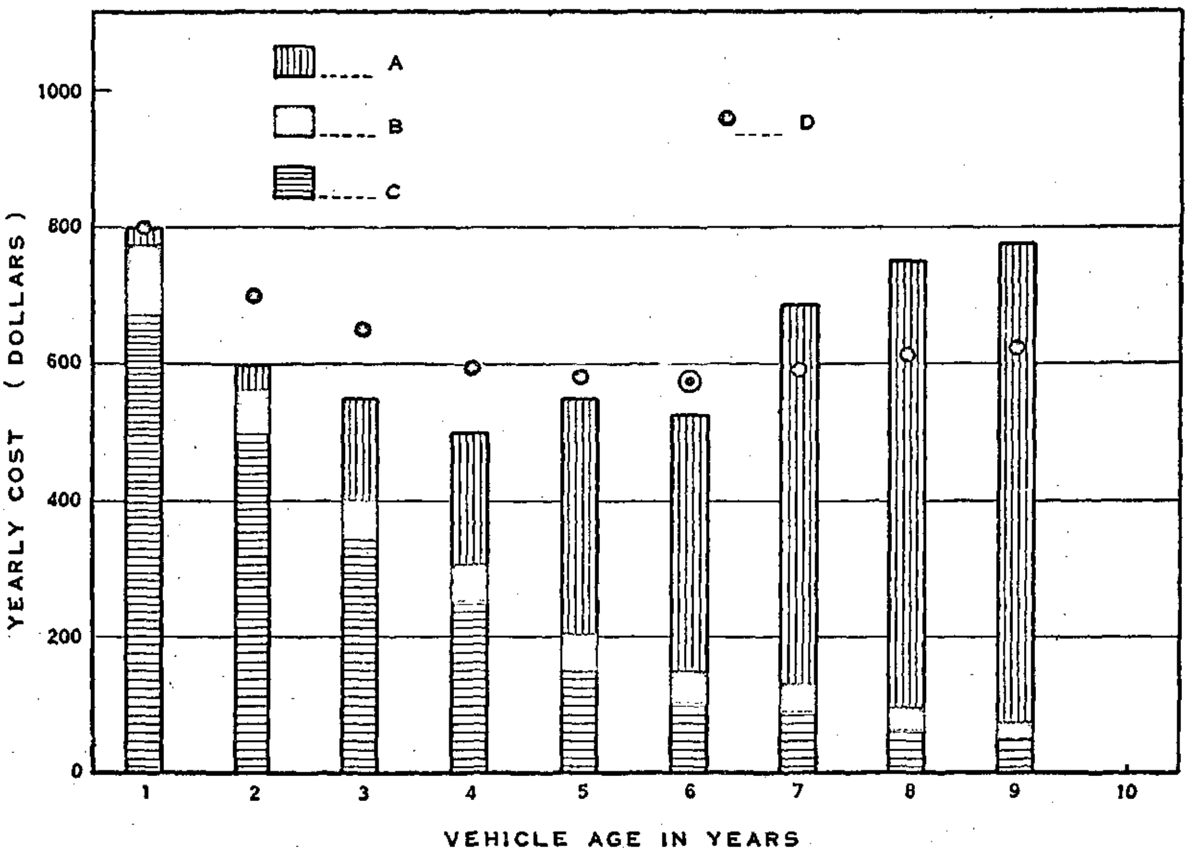

FIGURE 16

HYPOTHETICAL AVERAGE ANNUAL COSTS AND ACCUMULATED AVERAGE ANNUAL COSTS FOR A PARTICULAR CLASS OF VEHICLES

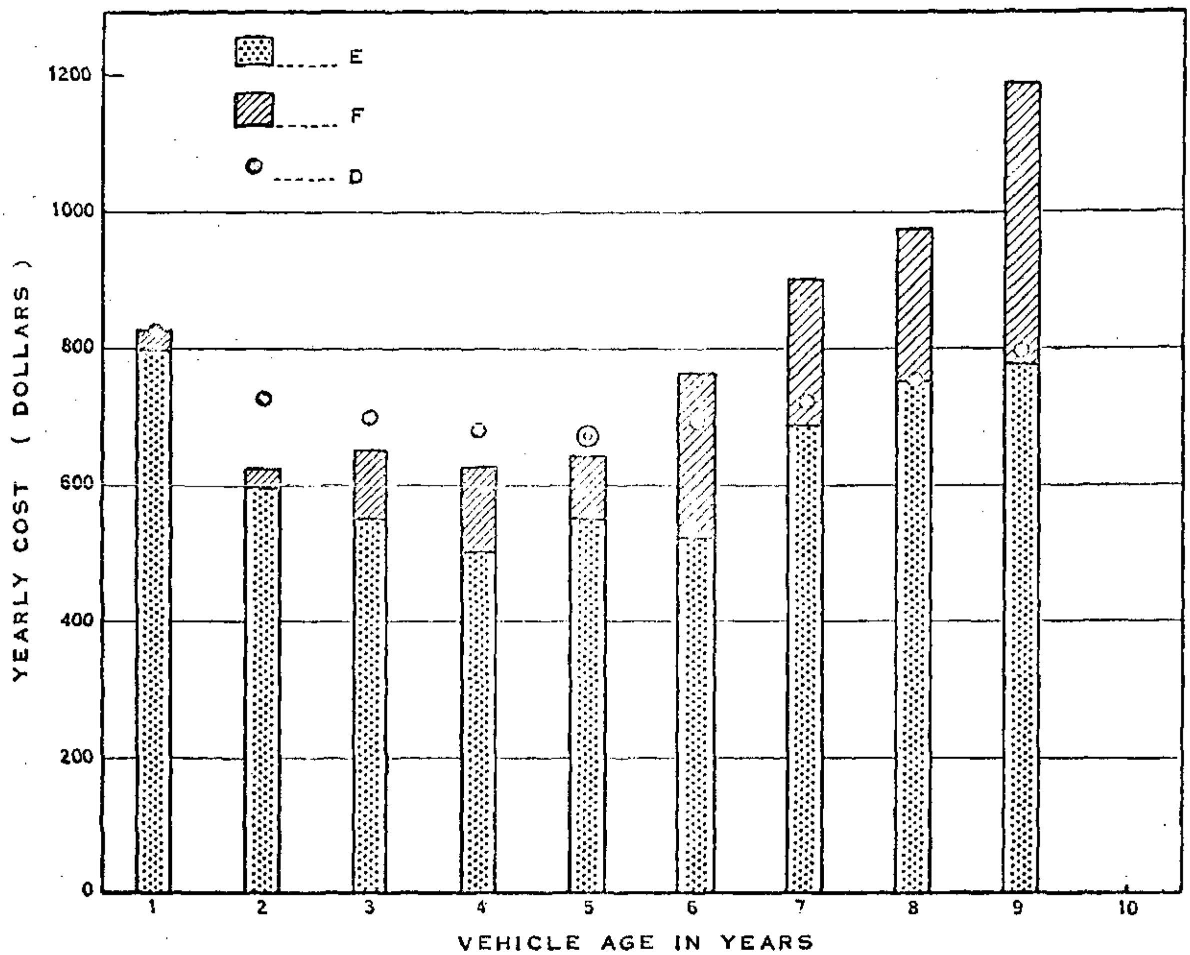

FIGURE 17

HYPOTHETICAL AVERAGE ANNUAL COSTS AND ACCUMULATED AVERAGE ANNUAL COSTS, INCLUDING UNSERVICEABILITY COSTS

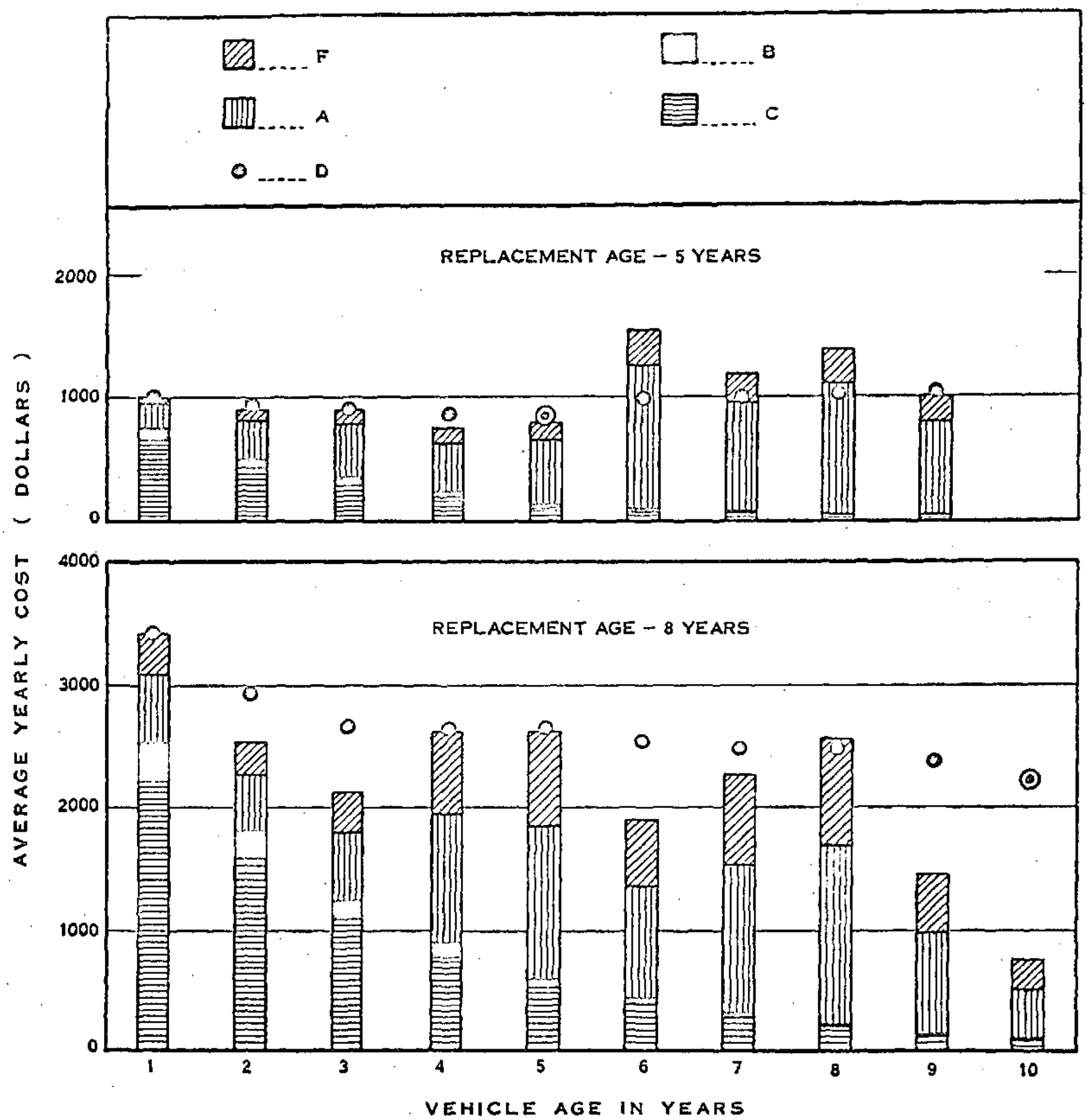

FIGURE 18

ACTUAL AVERAGE ANNUAL COSTS AND ACCUMULATED AVERAGE ANNUAL COSTS, INCLUDING UNSERVICEABILITY COSTS, FOR TWO CLASSES VEHICLES