BUILDING
ENERGY SYSTEMS
A DECISION ANALYSIS APPROACH

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1. INTRODUCTION:

This paper presents the methodology and conclusions of a decision analysis application to the problem of selecting the most economically attractive building energy system among a given set of alternatives. The specified problem involved the selection of a building energy system for the Conneticut General (Life) Insurance Company building to be constructed in Bloomfield Ct. The major actors in the process beside the decision analysis team were:

- Turner Construction Co.; Construction managers for the project and our client.
- Syska & Hennessy; Mechanical Consultants & designers.

1.1 Building Characteristics:

The building is a four story concrete structure of total floor area of 480,000 ft^2. Currently in the design phase, it is scheduled to go to construction during the latter part of 1980.

1.2 Alternative Energy Systems:

The concern of the owner with selecting the most cost efficient system that current technology would allow is clearly evident in the building program. The building successfully incorporates several passive energy concepts as a means toward meeting the above stated concern. The analysis evaluates the cost of the various alternatives both in terms of the initial capital cost and annual operating cost. It allows for the uncertainty inherent in the various variables, as encoded by our experts and accounts for the time value of money.
The following alternative systems are being considered:

1. Oil/gas conventional system:
2. Oil/gas conventional system and Low Temperature solar collector system. The solar system provides for part of the domestic hot water requirement of the building.
3. Oil/gas conventional system and High Temperature solar collector. The solar system provides for part of the domestic hot water, space heating & space cooling requirements of the building.
4. Oil/gas conventional system and Photovoltaic cell solar system. The photovoltaic system outputs electricity to be used to provide for part of the domestic hot water, space heating and space cooling requirements of the building.
5. Construction of a central plant on site. The plant will take electricity as an input and utilize available 50°F well water to provide for the domestic hot water, space heating and space cooling requirement of the building.
6. Electric conventional system
7. Electric conventional system and Low temperature solar collector system.
8. Electric conventional system and high temperature solar collector system.
9. Electric conventional system and photovoltaic cell solar system.

The above alternatives would provide for the total domestic hot water, space heating and space cooling requirements of the

building.

Light Shelf:

Probably the most pioneering energy saving proposal involves the construction of a "light shelf" designed to provide daytime natural lighting and reduce the electric lighting load of the building. The proposed light shelf would be equipped with shading devices to prevent direct sunlight from penetrating the building during the summer but would allow for diffused day light to contribute towards reducing the electric lighting load of the building.

Appendix F contains drawings of the building showing its location, characteristics, and the proposed light shelf design. Also, schematic drawings show the solar systems being considered.

1.3 Approach:

The decision analysis approach to problem solving consist of three phases.

1. Deterministic phase: the variables affecting the decision are identified and an influence diagram, showing the various relationships is constructed. Variables are divided into decision variables, or those controlled by the decision maker, and state variables, or those over which the decision maker exercises, no control but are a function of the problem environment. Using the upper and lower levels for each state variable as evaluated by the decision maker (or appointed experts) the sensitivity of each to the final outcome is determined. The least sensitive variables are set at their nominal value.

2. Probabilistic phase: the uncertainty around each of the more sensitive state variables is evaluated. A probability distribution is encoded for each of the state variables. The distributions are subsequently discretized and entered with their corresponding variable values on the decision tree. The phase would normally encompass the encoding of the owner's utility curve. Since, in this case, however, we are dealing with an owner which is not an individual but a company (board of directors) our problem defied definition of a utility curve. This element of the problem shaped the way that the results of the analysis are being presented.

3. Informational phase: During this phase, the results obtained by the analysis are reviewed and evaluated and the need for further information as well as the value for obtaining perfect information is assessed.

2. MODEL EVOLUTION

2.1. Influence Diagram.

Having realized what the problem was, at a preliminary level, we tried to identify the decisions and the state variables that affect such a problem in a general sense. The initial influence diagram that came out of this process is shown in fig. 2.1. A brief discussion of the decision and state variables used in this initial influence diagram follows:

- Decision on heat-light system: This decision concerns the choice of the conventional and solar heating and cooling systems and the choice of whether to incorporate light shelves in the building or not.

- Market price of fuel: This state variable refers to the future prices of gas, oil, and electricity, either in absolute terms or in terms of annual escalation factors. The latter approach seemed more feasible rather than trying to determine absolute prices for every single year.

- Weather: is the variable representing the environment and thus the change between the enviromental conditions and the interior of the building that the heating & cooling system has to produce.

- Heat Standard: is the limits set by federal and state agencies on what upper and lower bounds on humidity and temperature levels should be. The owner, also, may place more narrow bounds than the above for his own reasons.

- Energy loss coefficient: determines the transfer of heat between the outside and the inside of the building's envelope per unit of time and thus the required output of the heating

INITIAL INFLUENCE DIAGRAM

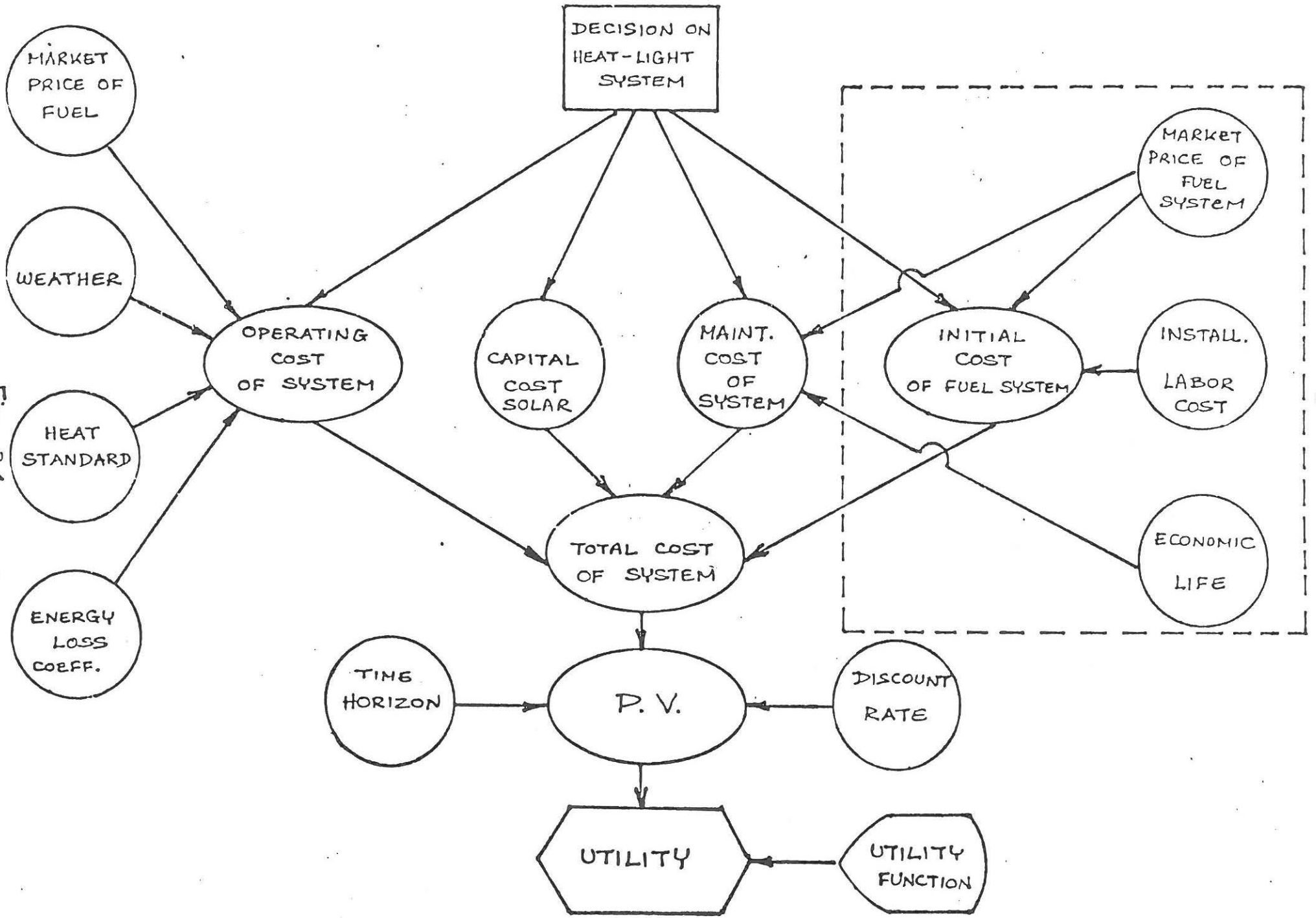


Fig. 2.1.

REVISED INFLUENCE DIAGRAM

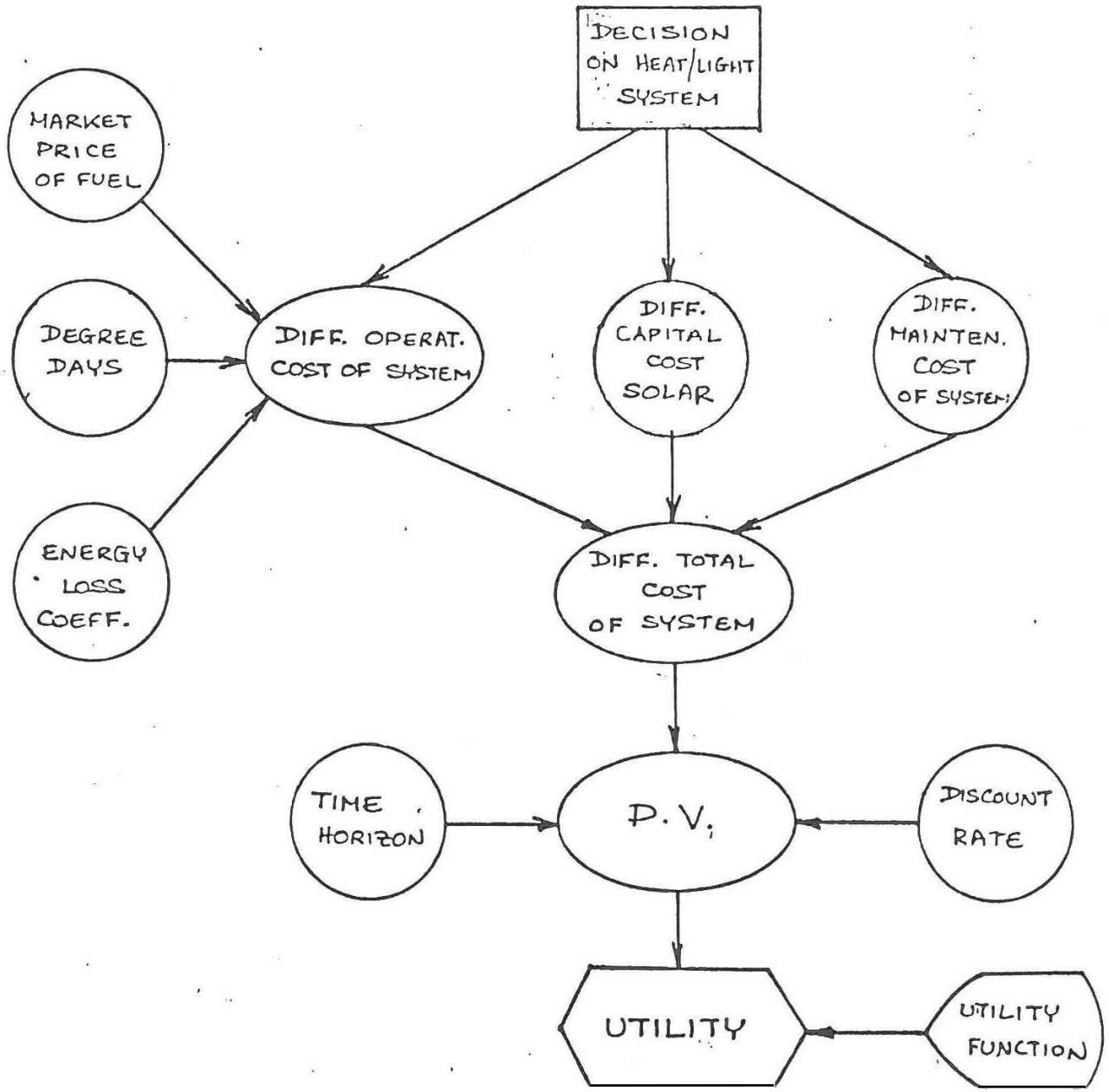


Fig. 2.2.

and cooling system.

All the above variables can be combined through an equation to represent the operating cost of the determined alternative.

- Capital Cost of the solar system: Depending on which solar system is chosen there exists a distribution of capital cost.

- Maintenance cost of system: This is the average annual cost for each of the conventional systems.

- Market price of fuel system: We have assumed that in a competitive market the price for each conventional system may vary, depending on such things as quality, availability, size etc.

- Installation labor cost. represents the amount of physical work that has to be encorporated in implementing each of the different alternatives within the general construction process.

- Economic Life: is the amount of time for which each of the systems will perform satisfactorily. Replacements within the time horizon of major parts have to be added to maintenance cost.

The choice of which system to use and the variables "market price of fuel system" and "installation labor cost" can provide us with the capital cost of the conventional system which along with the operating cost, the capital cost of the solar system and the maintenance cost go into the total cost of the system.

In order to find a present value of this total cost we must determine our time horizon and the discount rate to be used. Present values of cost can be inputed into the utility function and thus a decision can be reached as to which alternative is best.

After consulting with our client at this early phase we were informed that the variables inside the dashed line are almost the same for the alternatives considered (gas, oil, electricity, not central plant) and we thus decided to exclude them. The result is the revised influence diagram shown in fig. 2.2.

This revised influence diagram was looking at differential costs rather than total costs because it was our understanding that, no matter what the backup system would be, its capital cost would have been the same.

Later, however, after having talked with the mechanical consultants we realized that there was some difference in the capital cost of the different conventional systems and that another alternative, the Central Plant option, was being considered. After discussing our influence diagram we finally settled on what would be our final influence diagram structure (fig. 2.3, fig. 2.4).

We broke the initial decision in three parts:

a) decision on conventional heating/cooling system

b) decision on solar system alternatives

c) decision on whether to encorporate light shelves or not.

FINAL INFLUENCE DIAGRAM FOR HEATING/COOLING DECISIONS

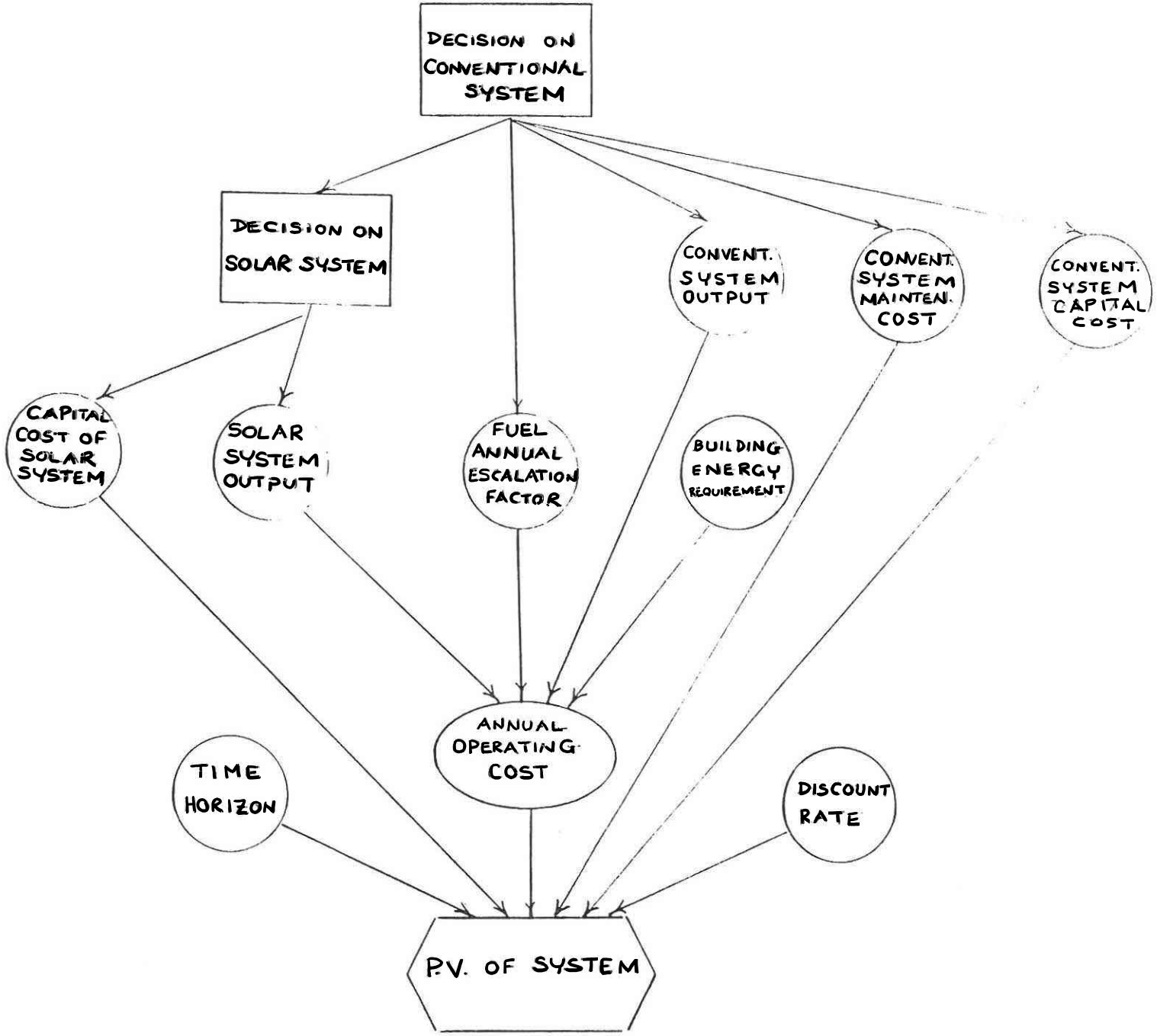


Fig. 2.3

FINIAL INFLUENCE DIAGRAM FOR DECISION ON LIGHT SHELF

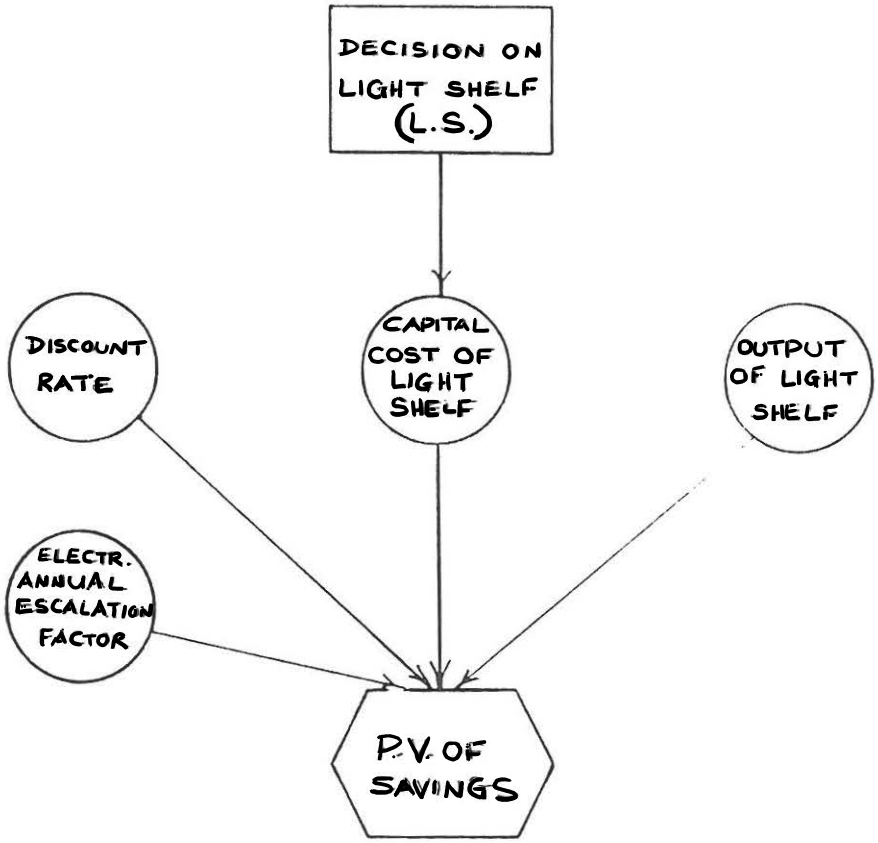


Fig. 2.4

The first two are shown in fig 2.3 and the last one in fig. 2.4 which are treated as separate entities. At the same time we condensed some of our variables into a new variable, e.g. Building Energy Requirement = F(weather, heat standard, energy loss coefficient).

We also added new variables like the efficiency of the conventional and solar alternatives reflected in

- Conventional System Output
- Solar system output
- Output of light shelf

At this point we were ready to proceed our analysis by constructing our value function.

2.2. Value Function

2.2.1 Heating/Cooling

Our value function is a straight forward present value formula that takes into account:

a) C_c: capital cost of the conventional system (gas, oil, electricity, central plant)

b) C_s: capital cost of the solar system (low temp, high temp, photovoltaic)

c) M : annual maintenance cost of the conventional system

d) B : annual building energy requirement (BTU/year)

e) Q_s: output of the solar system (BTU/year)

f) Q_c: output of the conventional system (BTU/Unit of fuel)

g) b : base price of fuel today ($/unit of fuel)

h) e : annual escalation factor for each kind of fuel (gas, oil, electricity)

i) i : discount rate

j) N : time horizon in years.

The basic formula for the present value of the total cost for each alternative is:

$$PV[TC] = C_c + C_s + \sum_{k=1}^{N} \frac{M}{(1+i)^k} + \sum_{k=1}^{N} \frac{B-Q_s}{Q_c}\, b\, \left(\frac{1+e}{1+i}\right)^k$$

Both summations represent the sum of the N first terms of geometric progressions and can be revised as follows:

$$\sum_{k=1}^{N} \frac{M}{(1+i)^k} = \frac{M}{(1+i)} \frac{\left(1 - \left(\frac{1}{1+i}\right)^N\right)}{1-1/(1+i)} = \frac{M}{i} \left(1 - (1+i)^{-N}\right)$$

$$\sum_{k=1}^{N} \frac{B-Q_s}{Q_c}\, b\, \left(\frac{1+e}{1+i}\right)^k = \frac{B-Q_s}{Q_c}\, b\, \left(\frac{1+e}{1+i}\right) \frac{\left(1 - \left(\frac{1+e}{1+i}\right)^N\right)}{1 - \left(\frac{1+e}{1+i}\right)}$$

2.2.2 Light Shelf

For the light shelf decision we have decided to use the present value of savings if the light shelves are used. The associated variables are:

a) Q_1: annual output of light shelf (KWH/year)

b) b : base price of electricity ($/KWH)

c) e : annual escalation factor for electricity

d) i : discount rate

e) c_1: light shelf capital cost

f) N : time horizon

The present value of savings, S, is:

$$PV(S) = \sum_{k=1}^{N} Q_1 b \left(\frac{1+e}{1+i}\right)^k - C_1$$

$$= Q_1 b \left(\frac{1+e}{1+i}\right) \frac{\left(1 - \left(\frac{1+e}{1+i}\right)^N\right)}{1 - \left(\frac{1+e}{1+i}\right)} - C_1$$

Fig. 2.5 summarizes the two formulas used.

P.V. OF TOTAL COST FORMULAS FOR HEATING/COOLING SYSTEMS

$$PV[\text{total cost}] = \text{Capital cost of Conventional system} + \text{capital cost of solar alternative} + \sum_{k=1}^{N} (\text{annual maint cost})/(1 + \text{discount rate})^{k} + \sum_{m=1}^{N} (\text{building energy req} - \text{output of solar})/(\text{output of conv. system}) \times (\text{base price of fuel}) \times (1 + \text{An. fuel esc. factor})^{m}/(1 + \text{discount rate})^{m}$$

Where: N = time horizon in years = 40 years

Discount rate = 15%

P.V. OF SAVINGS FORMULA FOR LIGHT SHELF

$$PV[\text{savings}] = \sum_{l=1}^{N} (\text{output of light shelf}) \times (\text{base price of electricity}) \times (1 + \text{electr. esc. factor})^{l}/(1 + \text{discount rate})^{l} - \text{light shelf capital cost}$$

Fig. 2.5

2.3. Preliminary Sensitivity Analysis.

It is evident from our final influence diagram that some of the state variables must not be treated probabilistically so that it would be feasible to make all the necessary value function calculations in a relatively short time. We have decided to keep the following state variables at their nominal value:

a) Cost of conventional system: It is highly a predictable cost in the current state of the industry. This was confirmed by the mechanical consultant, also.

b) Output of conventional system: It is a thermomechanical characteristic of a system which is predicted fairly accurately from experiments and past performance.

c) Building energy requirement: For the given type of building and its use the average requirement over a period of forty years is fairly stable.

At this point we considered it to be feasible for us to proceed with the construction of the generic decision trees for both the heating/cooling decision and the light shelf decision (fig. 2.6, fig. 2.7).

HEATING/COOLING GENERIC DECISION TREE

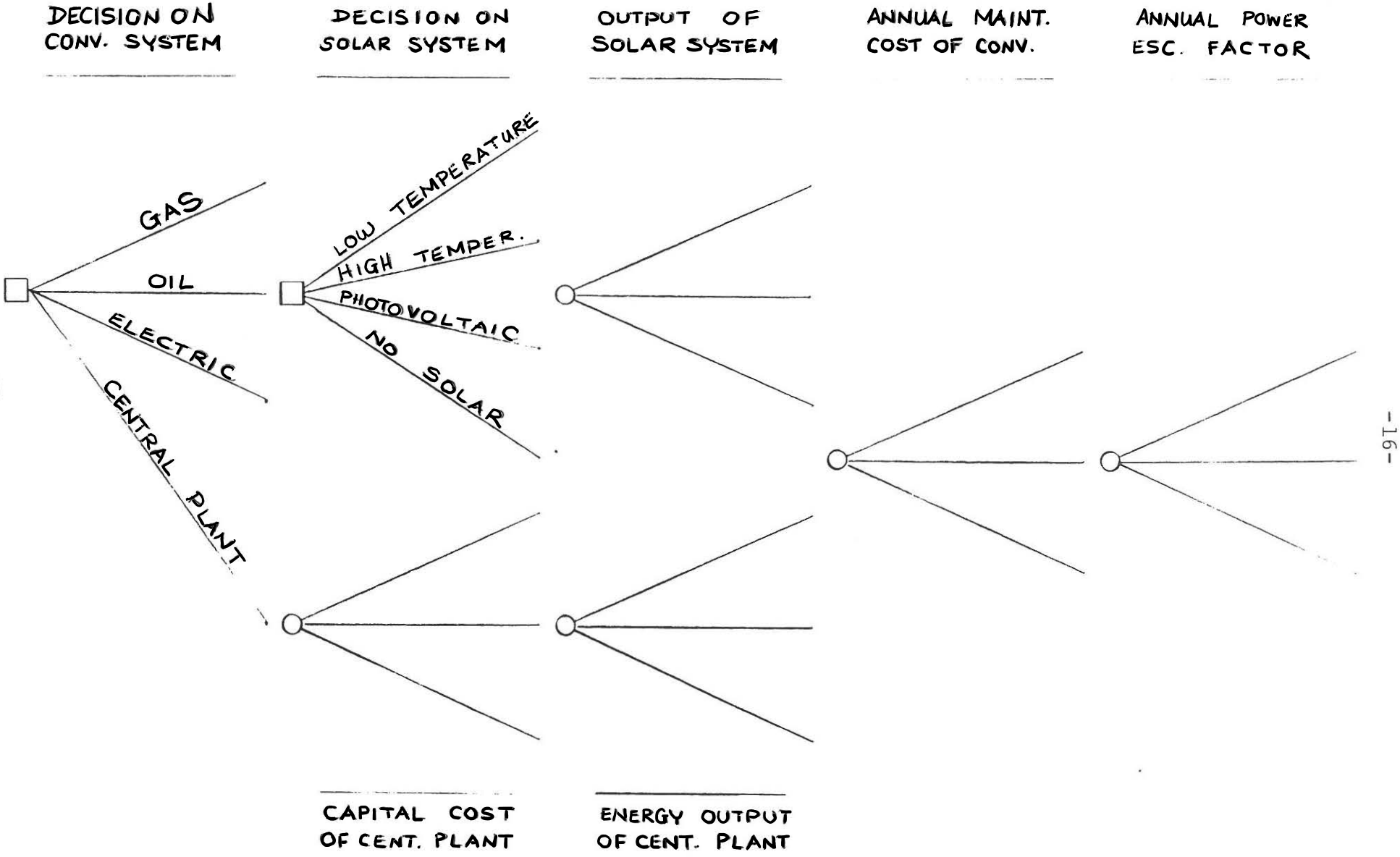


Fig. 2.6

GENERIC DECISION TREE FOR LIGHT SHELF DECISION

DECISION ON LIGHT SHELF

CAPITAL COST OF LIGHT SHELF

ENERGY OUTPUT OF LIGHT SHELF

ANNUAL ESCALATION FACTOR FOR ELECTRICITY

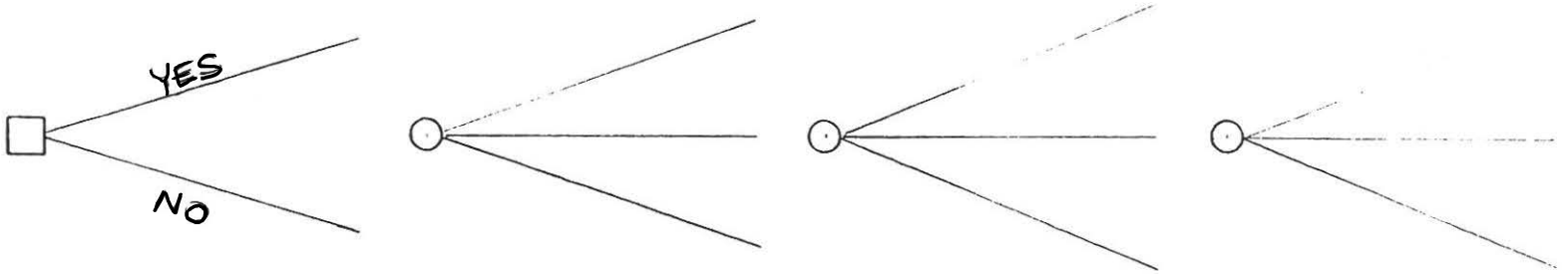


Fig. 2.7

3. PROBABILITY ENCODING

After establishing our generic trees, we obtained probability distributions for the required state variables from two persons:

- the Construction Manager of Turner Construction Co. which is our client and the Construction Consultant for the owner.
- and the Mechanical Engineer of Syska & Hennesy who are the mechanical consultants and designers.

We considered these two persons as the experts who would be able to provide us with the pertinent information needed as to the probability distributions of each variable.

Here, however, we have to admit that the above persons are not the appropriate experts as far as the annual escalation factors of oil, gas and electricity are concerned. The information concerning these escalation factors is due to a Sloan School professor who is considered to be an authority on this topic and is documented in a similar project conducted last year. We didn't feel that it was appropriate for us to go into the same probability encoding sessions with the same individual again since little has changed in the last year.

In encoding the probability distributions we used the P method. The encoder using this method fixes the values of the variables and asks questions about the probability values associated with these values. Our actual encoding process was done in the indirect mode by using the probability wheel.

The results were then tabulated and afterwards formed the data for plotting the cumulative probability functions shown

in Appendix A.

These cumulative curves were then discritized to three values for the "heating/cooling" decision tree and to five values for the "light-shelf" decision tree. Each discritized value was associated with an equal probability of 1/3 and 1/5 respectively. These values are shown in Appendix B.

Along with the probability associated variables we also got figures for the variables set at their nominal value. These values are also shown in Appendix B.

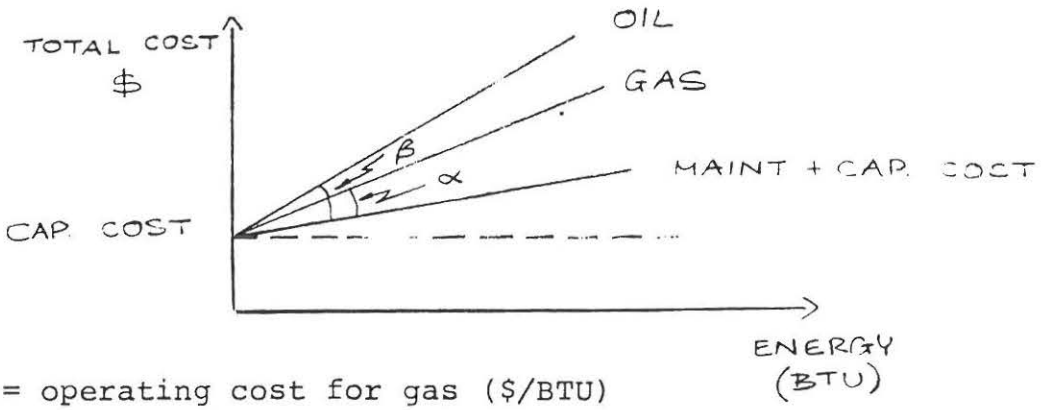
We should note here that a time horizon of forty years and a discount rate which is at least equal to the interest rate were required by the owner. This explains our choice of the discount rate being 15%, which is reasonable under the above assumption.

4. FURTHER MODEL CONSIDERATIONS.

At this stage our model was ready to undergo the standard deterministic sensitivity analysis. Since, however, we were planning to use a computer program to handle all calculations this procedure did not seem to be essential. Instead, we tried to find dominance in the alternatives considered and later we checked the sensitivity of the outcome as measured by changes in the solar collector area, the required discount rate and the fuel escalation factors. This was an essential step in our procedure in order to determine whether we should obtain better information or not.

4.1 Operating Cost Comparison of Oil & Gas Conventional Systems

According to our experts' opinion both systems have the same dist. for capital cost, maint. cost and both gas & oil have the same annual escalation factors (Ap.A)



α = operating cost for gas ($/BTU)

β = operating cost for oil ($/BTU)

	BASE PRICE OF GAS $/CF	OUTPUT (BTU/CF)		α $/BTU	
		LOW	HIGH	LOW	HIGH
GAS	0.0046	$0.955_3 \times 10^3$	$1.018_3 \times 10^3$	4.52×10^{-6}	4.82×10^{-6}

	BASE PRICE OF OIL $/GALLON	OUTPUT (BTU/GAL)		β $/BTU	
		LOW	HIGH	LOW	HIGH
OIL	0.88	$138.1_3 \times 10^3$	$140.2_3 \times 10^3$	6.28×10^{-6}	6.37×10^{-6}

It is evident that oil is dominated by gas. We have decided to delete oil from our final decision tree calculations.

4.2. Economic Evaluation of Solar Systems.

At this stage our final decision tree was constructed and all the associated values and the corresponding probabilities were determined. We then proceeded to calculate the present value of total cost function for each path of the decision tree.

During this process it became evident that the solar alternatives were not competitive, since the values of the value function for total cost concerning the conventional systems ranged between \$1.5 ∿ 3.5 million whereas the capital cost of the solar systems alone were \$12M and \$30 for the H.T and the Photovoltaic systems respectively. The solar systems' costs and outputs were as follows:

SYSTEM	C. COST/SQ.FT. $	OUTPUT/SQ.FT. BTU
Low Temperature	50	168,000
High Temperature	80	168,000
Photovoltaic	200	58,021

It is evident that low temperature dominates the other alternatives. The question is how much should the area of the collector be, and what should be the escalation factor of the most competitive conventional system's fuel be in order for the L.T. solar system to be economically acceptable.

$$PV[savings] = \sum_{k=1}^{N} [output/sq.ft]^{solar} \times [area]^{solar} \times [1/[output]^{conv}] \times [base\ value]^{fuel} \times [1 + escal]^{k} \times [1/[1 + R.R.]^{k}] - [cap.\ cost/sq.ft]^{solar} \times [area]^{solar}$$

And $PV[savings] \geq 0$ For solar to be acceptable

The equation can be written:

$$\sum_{k=1}^{N} \frac{Q_s \cdot A_s}{Q_c} \; b \; \left(\frac{1+e}{1+i}\right)^{k} - C_s \cdot A_s \geq 0$$

The most competitive conv. system uses gas and has the following characteristics:

Base Cost of Gas (b) = \$0.005/c.ft.

Output of gas system (Q_c) = 980 BTU/c.ft.

The above equation can be simplified as:

$$\frac{Q_s}{Q_c} \; b \; \frac{1+e}{1+i} \; \frac{1 - \left(\frac{1+e}{1+i}\right)^{k}}{1 - \left(\frac{1+e}{1+i}\right)} - C_s \geq 0$$

Taking N = 40 years and $\frac{1+e}{1+i} = r$ ——>

$$\frac{168000}{980} \times 0.005 \; \frac{r(1-r^{40})}{1-r} - 50 \geq 0 \quad \text{——>}$$

$r < 1 \quad 0.857\ r(1-r^{40}) \geq 50 - 50r$

solving for r we get $\quad 1 \leq r \leq 1.0175$

which is impossible

$r > 1 \quad 0.857\ r(1-r^{40}) \leq 50 - 50r$

solving for r we get $\quad r < 1 \qquad r > 1.0175$

which means $\quad \frac{1+e}{1+i} > 1.0175 \quad \longrightarrow$

$$e > .0175 + 1.0175i$$

For $i = 15\% \longrightarrow e \geq 17\%$

$i = 20\% \longrightarrow e \geq 22\%$

$i = 30\% \longrightarrow e \geq 32\%$

This result leads to the conclusion that:

The solar system competiveness

a) does not depend on the building energy requiremnt

b) does not depend on the collector's area

c) does not depend (to a certain degree) on the output of the solar system

d) depends on its capital cost per square foot

e) depends on the relation between the escalation factor of the conventional system's fuel and the discount rate required by the owner.

Prepositon (c) can be inferred from the final form of the savings equation. We can observe that as the output per square foot of the solar system increases only Δi in the relation $e \geq i + \Delta i$ decreases.

We believe that the above statement is one of the most important findings of our project which at the same time justifies our procedure.

We can also observe that since the escalation factors are usually lower than the discount rate it is not economically feasible, for the given conditions, to use any of the solar systems until their capital cost is reduced.

Our final results are presented in the next chapter.

5. ANALYSIS AND RESULTS

5.1 Analysis of the model

The most common approach, in analyzing the decision tree model, is to fold back the tree by calculating the expected values of the probability distributions at the state nodes and by selecting the alternatives with the most preferred values at the decision nodes. The main problem in this folding-back approach, however, is that it does not carry the whole probability distribution but carries only the expected value which is only the mean or central tendency of the probability distribution. This problem becomes serious when the degree of variation differs very much between two branches while their expected values do not differ very much. Furthermore, this kind of bias at a decision node is confounded when we have a series of different decision nodes in our tree.

To avoid the potential problems in using the folding-back calculation approach, we adopted a simulation approach to analyze our decision tree model. Basically what the simulation approach does, is to carry the whole probability distribution instead of a single value, that is, the expected value. (The logical flow diagram of this simulation approach and the program listing is shown in Appendix C and D.)

In adopting the simulation approach, we also defined the "dominance index" for each decision node which represents the frequency with which one alternative dominates over the other. For instance, an alternative with dominance index of .7 implies that the alternative dominates over the other altern-

atives at that decision node with a frequency of .7 out of 1.0. Similarly, an alternative with dominance index of 1.0 implies that it perfectly dominates over the other alternatives.

5.2 Results

We performed simulation on our decision tree based on the run length obtained as a result of our analysis on determination of appropriate sample size in simulation. (This analysis is shown in Appendix E.) The results of our analysis are shown in fig. 5.1, fig. 5.2, fig. 5.3, and fig. 5.4 for the main decision regarding the conventional and solar system options, and in fig. 5.5 for the light-shelf decision.

Fig. 5.1 shows the front-end part of the decision tree model with averaged value, dominance index, and value range for each alternative.

Fig. 5.2 shows the cumulative probability distributions for the three options at the decision node 1, that is, gas option, central plant option, and electricity option.

Fig. 5.3 shows the cumulative probability distributions for the two options at the decision node 10, that is, low temperature system for gas option, and no solar system for gas option.

Fig. 5.4 shows the cumulative probability distributions for the two options at the decision node coded 12, that is, low temperature system for electricity option, and no solar system for electricity option.

Fig. 5.5 shows the cumulative probability distributions for the two alternatives regarding the light-shelf decision, that

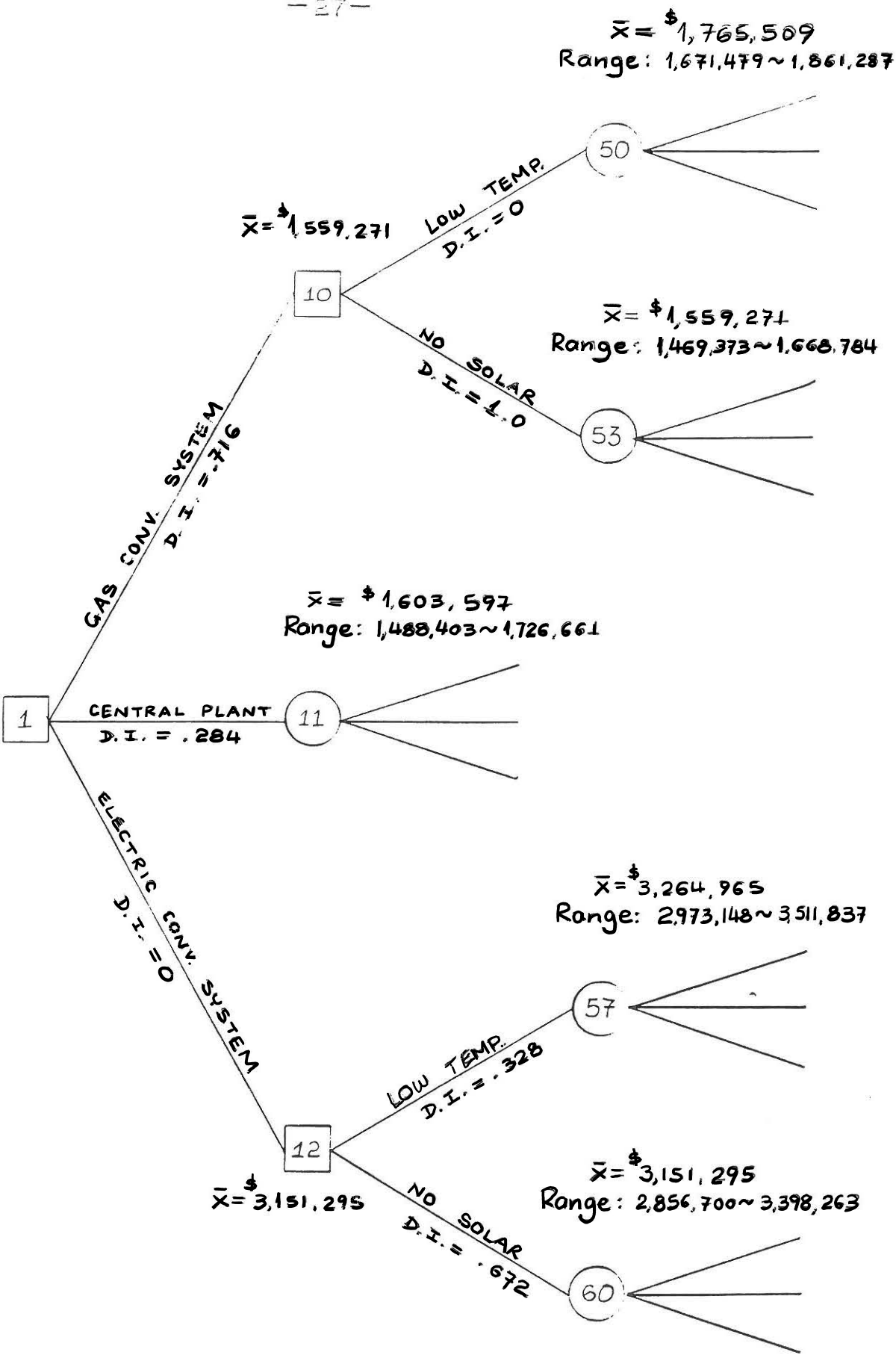
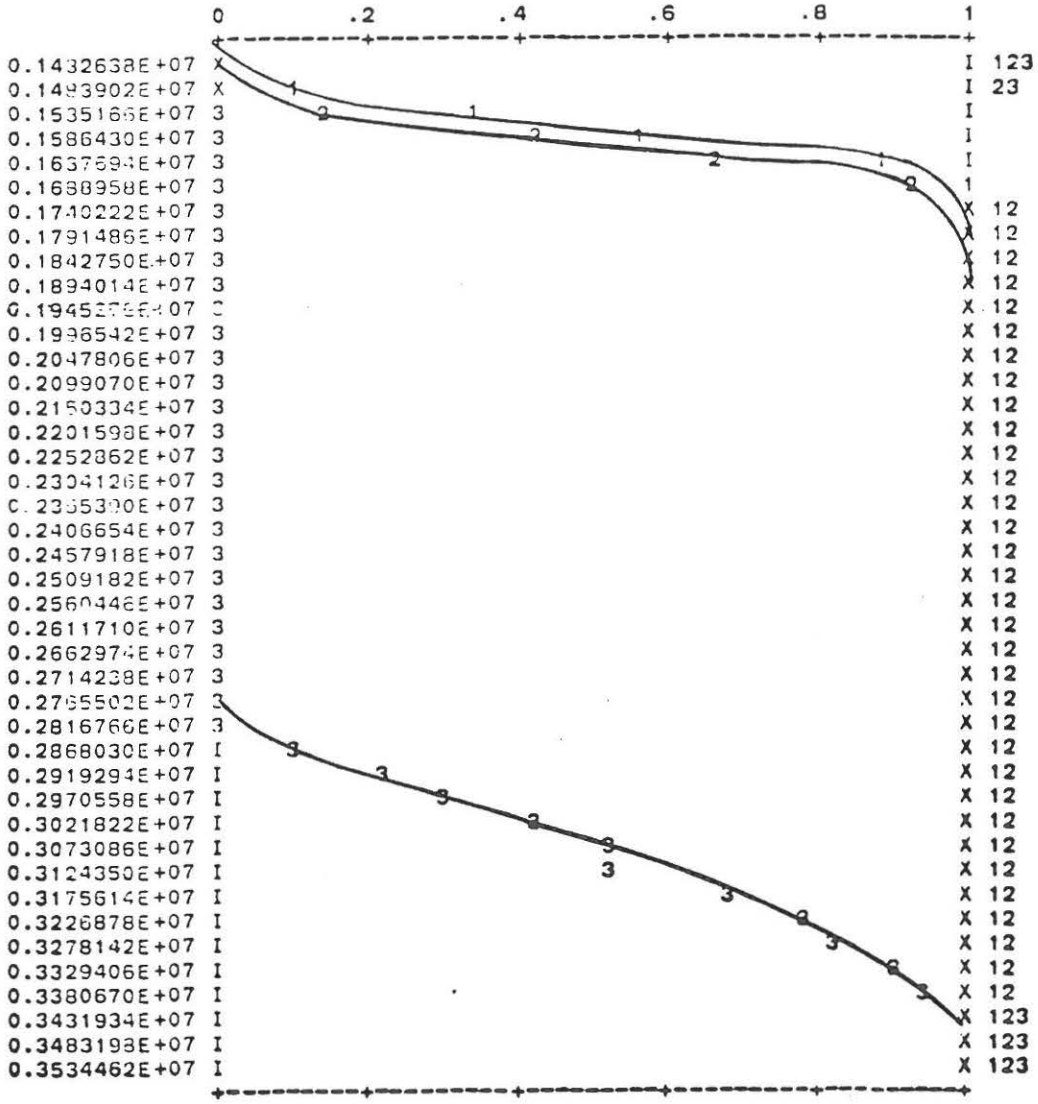

$\bar{x}$ = $1,765,509
Range: 1,671,479 ~ 1,861,287
50
LOW TEMP.
D.I. = 0
$\bar{x}$ = $1,559,271
10
NO SOLAR
D.I. = 1.0
$\bar{x}$ = $1,559,271
Range: 1,469,373 ~ 1,668,784
53
GAS CONV. SYSTEM
D.I. = -.716
$\bar{x}$ = $1,603,597
Range: 1,488,403 ~ 1,726,661
1
CENTRAL PLANT
D.I. = .284
11
ELECTRIC CONV. SYSTEM
D.I. = 0
$\bar{x}$ = $3,264,965
Range: 2,973,148 ~ 3,511,837
57
LOW TEMP.
D.I. = .328
12
$\bar{x}$ = $3,151,295
NO SOLAR
D.I. = .672
$\bar{x}$ = $3,151,295
Range: 2,856,700 ~ 3,398,263
60

Fig. 5.1.

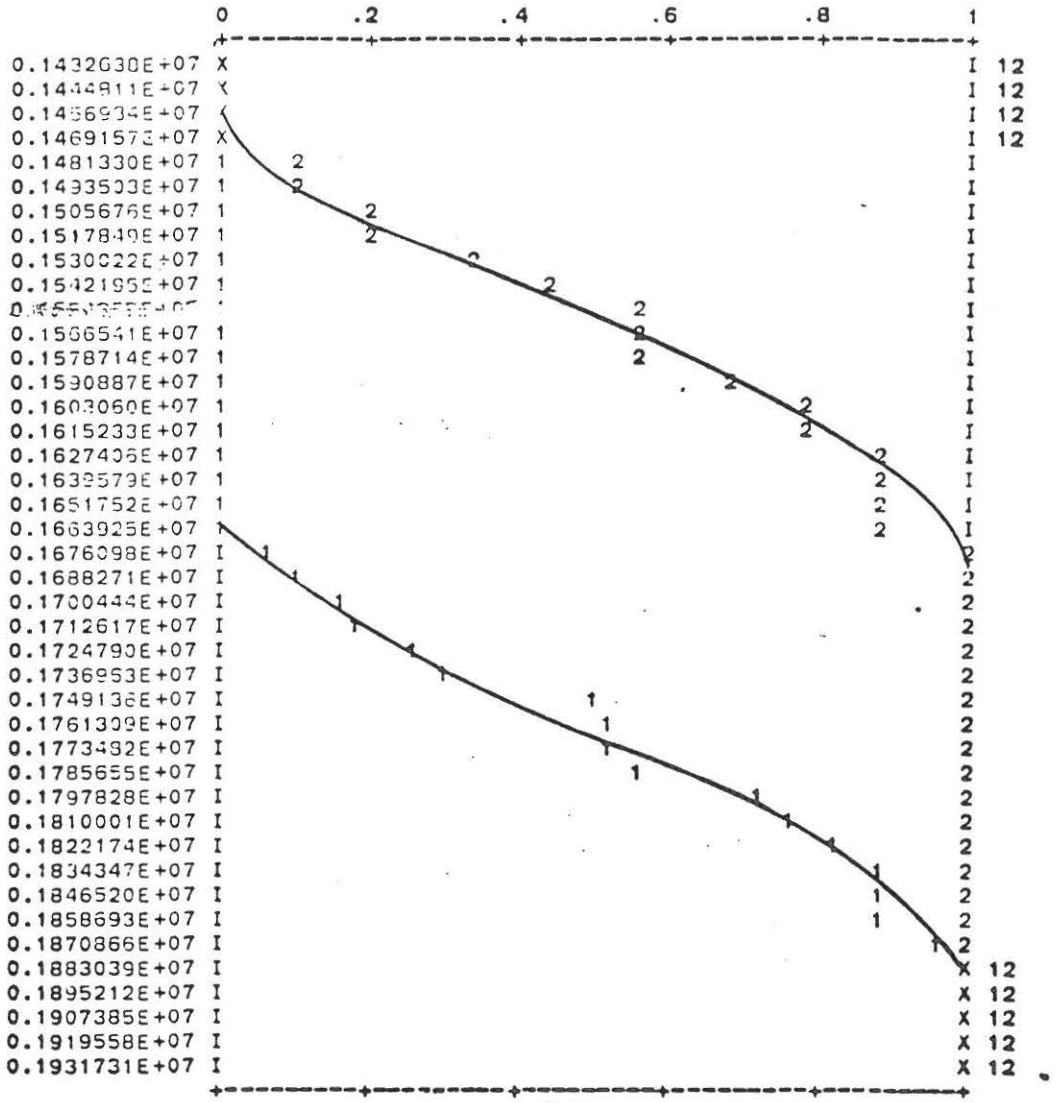
1 : OIL/GAS OPTION
2 : CENTRAL PLANT OPTION
3 : ELECTRICAL OPTION



I	J	AVG	DOM INDEX	DESCRIPTION
1	10	0.1559271E+07	0.716000	OIL/GAS OPTION
1	11	0.1603597E+07	0.284000	CENTRAL PLANT OPTION
1	12	0.3084219E+07	0.0	ELECTRICAL OPTION
10	50	0.1765509E+07	0.0	LOW TEMP SYSTEM (OIL/GAS)
10	53	0.1559271E+07	1.000000	NO SOLAR SYSTEM (OIL/GAS)
12	57	0.3264965E+07	0.328000	LOW TEMP (ELECTRICAL)
12	60	0.3151295E+07	0.672000	NO SOLAR SYSTEM (ELECTRICAL)

Fig. 5.2

1 : LOW TEMP SYSTEM (OIL/GAS)
2 : NO SOLAR SYSTEM (OIL/GAS)



I	J	AVG	DOM INDEX	DESCRIPTION
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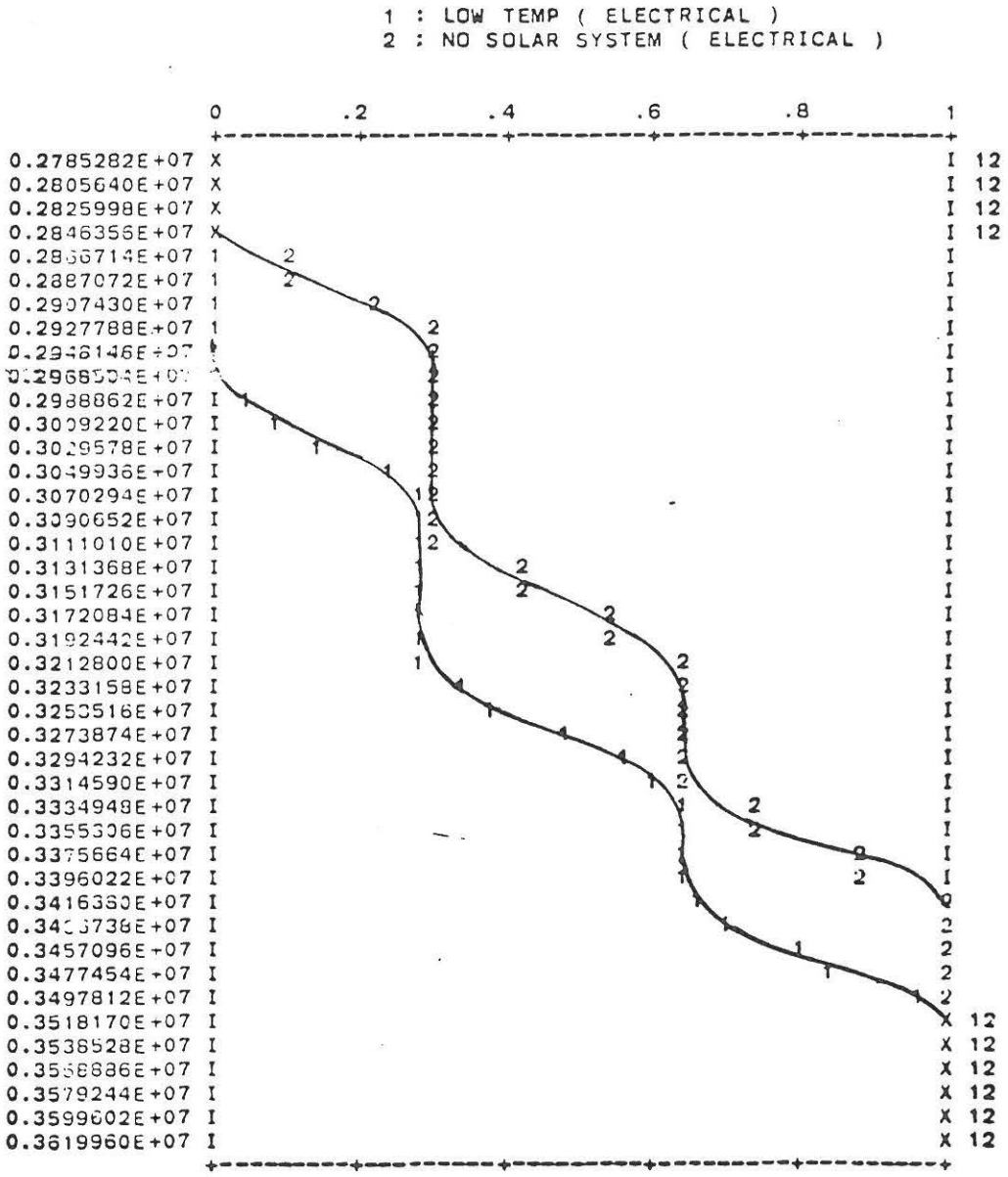
1	11	0.1603597E+07	0.284000	CENTRAL PLANT OPTION
1	12	0.3084219E+07	0.0	ELECTRICAL OPTION
10	50	0.1765509E+07	0.0	LOW TEMP SYSTEM (OIL/GAS)
10	53	0.1559271E+07	1.000000	NO SOLAR SYSTEM (OIL/GAS)
12	57	0.3264965E+07	0.328000	LOW TEMP (ELECTRICAL)
12	60	0.3151295E+07	0.672000	NO SOLAR SYSTEM (ELECTRICAL)

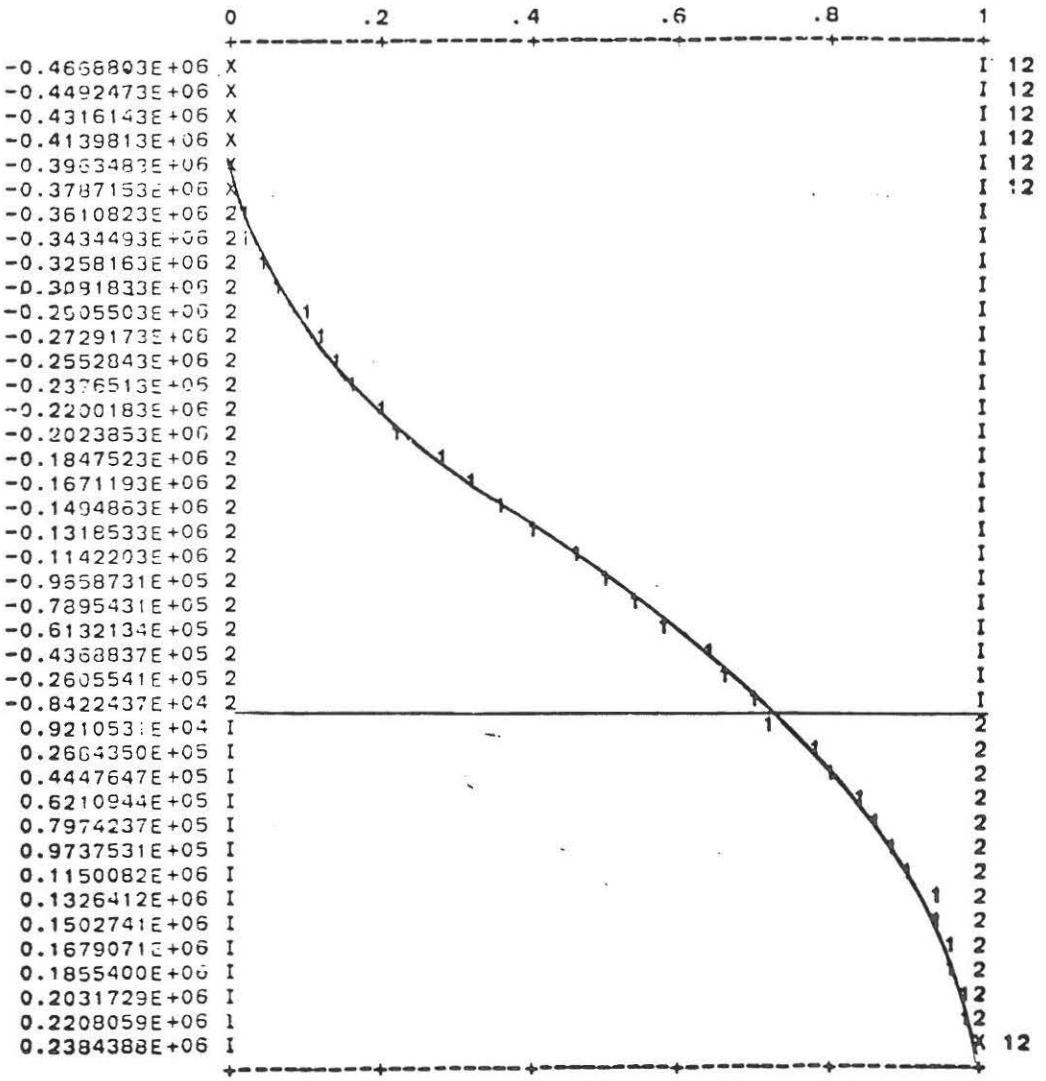
Fig. 5.3



I	J	AVG	DOM INDEX	DESCRIPTION
1	10	0.1559271E+07	0.716000	OIL/GAS OPTION
1	11	0.1603597E+07	0.284000	CENTRAL PLANT OPTION
1	12	0.3084219E+07	0.0	ELECTRICAL OPTION
10	50	0.1765509E+07	0.0	LOW TEMP SYSTEM (OIL/GAS)
10	53	0.1559271E+07	1.000000	NO SOLAR SYSTEM (OIL/GAS)
12	57	0.3264965E+07	0.328000	LOW TEMP (ELECTRICAL)
12	60	0.3151211E+07	0.672000	NO SOLAR SYSTEM (ELECTRICAL)

Fig. 5.4

1 : LIGHT-SHELF SYSTEM
2 : NO LIGHT-SHELF SYSTEM



I	J	AVG	DOM INDEX	DESCRIPTION
1	2	-0.9527112E+05	0.282000	LIGHT-SHELF SYSTEM
1	3	0.0	0.718000	NO LIGHT-SHELF SYSTEM

Fig. 5.5

is, adopting the light-shelf system, and not adopting the light-shelf system.

As shown in the above figures, our final results are summarized as follows:

1) For the main decision on the conventional and solar systems

a) The "gas" option (average cost of $1,559,271) dominates with frequency of .716, the "central plant" option (average cost of $1,603,597) dominates with frequency of .284, and the "electricity" option (average cost of $3,084,219) is perfectly dominated by the other two options for the main decision on the selection of a conventional system.

b) The "no solar system" option (average cost of $1,559,271) perfectly dominates the "low temperature system" (average cost of $1,765,509) if we adopt the "gas system."

c) The "no solar system" (average cost of $3,151,295) dominates the "low temperature system" (average cost of $3,264,965) with frequency of .672 if we adopt the "electrical system." This option, however, is to be disregarded since the "electrical system" option is perfectly dominated by the "gas system" option and "central plant" option.

2) For the decision on the light-shelf system, the "no light-shelf" option (average cost of $ 0.0) dominates the "light-shelf" option (average cost of $-952,711.2) with frequency of .718.

5.3 Comments

We have approached the decision problem of selecting the most attractive alternative regarding the building energy system in the context of decision analysis methodology.

At this point, we think it would be quite worthwhile to make a couple of comments on our approach in this decision problem:

1) This problem is basically a multi-attribute decision problem which implies that a decision on dollar value alone might not really represent the decision makers's real attitude towards preference. For instance, the decision maker might select the light-shelf system option, which is less cost-effective based on our result, because he would like to be a pioneer in implementing a system of advanced technology. Also, there are other factors such as consideration of pollution, environmental impact, etc.

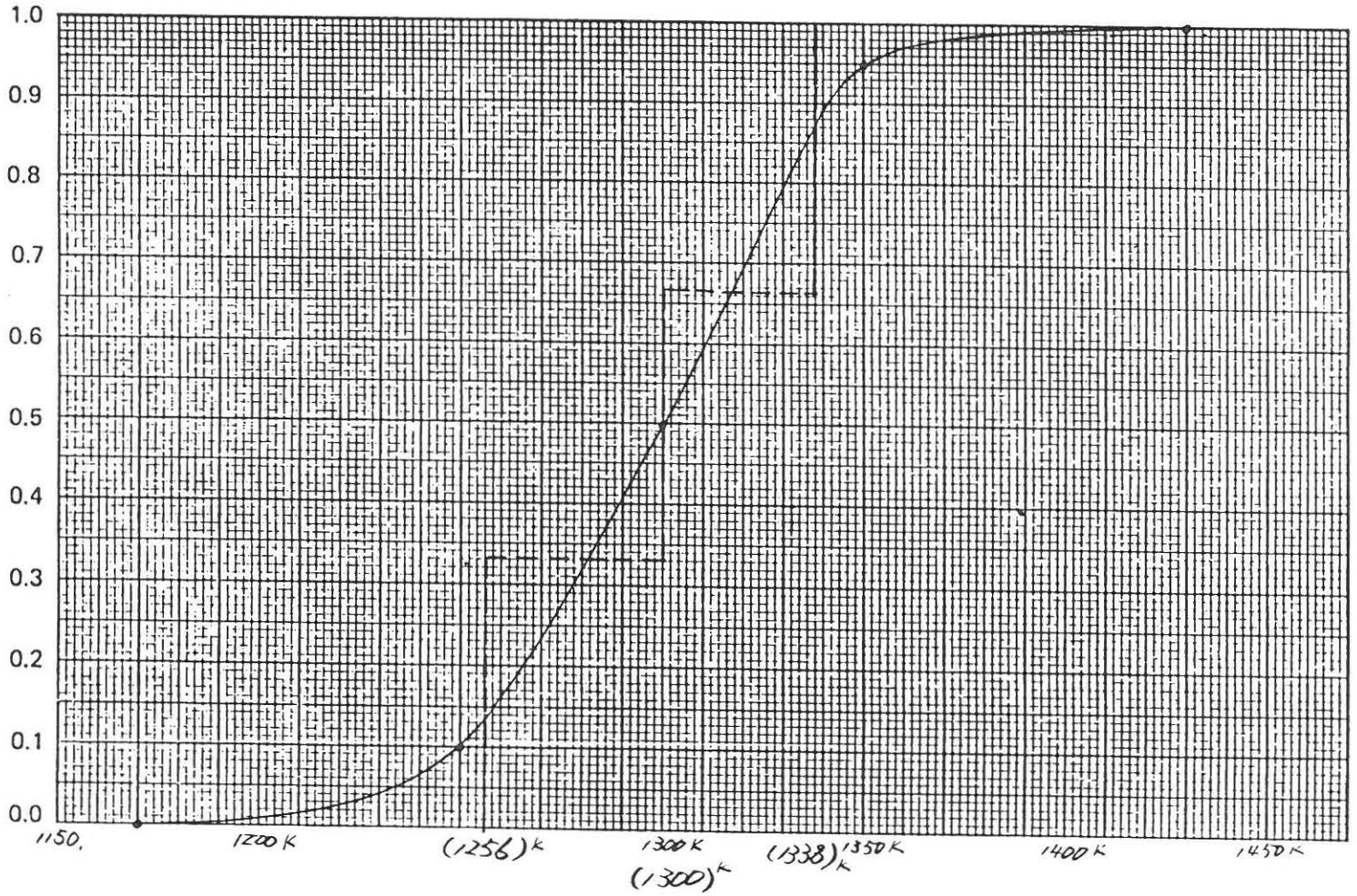
2) Our client is not an individual decision maker. We are faced with a company which has to document its findings concerning the different alternatives and present them to the owner. Since the owner is also a company the task of encoding a utility curve becomes practically impossible.

Due to the points mentioned above, we decided not to incorporate the utility concept in our analysis since an un-appropriate application of utility function could distort the whole analysis. Furthermore, we believe that it is quite reasonable and practical to leave the remaining final decision to the judgement of the real decision makers, which basically represents their attitude toward preference, by just presenting

dominance indexes, average values, and value ranges for all alternatives.

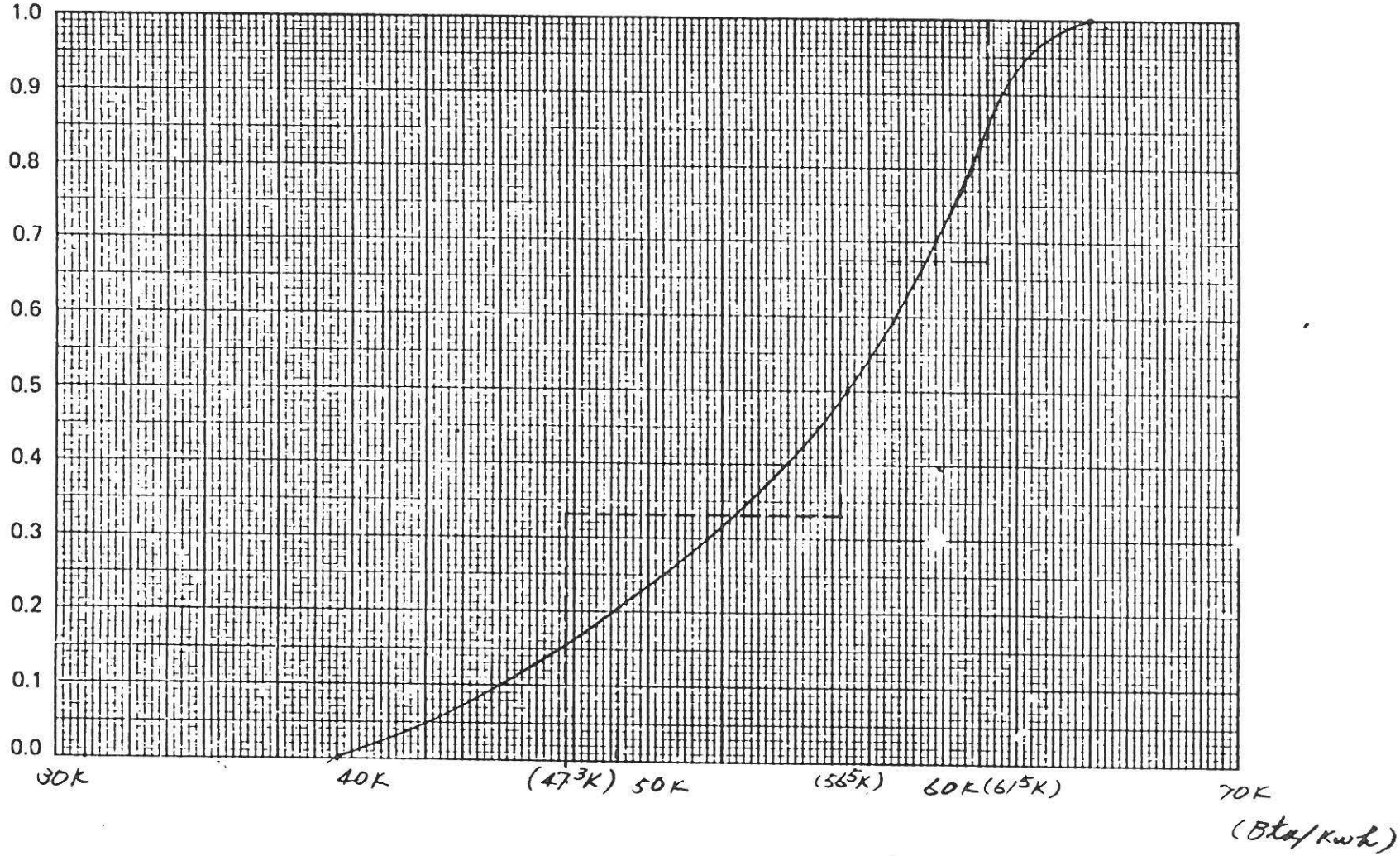
Appendix A

SUBJECT _____ DATE _____



VARIABLE Capital Cost of Central Plant

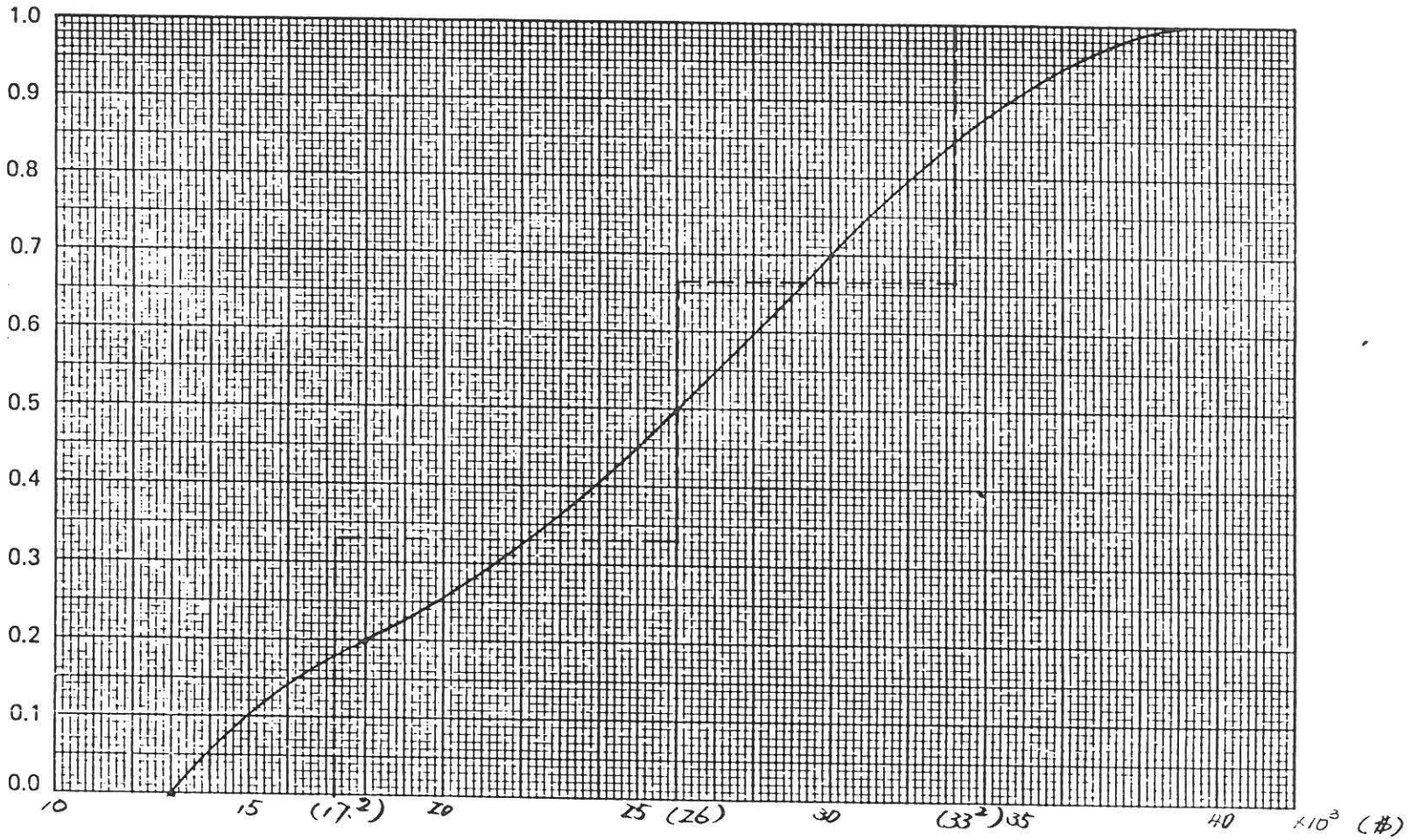
SUBJECT OBIE ATHWAL DATE



VARIABLE Central Plant Output

SRI—PROBABILITY ENCODING FORM—MAY 1969

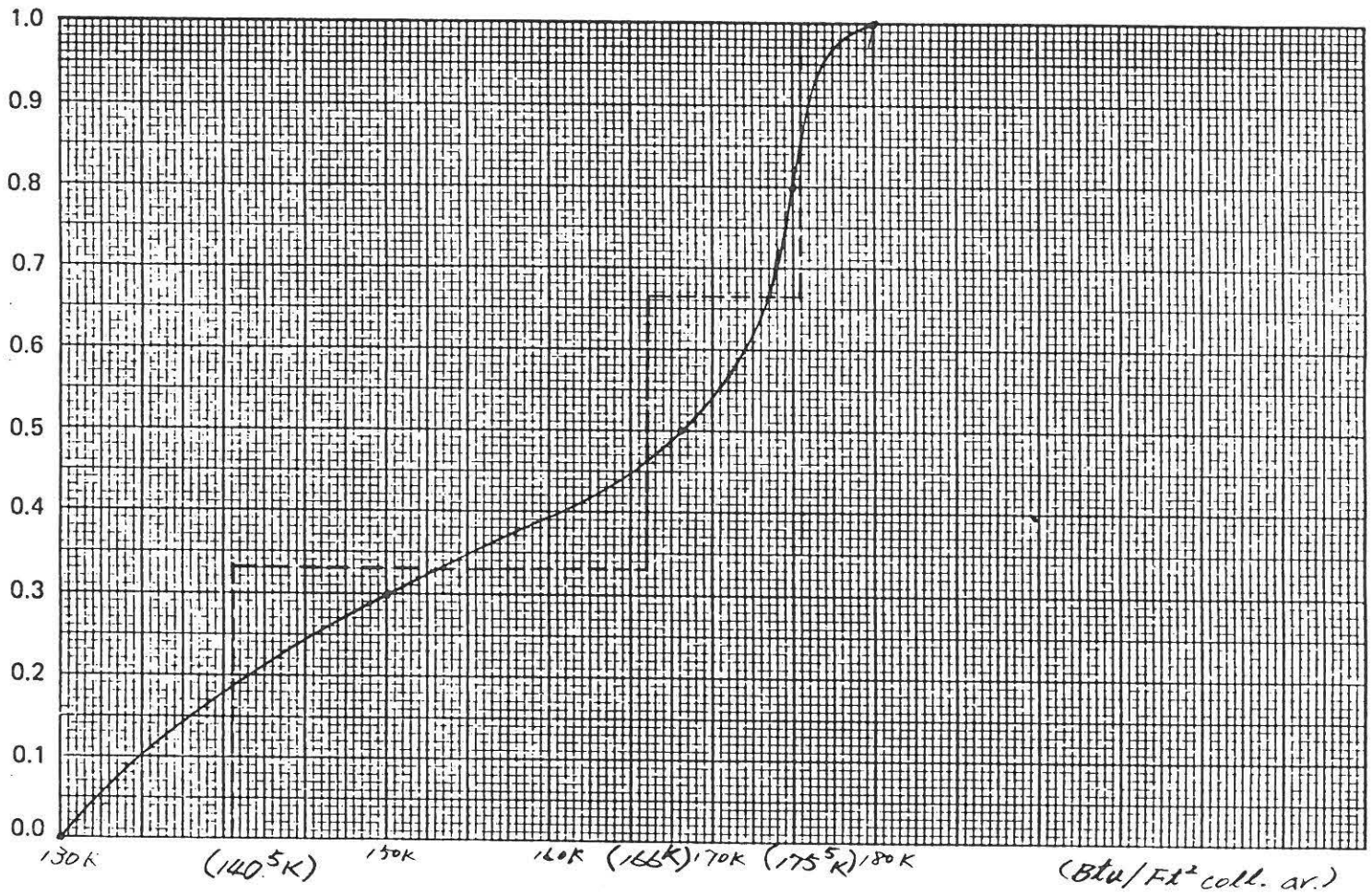
SUBJECT _____ DATE _____



VARIABLE *Annual Maint. Cost of Central Plant*

SRI—PROBABILITY ENCODING FORM—MAY 1969

SUBJECT _____ DATE _____

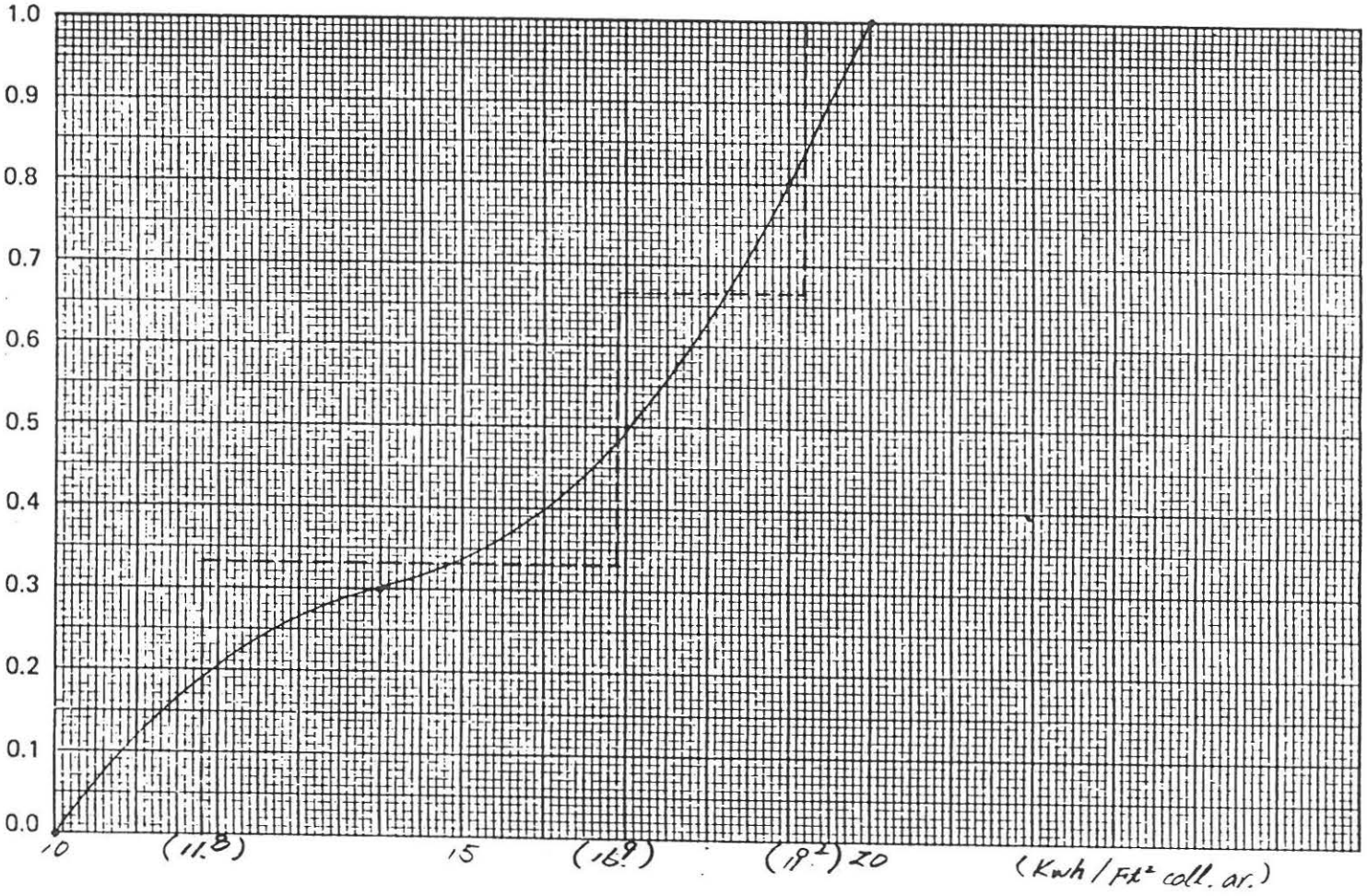


VARIABLE *Output of LT & HT Solar System*

H.T. Area 150,000 sq feet
L.T. Area. 5 000 sq feet

SRI—PROBABILITY ENCODING FORM—MAY 1969

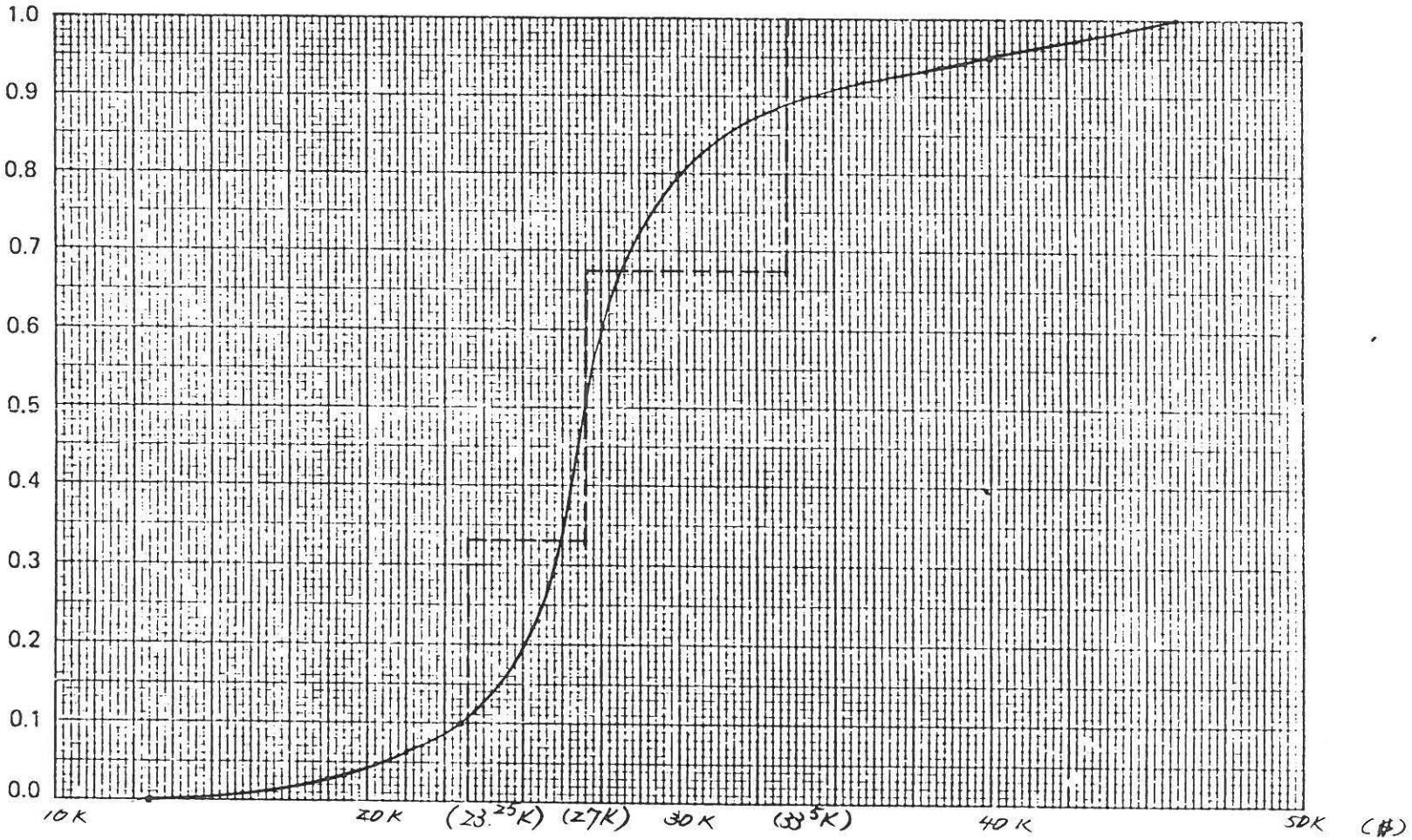
SUBJECT _____ DATE _____



VARIABLE *Output of Photov. Solar System*

SRI—PROBABILITY ENCODING FORM—MAY 1969

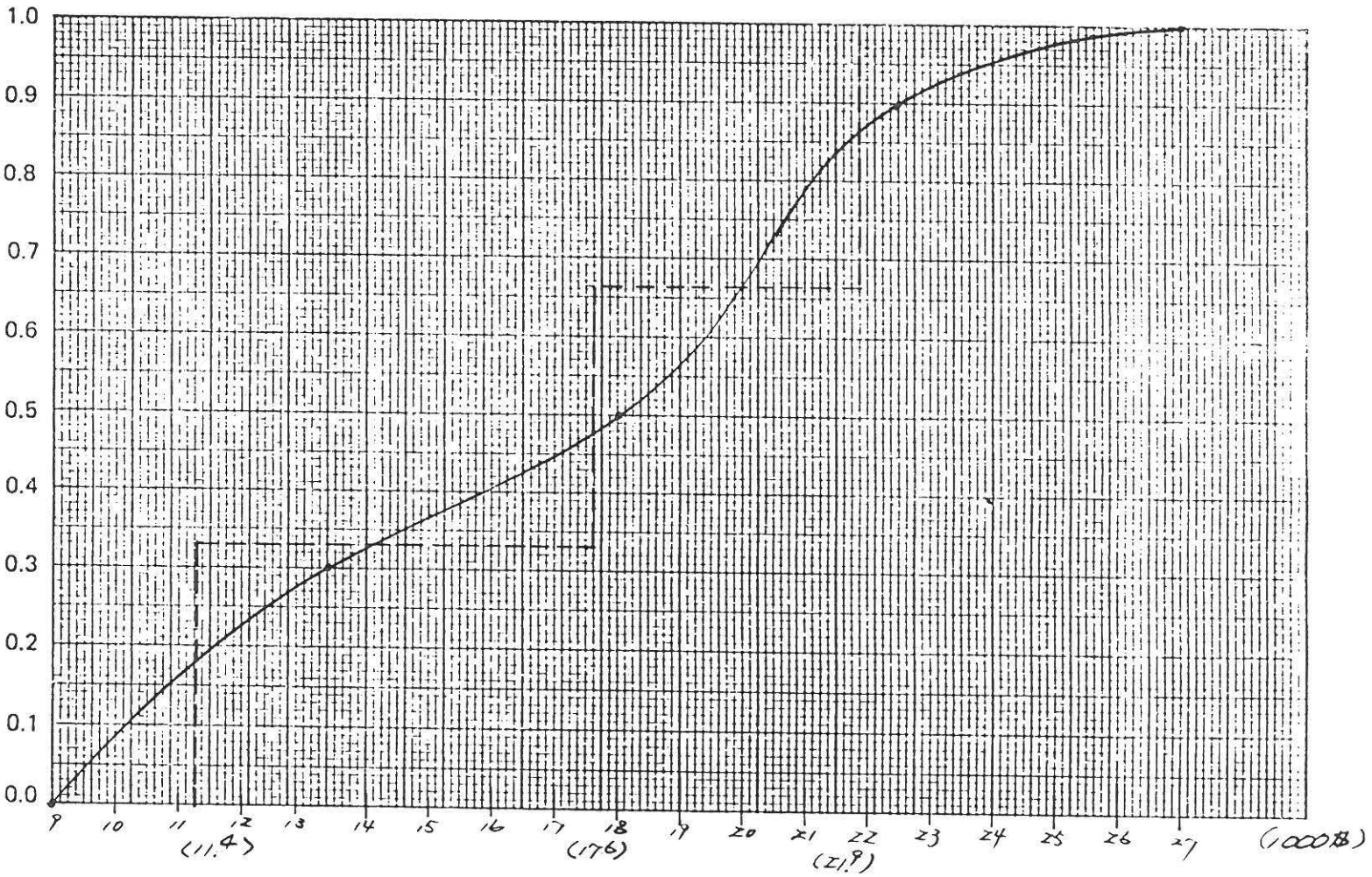
SUBJECT _____ DATE _____



VARIABLE *Annual Maint. Cost of Oil/Gas System*

SRI—PROBABILITY ENCODING FORM—MAY 1969

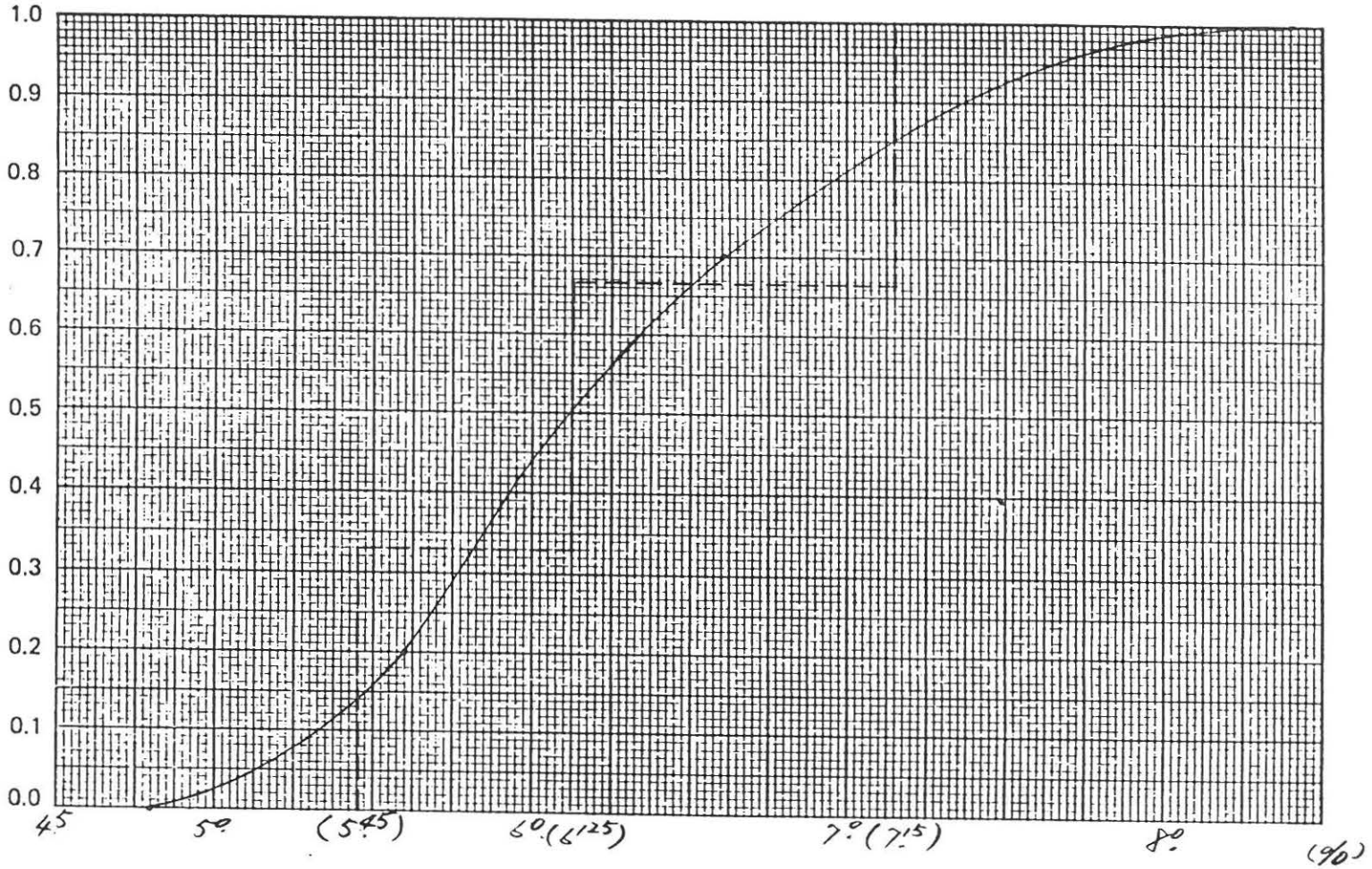
SUBJECT _____ DATE _____



VARIABLE *Annual Maint Cost of Electric System*

SRI—PROBABILITY ENCODING FORM—MAY 1969

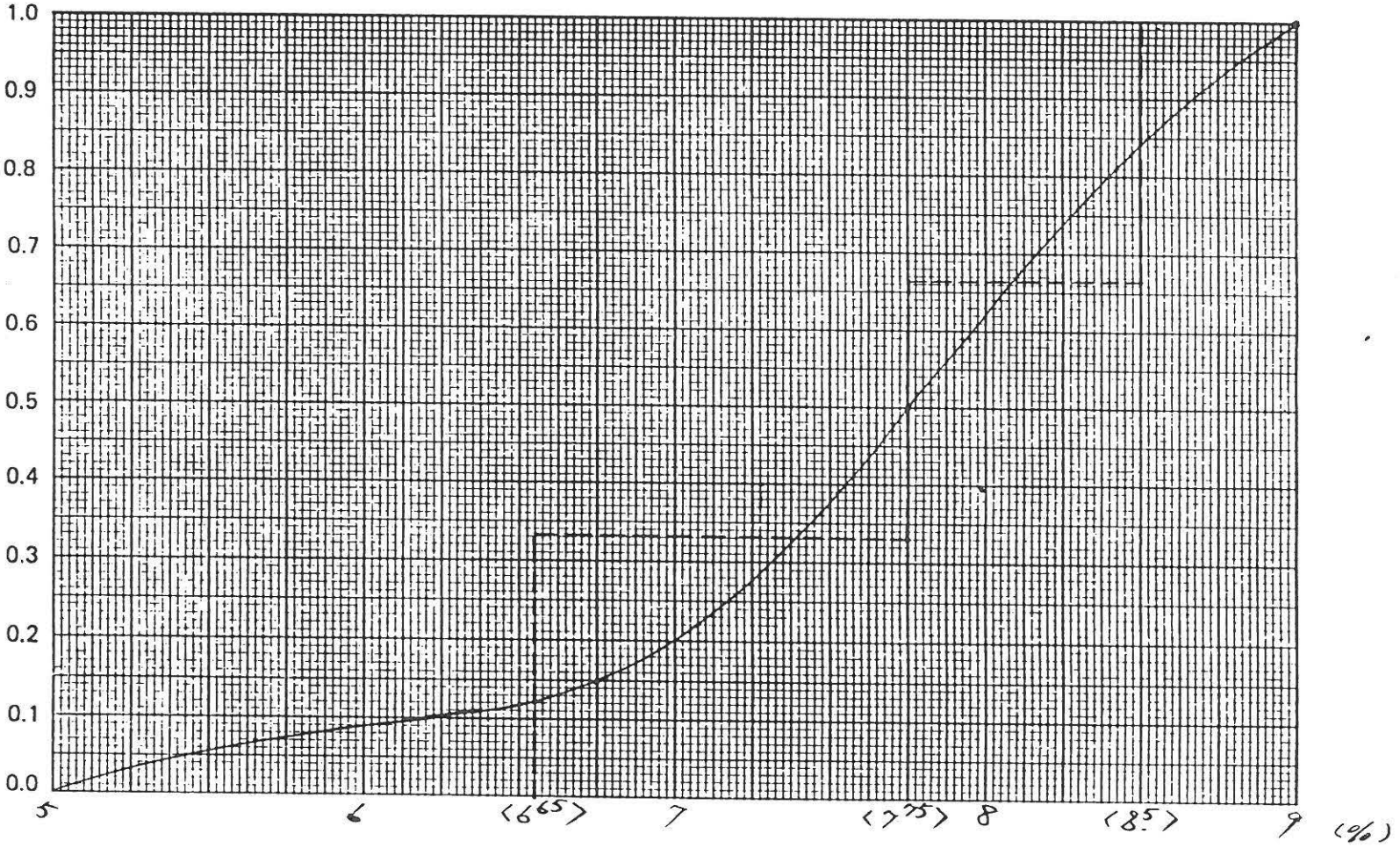
SUBJECT _____ DATE _____



VARIABLE *Annual Cost Escalation for Fossil Fuel*

SRI—PROBABILITY ENCODING FORM—MAY 1969

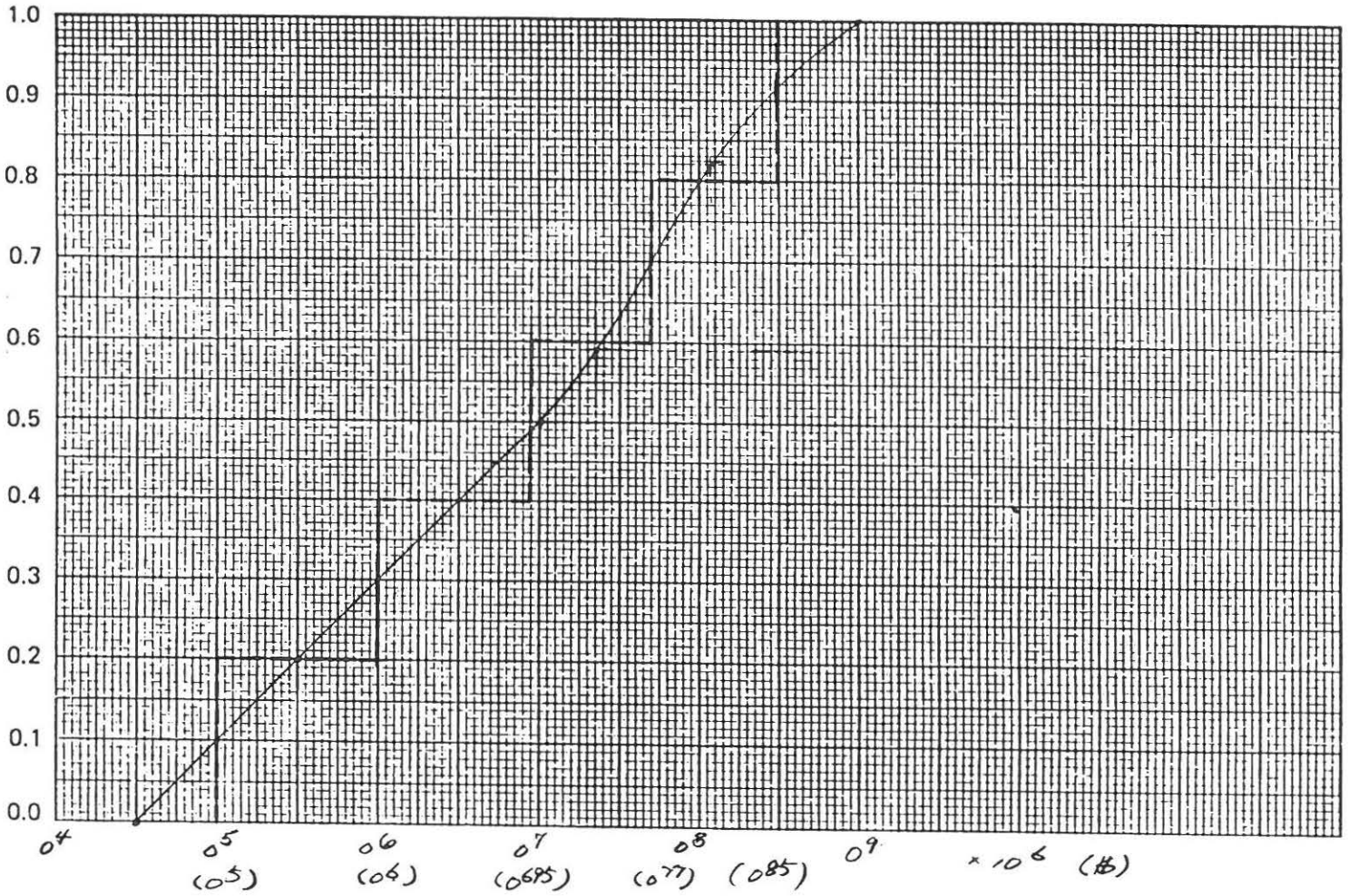
SUBJECT _____ DATE _____



VARIABLE *Annual Cost Escalation for Electricity*

SRI—PROBABILITY ENCODING FORM—MAY 1969

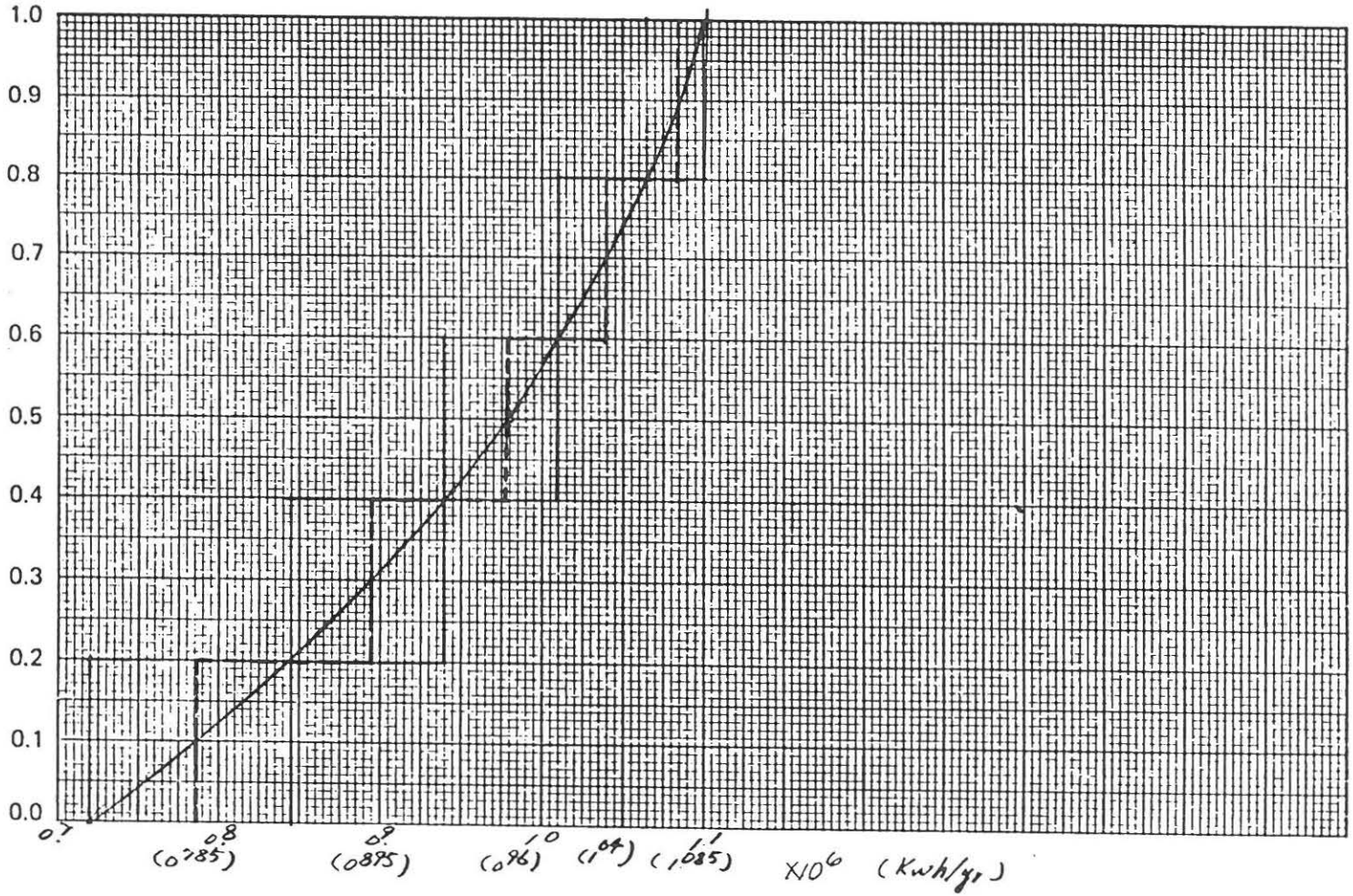
SUBJECT _____ DATE _____



VARIABLE Capital Cost of Light Shelf

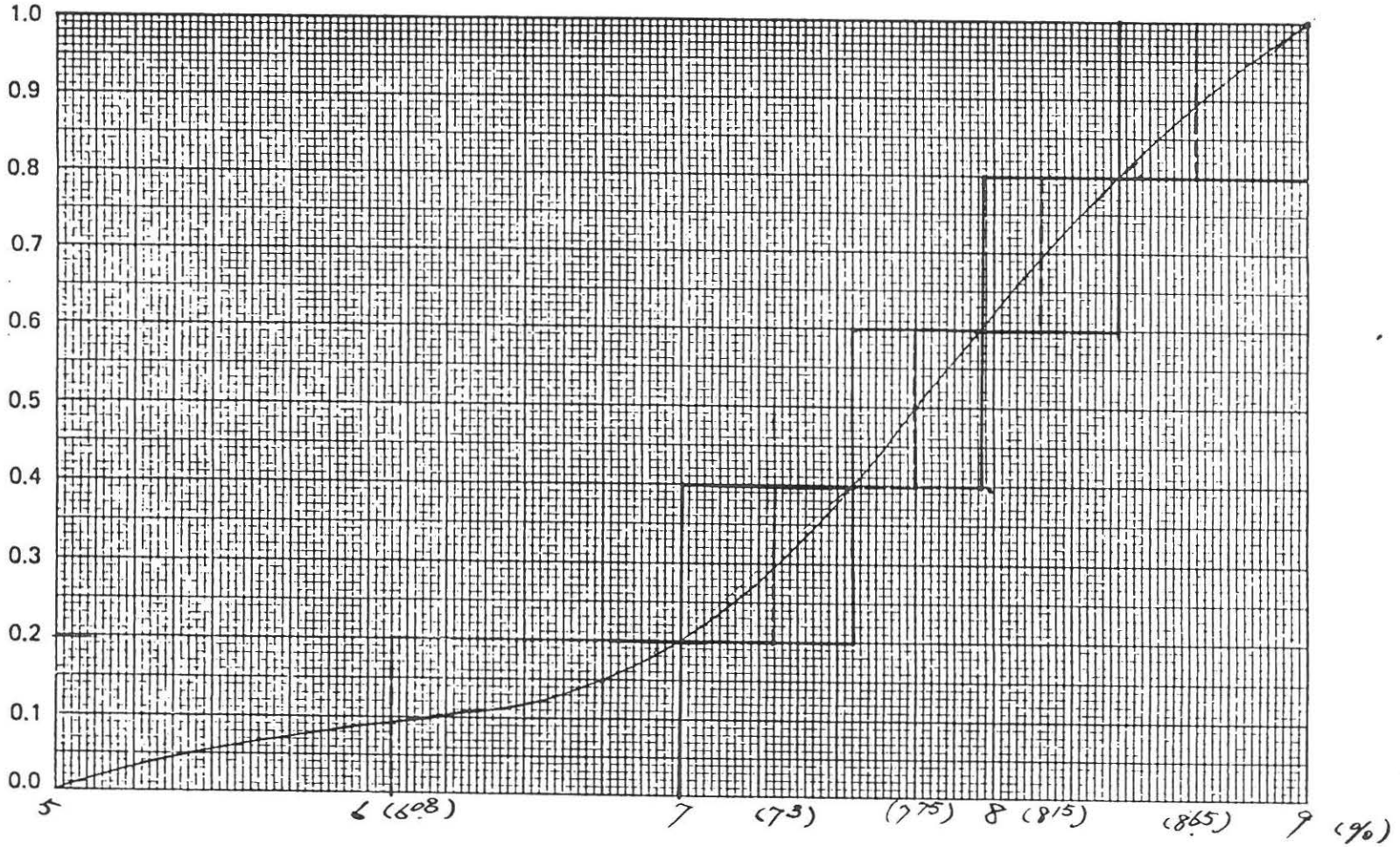
SRI—PROBABILITY ENCODING FORM—MAY 1969

SUBJECT _____ DATE _____



VARIABLE *Output of Light Shelf*

SUBJECT _____ DATE _____

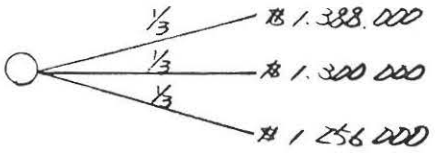


VARIABLE Annual Cost Escalation for Electricity

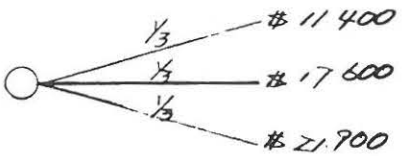
SRI—PROBABILITY ENCODING FORM—MAY 1969

Appendix B

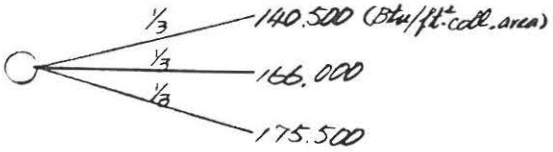
Capital Cost of Central Plant



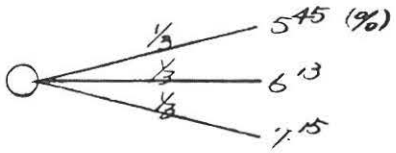
Annual Maint Cost of Electric System



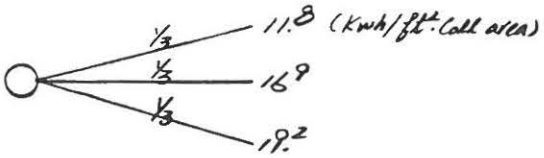
Output of LT & HT Solar System



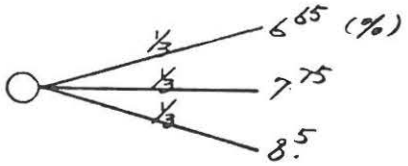
Annual Cost Escalation for Fossil Fuel



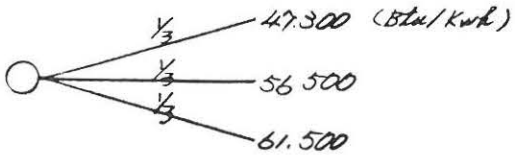
Output of Photovoltaic Solar System



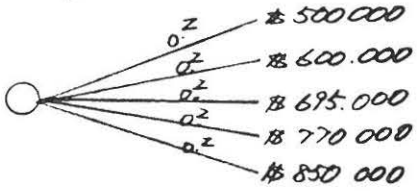
Annual Cost Escalation for electricity



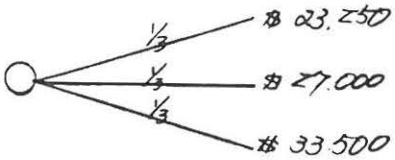
Output of Central plant



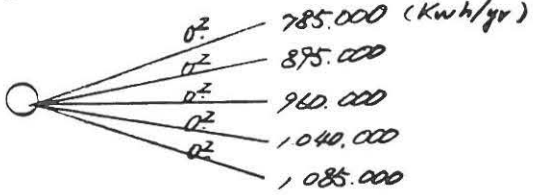
Capital Cost of Light Shelf



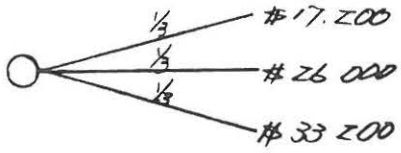
Annual Maint. Cost of Oil/Gas System



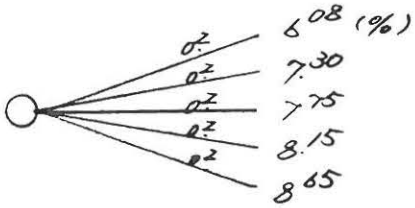
Output of Light Shelf



Annual Maint. Cost of Central plant



Annual Cost Escalation for electricity



CONVENTIONAL SYSTEM	CAPITAL COST	OUTPUT
OIL	$660,000	139,000 BTU/GALLON
GAS	$660,000	990 BTU/CUB FT
ELECTRICITY	$922,000	3413 BTU/KWH

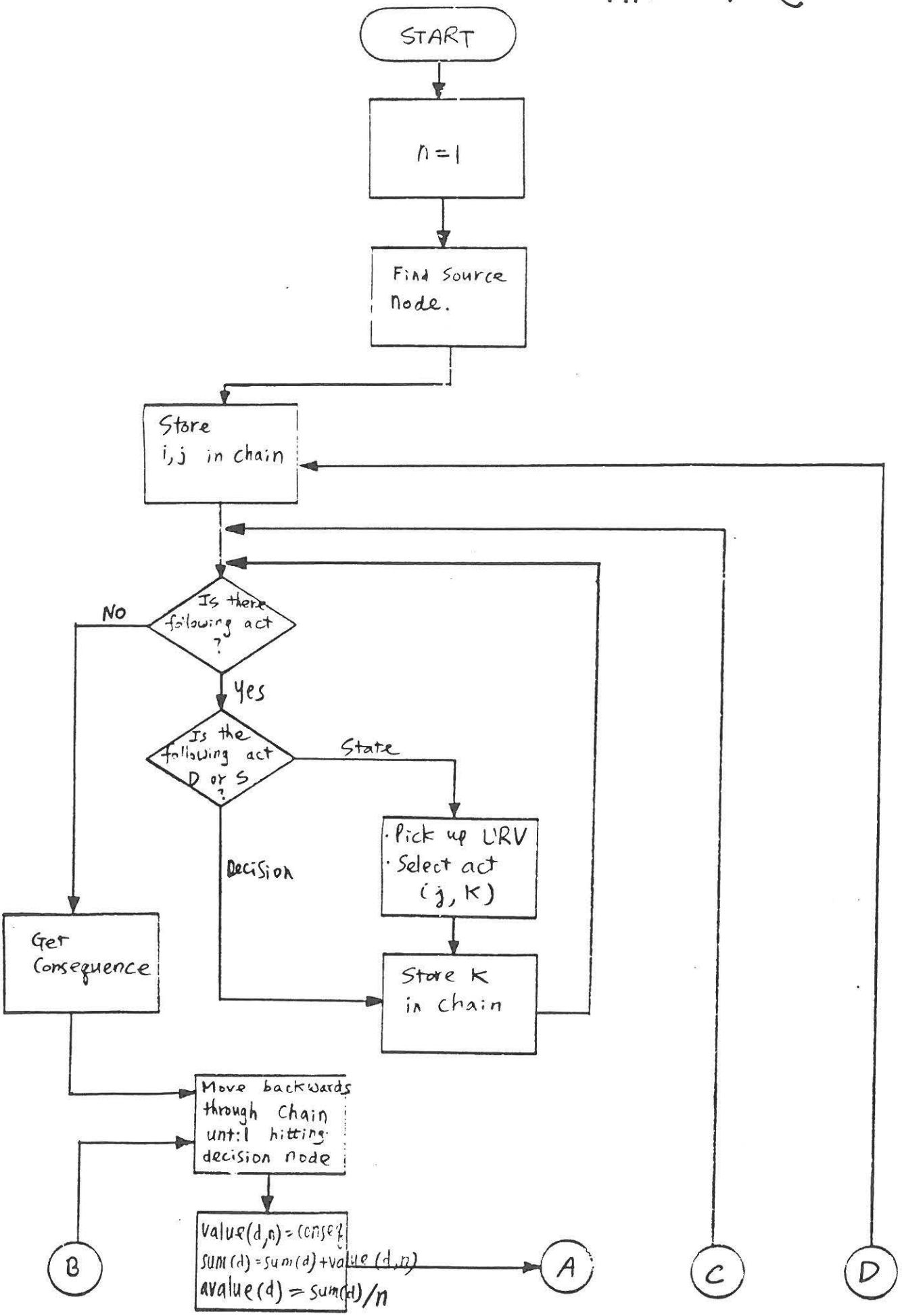
SOLAR SYSTEM	COLLECTOR AREA sq. ft.	UNIT COST $/sq. ft.	TOTAL COST $
LOW TEMPERATURE	5,000	50	250,000
HIGH TEMPERATURE	150,000	80	12,000,000
PHOTOVOLTAIC	150,000	200	30,000,000

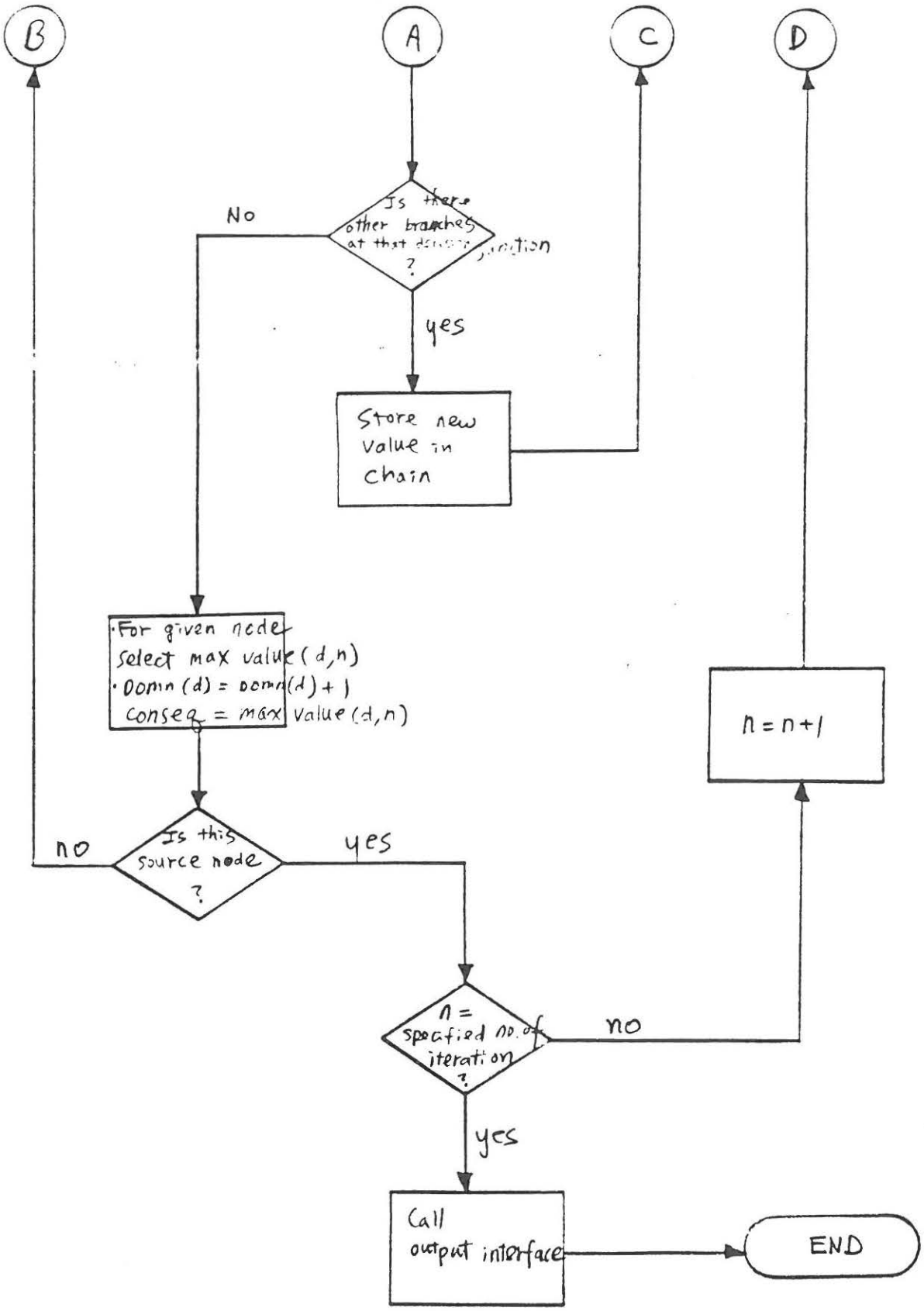
BUILDING ENERGY REQUIREMENT : 1.2×10^{10} BTU/YEAR

DISCOUNT RATE : 15 %

TIME HORIZON (FOR PRESENT VALUES) : 40 YEARS

APPENDIX C


START
n=1
Find Source Node.
Store i,j in chain
Is there folowing act ?
NO
Yes
Is the folloWing act D or S ?
State
Decision
· Pick up URV
· Select act (j, K)
Get Consequence
Store K in chain
Move backwards through Chain unt:l hitting decision node
value(d,n) = conseq
sum(d) = sum(d) + value(d,n)
avalue(d) = sum(d)/n
A
B
C
D


B
A
C
D
Is there other branches at that decision ?
No
yes
Store new value in chain
For given node
select max value (d,n)
Domin (d) = domin(d) + 1
conseq = max value (d,n)
Is this source node ?
no
yes
n = n+1
n = specified no. of iteration ?
no
yes
Call output interface
END

Appendix E

A) If we can assume normality in population

$$\bar{x} - \frac{\sigma}{n} \cdot Z_{\alpha/2} \leq \mu \leq \bar{x} + \frac{\sigma}{n} \cdot Z_{\alpha/2}$$

If we let

$$d = \frac{\sigma}{\sqrt{n}} \cdot Z_{\alpha/2}$$

then

$$n = \left(\frac{\sigma \cdot Z_{\alpha/2}}{d}\right)^2$$

By using $d = \frac{\sigma}{10}$, $\alpha = .05$, we get $n = 384.16$.

B) If we cannot assume normality in population

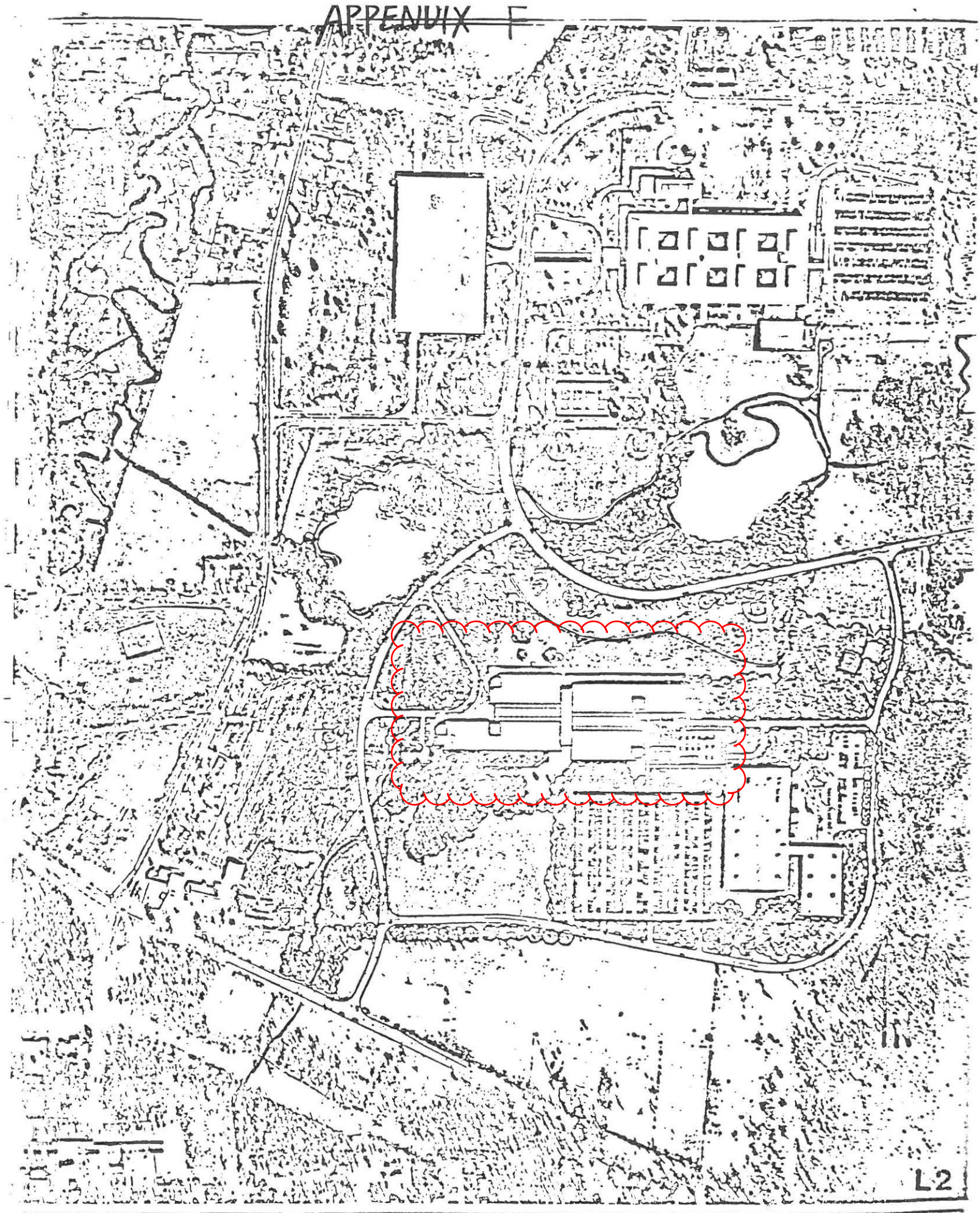
$$n = \frac{K^2}{\alpha} \text{ (from Tchebycheff's theorem)}$$

where $d = \frac{\sigma}{K}$.

By using $K = 10$, $\alpha = 105$, we get $n = 2000$.

Based on A) and B) we decided to use $n = 1000$.

APPENDIX F

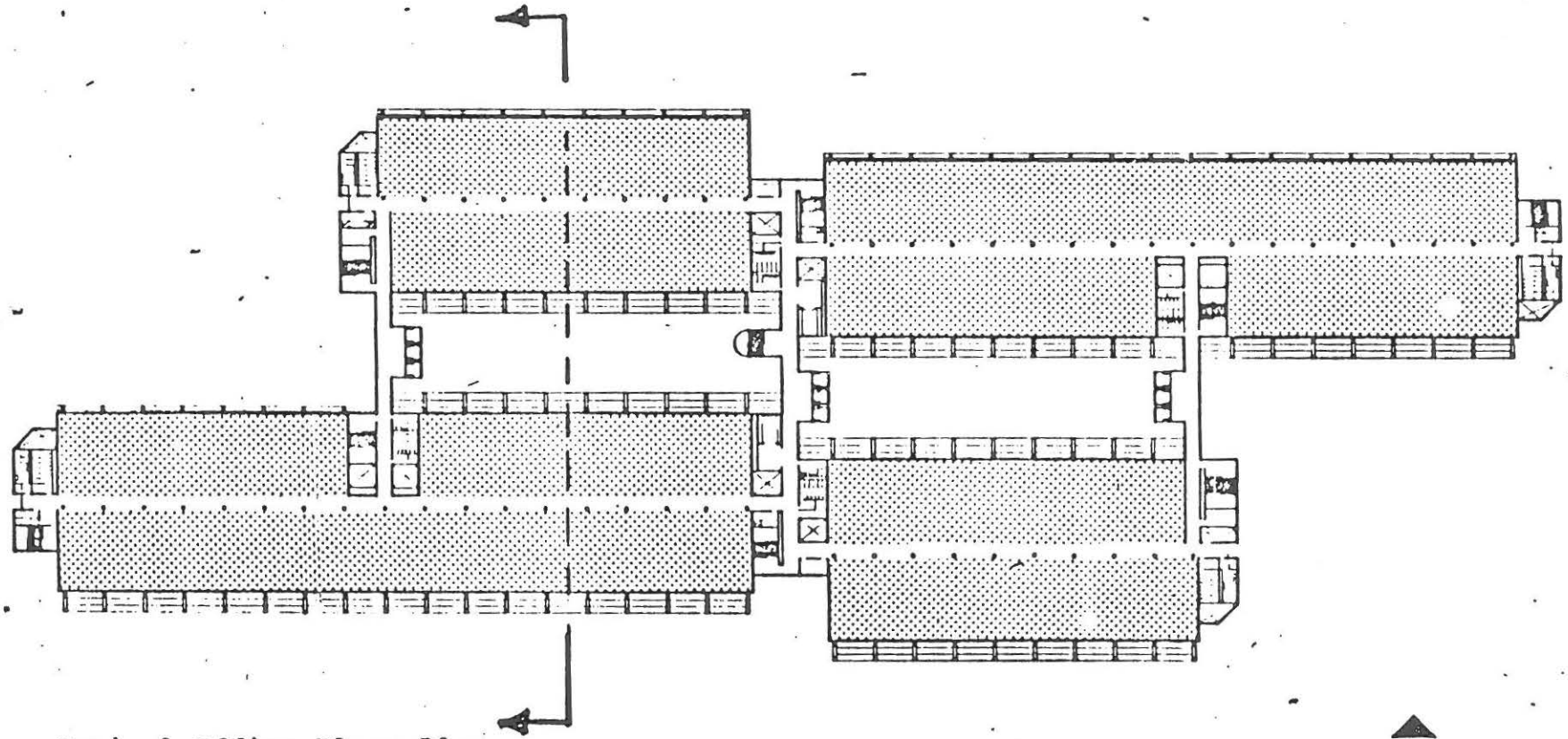


L2

Schematic Design 1
Connecticut General Life Insurance Company
February 6, 1990

Site Plan - Alternate A

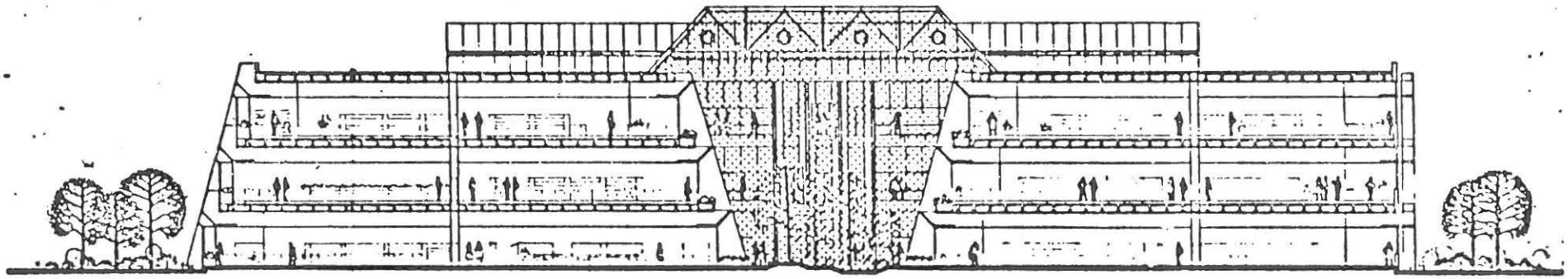
The Architects Collaborative
Interspace Incorporated L2



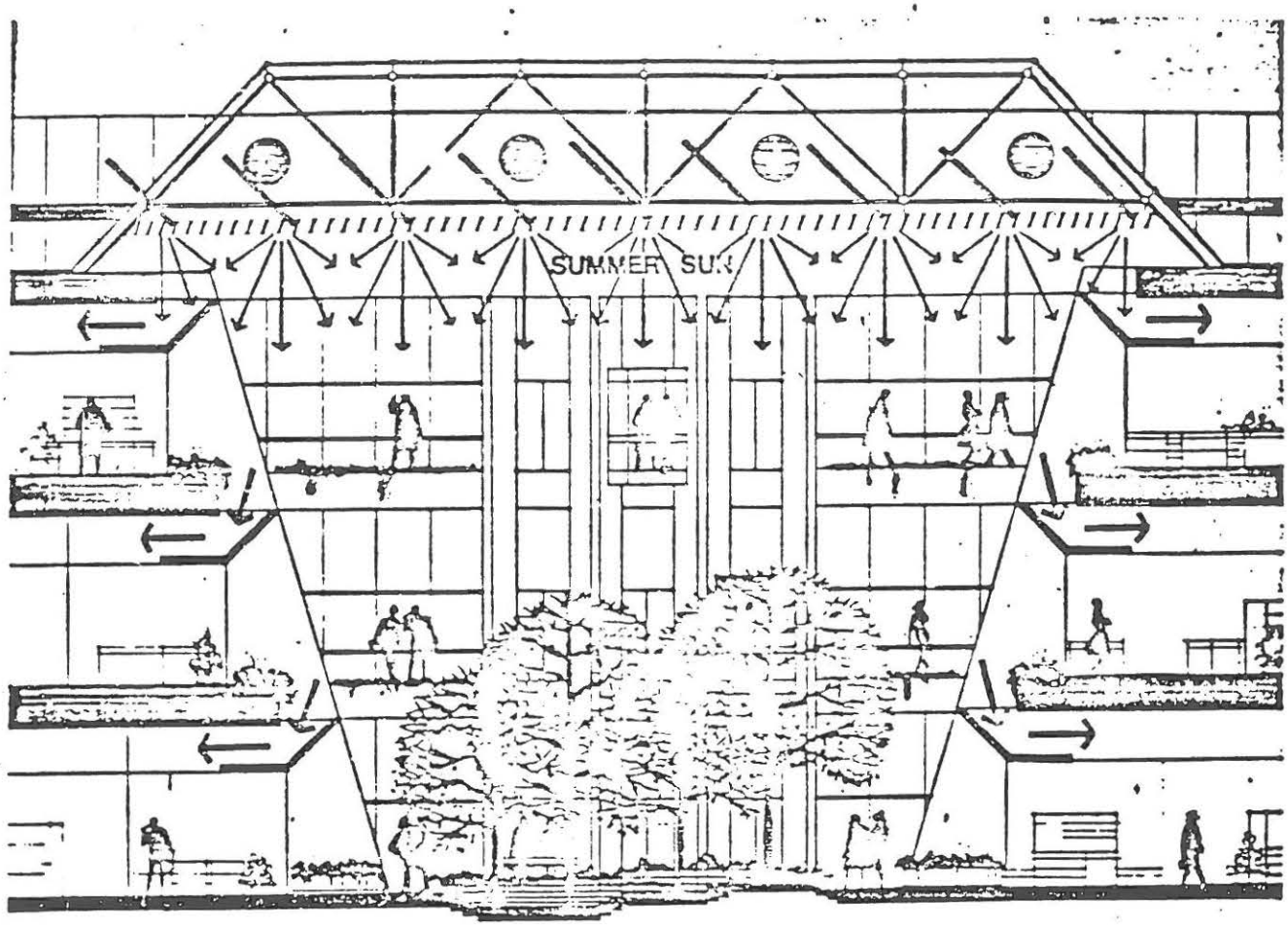
Typical Office Floor Plan
Alternate A

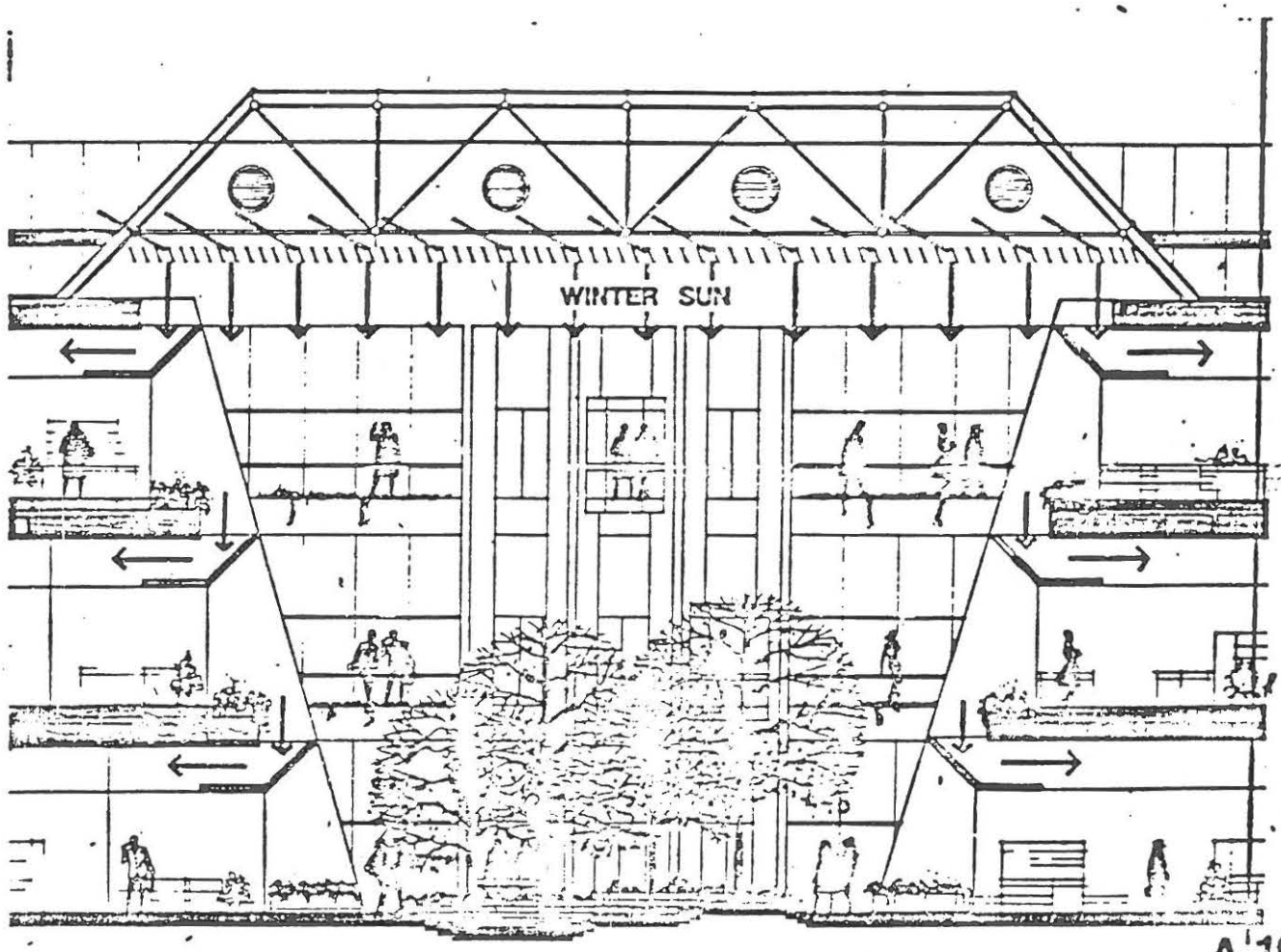
N

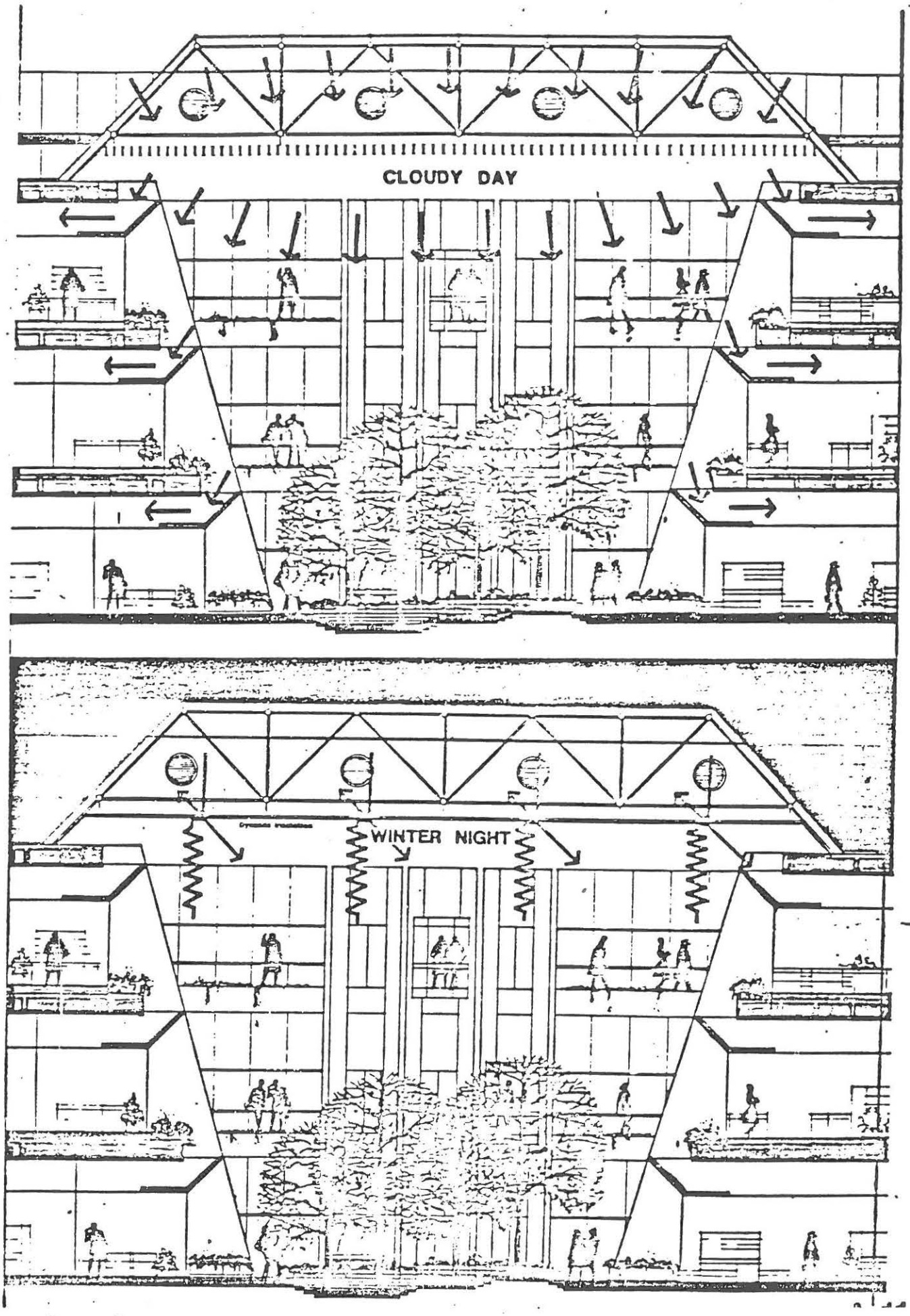
A1



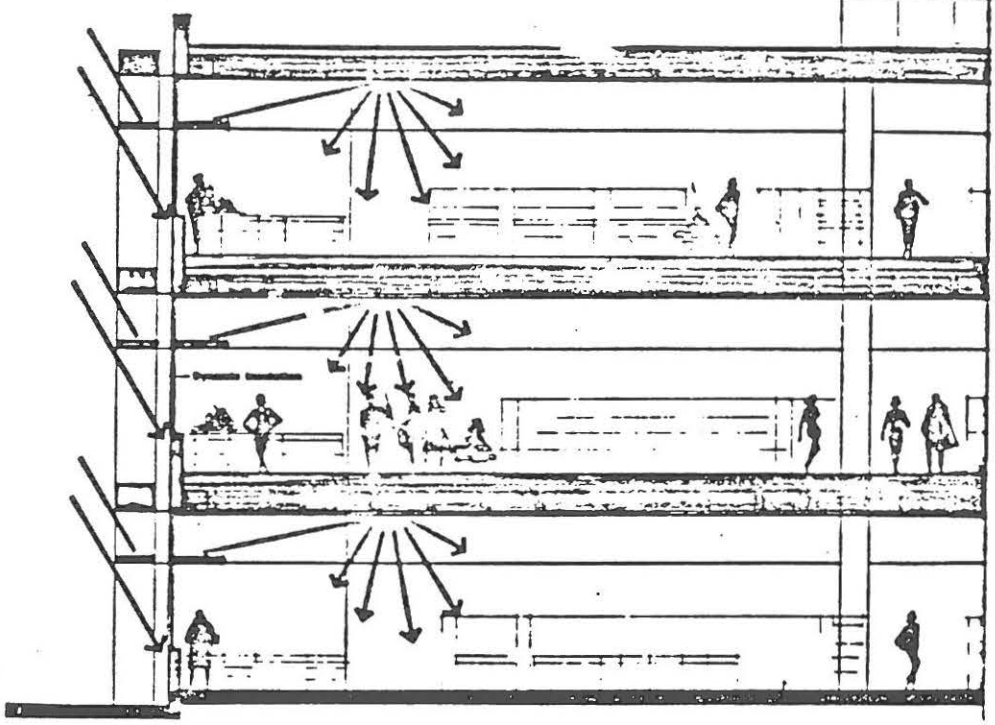
Alternate .A
Section - First Floor Atrium
Scale 1/8" = 1'-0"


SUMMER SUN

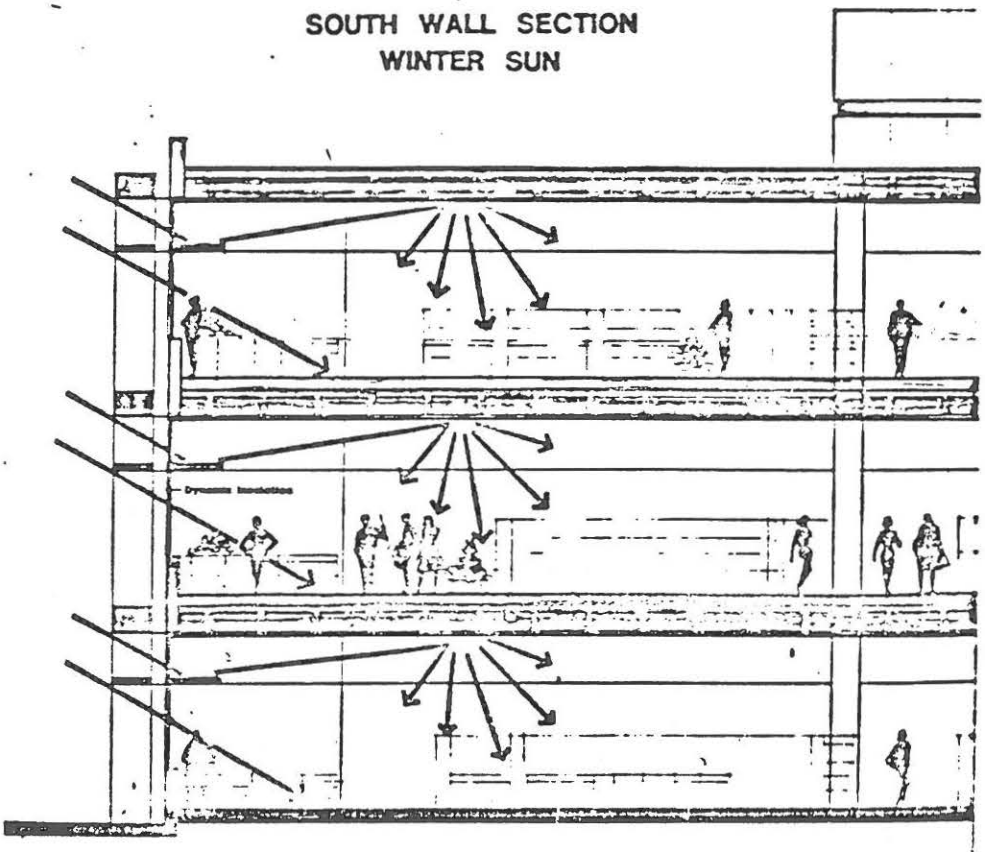

WINTER SUN


CLOUDY DAY
WINTER NIGHT

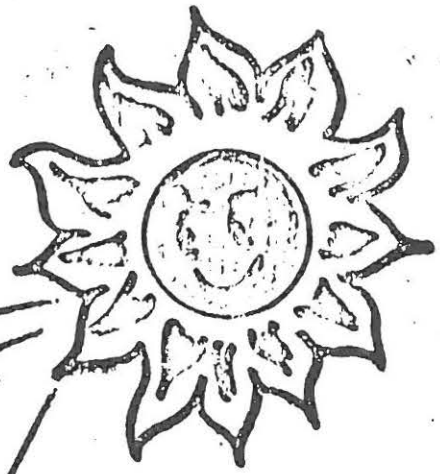
SOUTH WALL SECTION
SUMMER SUN



SOUTH WALL SECTION
WINTER SUN



ALTERNATIVES



ALT. 1

ALT. 2

ALT. 3

PHOTOVOLTAIC PANEL

SOL. COL. LOW TEMP

SOLAR COLLECTOR HIGH TEMPERATURE

ELECTRICITY

HOT WATER

HOT WATER

LIGHTING

ELEC. MOTORS

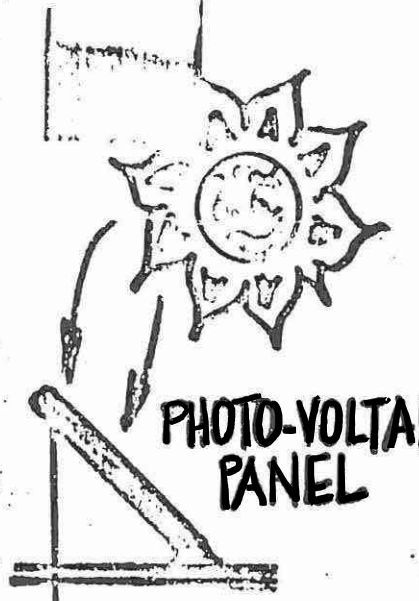
DOMESTIC HOT WATER

DOMESTIC HOT WATER

SPACE COOLING

SPACE HEATING

ALTERNATE 1 : SOLAR INTO ELECTRICITY

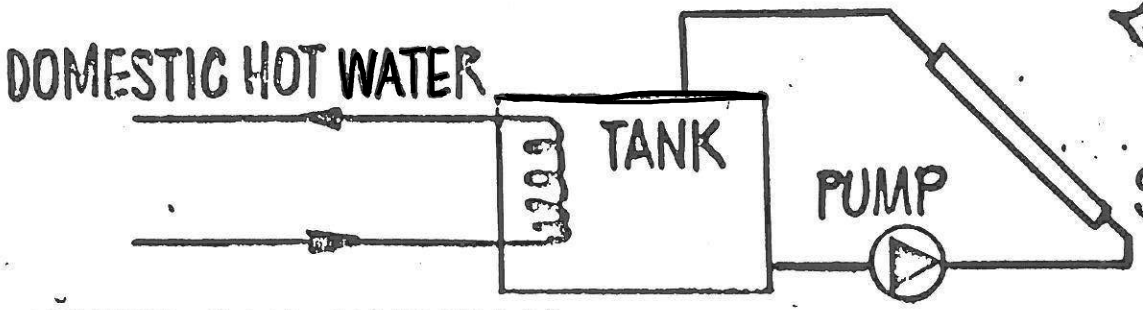


PANEL AREA	: 150,000 SQ. FT.
INSTALLED COST	: $80,000,000
PEAK TOWER OUTPUT	: 1 800 KW.
ANNUAL ENERGY OUTPUT	2.55×10^6 KWH
ANNUAL SAVINGS @ 4 ¢/KWH (INCLUDING DEMAND)	$102,000
SIMPLE PAY-BACK (BASED ON 100% USAGE FACTOR)	294 YEARS

COST OF PHOTO-VOLTAIC SYSTEM : $17,000/KW.
(PANEL COST IS 80% SYSTEM COST)

APPROX. SYSTEM EFFICIENCY : 12%

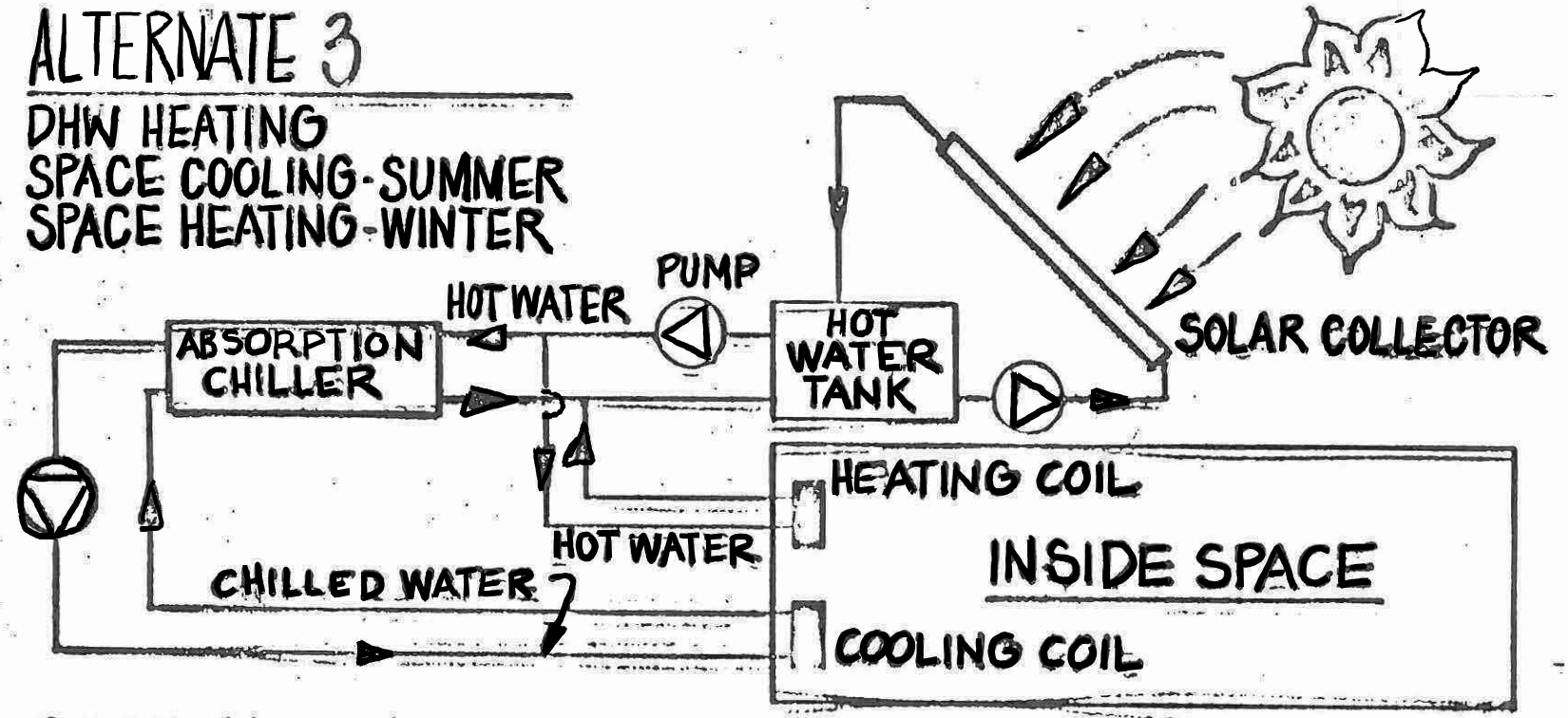
ALTERNATE 2 : DOM. HOT WATER SYSTEM



WATER CONSUMPTION	: 10,000 GALLONS/ DAY
APPROX. USAGE FACTOR	: 80%
SOLAR COLLECTOR PANEL AREA	: 5,000 SQ. FT.
INSTALLED COST OF SYSTEM @ $50/SQ. FT.	: $250,000
ANNUAL USEFUL SOLAR ENERGY COLLECTED PER SQ. FT. COLLECTOR (BASED ON 100% USAGE FACTOR).	: 168,000 BTU = 225 CFT OF NAT. GAS @ 75% EFFICIENCY.
ANNUAL SAVINGS @ 28 ¢/100 CFT GAS	: $3,150
SIMPLE PAYBACK	: 79 YEARS

ALTERNATE 3

DHW HEATING
SPACE COOLING - SUMMER
SPACE HEATING - WINTER



SOLAR COLLECTOR PANEL AREA.	150,000 SQ. FT.
INSTALLED COST OF ENTIRE SYSTEM @ $80/SQ. FT. (600 TON CHILLER).	: $12,000,000
ANNUAL USEFUL SOLAR ENERGY COLLECTED PER SQ. FT. COLLECTOR (BASED ON 100% USAGE FACTOR).	: 168,000 BTU = 225 CFT OF GAS @ 75% EFF.
ANNUAL SAVINGS @ 28¢/100 CFT GAS.	$94,500
SIMPLE PAYBACK.	130 YEARS

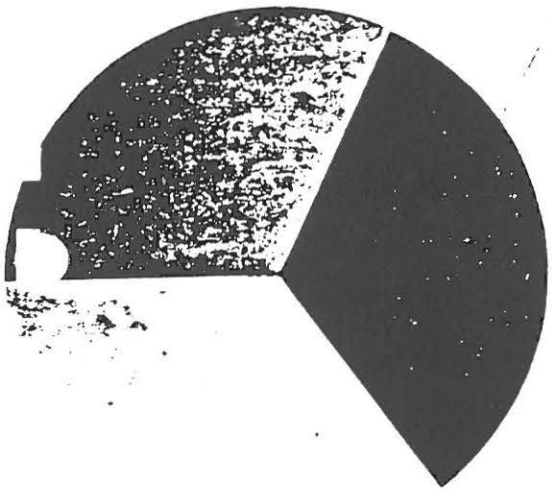
LIGHTING
COOLING AND FANS
HEATING AND DOMESTIC HOT WATER

BUILDING ENERGY CONSUMPTION PATTERN



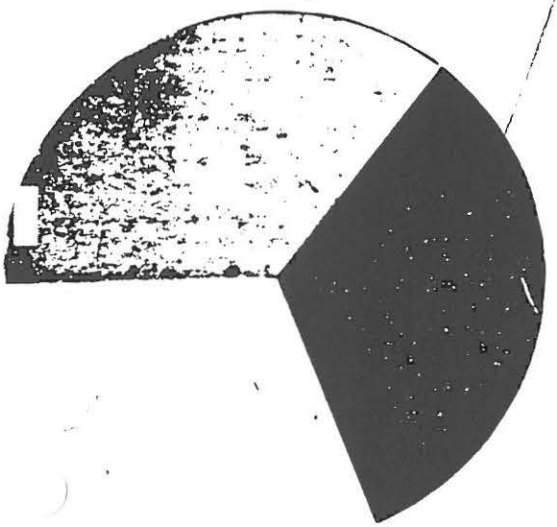
ALTERNATE A (37,000 BTU/SQ.FT./YR.)

LIGHTING	- 12,000 BTU/S.F./YR.	(32.5%)
COOLING AND FANS	- 12,000 " " "	(32.5%)
HEATING AND DOMESTIC HOT WATER	- 13,000 " " "	(35%)
TOTAL	- 37,000 " " "	(100%)



ALTERNATE B (37,500 BTU/SQ.FT./YR.)

LIGHTING	- 12,000 BTU/S.F./YR.	(32%)
COOLING AND FANS	- 12,500 " " "	(33.3%)
HEATING AND DOMESTIC HOT WATER	- 13,000 " " "	(34.7%)
TOTAL	- 37,500 " " "	(100%)



ALTERNATE C (44,500 BTU/SQ.FT./YR.)

LIGHTING	- 16,000 BTU/S.F./YR.	(36%)
COOLING AND FANS	- 15,000 " " "	(33.7%)
HEATING AND DOMESTIC HOT WATER	- 13,500 " " "	(30.3%)
TOTAL	- 44,500 " " "	(100%)

P.V. OF TOTAL COST FORMULAS FOR HEATING/COOLING SYSTEMS

$$PV[\text{TOTAL COST}] = \text{CAPITAL COST OF CONVENTIONAL SYSTEM} +$$
$$+ \text{CAPITAL COST OF SOLAR ALTERNATIVE} +$$
$$+ \sum_{k=1}^{N} (\text{ANNUAL MAINT COST}) / (1 + \text{DISCOUNT RATE})^{k}$$
$$+ \sum_{m=1}^{N} (\text{BUILDING ENERGY REQ} - \text{OUTPUT OF SOLAR}) /$$
$$(\text{OUTPUT OF CONV. SYSTEM}) \times (\text{BASE PRICE OF FUEL}) \times$$
$$\times (1 + \text{AN. FUEL ESC. FACTOR})^{m} / (1 + \text{DISCOUNT RATE})^{m}$$

WHERE: N = TIME HORIZON IN YEARS = 40 YEARS

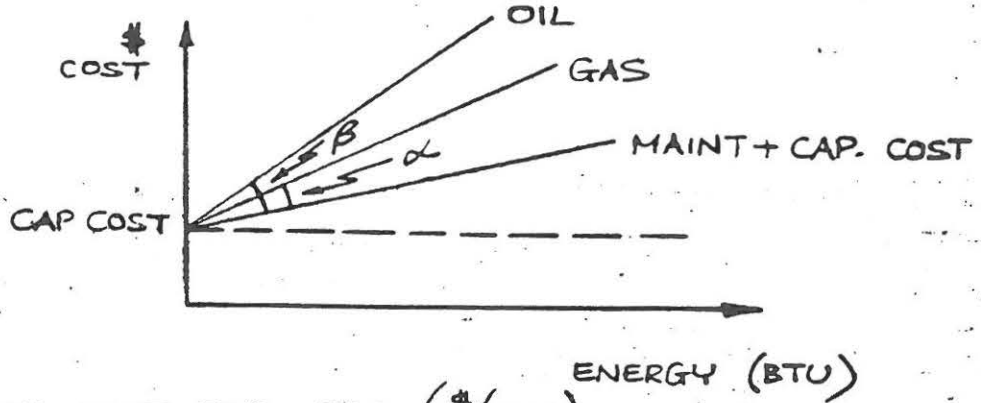
DISCOUNT RATE = 15 %

P.V. OF SAVINGS FORMULA FOR LIGHT SHELF

$$PV[\text{SAVINGS}] = \sum_{l=1}^{N} (\text{OUTPUT OF LIGHT SHELF}) \times$$
$$\times (\text{BASE PRICE OF ELECTRICITY}) \times$$
$$\times (1 + \text{ELECTR. ESC. FACTOR})^{l} /$$
$$(1 + \text{DISCOUNT RATE})^{l}$$
$$- \text{LIGHT SHELF CAPITAL COST}$$

OPERATING COST COMPARISON FOR OIL & GAS CONVENTIONAL SYSTEMS.

ACCORDING TO OUR EXPERTS' OPINION BOTH SYSTEMS HAVE THE SAME DIST. FOR CAPITAL COST, MAINT. COST AND BOTH GAS & OIL HAVE THE SAME ANNUAL ESCALATION FACTORS.



α = OPERATING COST FOR GAS ($/BTU)

β = OPERATING COST FOR OIL ($/BTU)

	BASE PRICE OF GAS $/CF	OUTPUT (BTU/CF)		α $/BTU	
		LOW	HIGH	LOW	HIGH
GAS	0.0046	0.955×10^3	1.018×10^3	4.52×10^{-6}	4.82×10^{-6}

	BASE PRICE OF OIL $/GALLON	OUTPUT (BTU/GAL)		β $/BTU	
		LOW	HIGH	LOW	HIGH
OIL	0.88	138.1×10^3	140.2×10^3	6.28×10^{-6}	6.37×10^{-6}

IT IS EVIDENT THAT OIL IS DOMINATED BY GAS. WE HAVE DECIDED TO DELETE OIL FROM OUR FINAL DECISION TREE CALCULATIONS.

ECONOMIC EVALUATION OF SOLAR SYSTEMS

SYSTEM	C. COST/SQ. FT $	OUTPUT/SQFT. BTU
LOW TEMPERATURE	50	168,000
HIGH TEMPERATURE	80	168,000
PHOTOVOLTAIC	200	58,021

IT IS EVIDENT THAT LOW TEMPERATURE DOMINATES THE OTHER ALTERNATIVES. THE QUESTION IS HOW MUCH SHOULD THE AREA OF THE COLLECTOR BE, AND WHAT SHOULD BE THE ESCALATION FACTOR OF THE MOST COMPETITIVE CONVENTIONAL SYSTEM'S FUEL BE IN ORDER FOR THE L.T. SOLAR SYSTEM TO BE ECONOMICALLY ACCEPTABLE.

$$PV[SAVINGS] = \sum_{k=1}^{N} \Big\{ [OUTPUT/SQ.FT]^{SOLAR} \times [AREA]^{SOLAR} \times 1/[OUTPUT]^{CONV} \times [BASE\ VALUE]^{FUEL} \times [1+ESCAL]^{k} \times 1/[1+R.R.]^{k} \Big\} - [CAP.\ COST/sq.ft]^{SOLAR} \times [AREA]^{SOLAR}$$

AND $PV[SAVINGS] \geq 0$ - FOR SOLAR TO BE ACCEPTABLE

THE EQUATION CAN BE WRITTEN:

$$\sum_{k=1}^{N} \left(\frac{Q_s \cdot A_s}{Q_c} \; b \left(\frac{1+e}{1+i} \right)^k \right) - C_s A_s \geq 0$$

THE MOST COMPETITIVE CONV. SYSTEM USES GAS AND HAS THE FOLLOWING CHARACTERISTICS:

BASE COST OF GAS $(b) =$ \$ 0.005 / c.ft.

OUTPUT OF GAS SYSTEM $(Q_c) =$ 980 BTU/c.ft.

THE ABOVE EQ. CAN BE SIMPLIFIED AS:

$$\frac{Q_s}{Q_c} b \left(\frac{1+e}{1+i} \right) \frac{\left(1 - \left(\frac{1+e}{1+i} \right)^N \right)}{1 - \left(\frac{1+e}{1+i} \right)} - C_s \geq 0$$

TAKING $N = 40$ YEARS AND $\frac{1+e}{1+i} = r \Rightarrow$

$$\frac{168000}{980} \times 0.005 \; \frac{r(1-r^{40})}{1-r} - 50 \geq 0 \Rightarrow$$

$r < 1$ $\quad 0.857\, r(1-r^{40}) \geq 50 - 50r$

SOLVING FOR r WE GET $1 \leq r \leq 1.017$

WHICH IS IMPOSSIBLE

$r > 1$ $\quad 0.857 r(1-r^{40}) \leq 50 - 50r$

SOLVING FOR r WE GET $r > 1$ $\quad \boxed{r > 1.0175}$

WHICH MEANS $\frac{1+e}{1+i} > 1.0175 \Rightarrow$

$$\boxed{e > .0175 + 1.0175\, i}$$

FOR $i = 15\% \Rightarrow e \geq 17\%$

$i = 20\% \Rightarrow e \geq 22\%$

$i = 30\% \Rightarrow e \geq 32\%$

K·E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO MADE IN U.S.A.

