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Life Cycle Cost Analyses of U.S. Air Force Heating Plants

V. K. Wilkinson

OPERATED BY
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The overall objective of the effort was to provide the Air force, through the Air Force Engineering and Services Center (AFESC), a defensible plan to meet the provisions of a Defense Appropriation Act which directed that a program be implemented to rehabilitate and convert current heating plants at U.S. defense facilities to allow them to use coal. (continued)

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LIFE CYCLE COST ANALYSES OF U.S. AIR FORCE HEATING PLANTS

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CONTENTS

CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIFE CYCLE COST ANALYSES OF U.S. AIR FORCE HEATING PLANTS*

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ABSTRACT

The purpose of this study was the development of a life cycle costing forecasting methodology for U.S. Air Force heating plants and the translation of the resulting cost estimating relationships (CERs), algorithms, and data into a Heating Plant Cost Analysis Model. The model and methodology can be used for day-to-day cost trade-off analyses for both new equipment installation and modifications of existing facilities.

The overall objective of the effort was to provide the Air Force, through the Air Force Engineering and Services Center (AFESC), a defensible plant to meet the provisions of a Defense Appropriation Act which directed that a program be implemented to rehabilitate and convert current heating plants at U.S. defense facilities to allow them to use coal.

The report describes: 1) the approach including the methodology, data sources, data, and data analyses, 2) the Heating Plant Cost Analysis Model and the cost parameters for conventional Stoker coal technology along with some typical results, and 3) the primary conclusions reached thus far in the study with some plans for additional work.

1. INTRODUCTION

The purpose of this paper is to review the development of a life cycle costing forecasting methodology for U.S. Air Force heating plants

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and the translation of the resulting cost estimating relationships (CERs), algorithms, and data into a Heating Plant Cost Analysis Model. The model and methodology summarized in this paper can be used for day-to-day cost trade-off analyses for both new equipment installation and modifications of existing facilities.

The overall objective of this effort is to provide the Air Force, through the Air Force Engineering and Services Center (AFESC), a defensible plan to accomplish the Air Force program to meet the provisions of the Defense Appropriation Act (PL 99-190 Sect. 8110). This act directs that a program be implemented to rehabilitate and convert current heating plants at U.S. defense facilities to allow them to use coal.

This introduction concludes with a brief background and tasks involved in the study. The second section describes the approach including the methodology, data sources, data, and data analyses. The Heating Plant Cost Analysis Model and the cost parameters for conventional stoker coal technology are shown in the third section followed by some typical results in section four. The last section presents the primary conclusions reached thus far in the study with some plans for additional work.

The example results and parametric relationships shown in this paper only apply to a generic stoker coal fired heating plant. Follow-on work will modify individual inputs and parametric relationships to account for site and fuel technology specifics such that each site and technology at that site will ultimately be represented by its own individual life cycle cost model.[11,12]

1.1 Background

The FY 1986 Defense Appropriation Act (PL99-190) directs that a program be implemented to rehabilitate and convert current heating plants at defense facilities in the United States to coal burning facilities. The act sets a coal consumption target of 1.6 million short tons per year above the current consumption levels by 1994. A comprehensive Air Force program to increase coal consumption is currently under development. All aspects of this program must be as flexible and open as possible to permit the full range of private sector innovation and technologies for coal use. The Air Force plans to increase coal use by major alterations or replacements of existing plants using new technology coal fuels.

A primary driver in this coal conversion is project **COST EFFECTIVENESS.** This paper provides the bases for that evaluation as well as a method to quantify the uncertainty of and confidence in the results.

1.2 Tasks

The following is a summary of the principal tasks involved in this project. This paper will only address tasks 3 **ECONOMIC EVALUATION** and 4 **LIFE CYCLE COST MODELING.**

1.2.1 Task 1 - Data collection

Heating plant performance and cost data will be collected to provide an accurate picture of the combustion equipment currently in place and the operating and maintenance (O&M) costs of government owned and or operated heating plants.

1.2.2 Task 2 - Technical evaluation

Each basic type of combustion system will be evaluated to determine the technical requirements to convert to coal. This conversion may be one or more of several available options and either be a replacement boiler(s) or a modification of the existing combustion equipment.

1.2.3 Task 3 - Economic evaluation

The data will be analyzed by type of fuel (coal, oil, or gas) to evaluate the cost of ownership of heating plants. The analyses will develop cost estimating relationships for each type of fuel for both investment and operating costs.

1.2.4 Task 4 - Life cycle cost modeling

Task 2 and 3 evaluations will be used to develop a model to perform cost benefit analyses and estimate life cycle cost for each candidate site. The model will exceed the requirements of AFR 178-1 (Ref. 1) in providing both single and multi-variable sensitivity analyses to examine the effect of input variabilities (such as future fuel costs, return on investment, inflation, etc.) on the cost of ownership.

1.2.5 Task 5 - Third party financing

Third party financing of similar type projects will be assessed to obtain a basis for financing these projects. Based on this assessment, strategies for third party financing will be developed.

1.2.6 Task 6 - Specification preparation and procurement support

A functional specification will be prepared defining the technical and design requirements to be used by the successful bidder in the design, fabrication, and installation of the coal conversion equipment or plant. During the design, construction, installation, and start-up of the coal conversion system, technical evaluations will be made to provide the Air Force assurance that the system will meet their performance and budget needs.

2. APPROACH

The approach was based on discussions with heating plant equipment manufacturers, component designers, and operators as well as engineers with related experience and the author's experience on similar projects. This section describes that approach and the study parameters.

Figure 1 depicts the methodology used in selecting the coal conversion candidates for life cycle cost analyses and quantification of

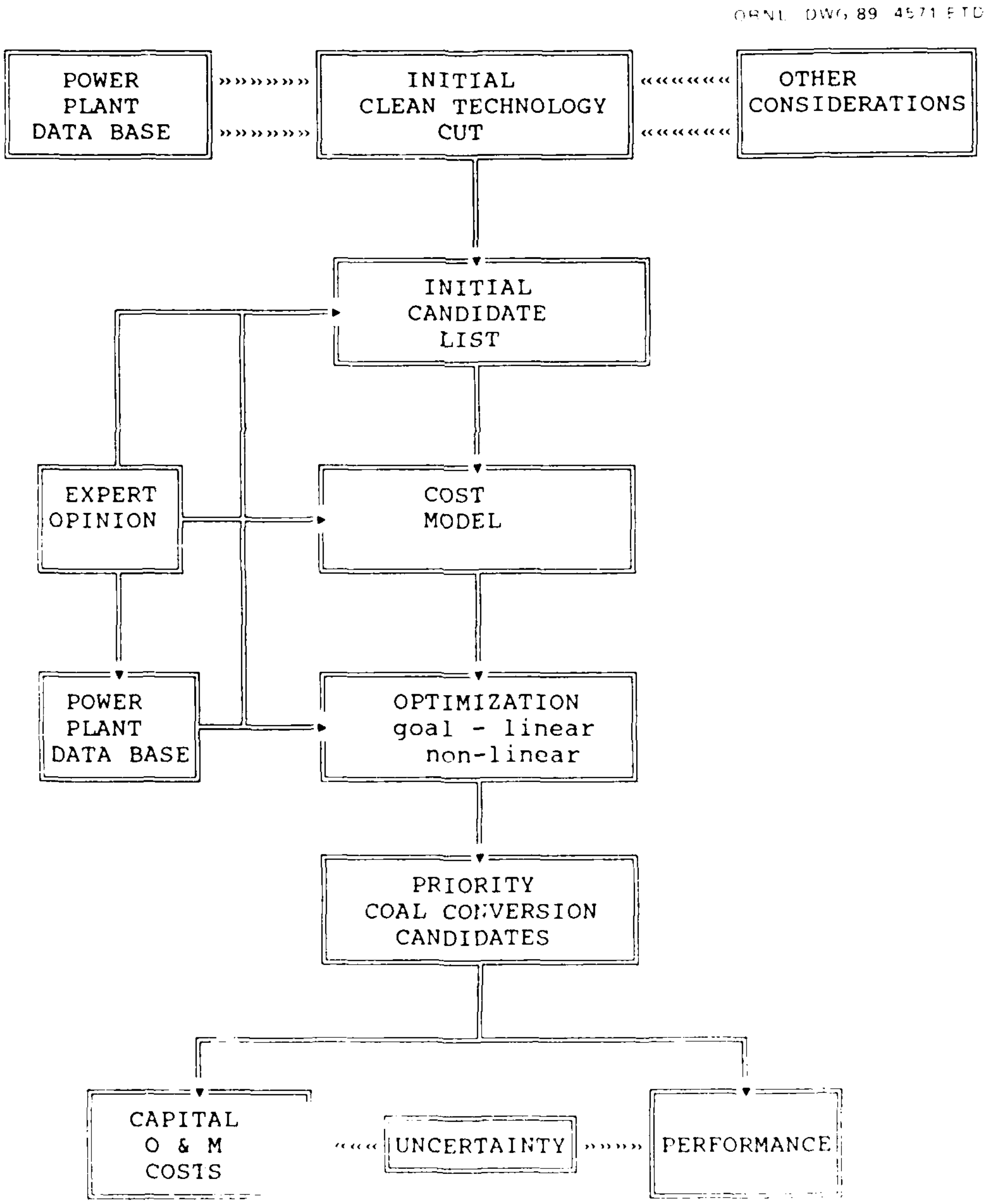

Fig. . Analysis Methodology.

cost and performance uncertainties. The use of expert opinion at various phases of the work is a modified Delphi analysis or peer review of the rationale for the list of initial candidate sites, cost modeling, and results of any optimization procedures. This effort will result in a prioritized list of candidate heating plants for coal conversion with their expected costs and performances as well as their associated uncertainties. This selection process, the technologies considered, and other considerations used in the selection process will be the subject of other reports. This report will deal strictly with the development of the Heating Plant Cost Analysis Model and its parameters.

Shown as Fig. 2 is a pictorial representation of the development of the Heating Plant Cost Analyses Model and its principal outputs. The data bases and the analyses of that data is the subject of the remainder of this section. The translation of the data analyses into the Heating Plant Cost Analysis Model is then covered in section three.

2.1 Data Bases

Data for the analyses came primarily from the Air Force Heating Plant Data Base (Figure 2) under development as part of the overall project. In addition to these data the current and projected fuel and transportation costs were obtained from a review of periodicals and pricing indexes, an example of which is shown as Table 1. Note that both coal price and transportation costs are combined in Table 1; i.e., transportation data is not a function of heat content as it would appear in the table.

The New Coal Technology Data Base was also used in these analyses. This data base is a compendium of in-house data on the availability, risk, and expected performance of the various new coal technologies.[2]

The Small Coal Plant Data Base formed the basis for the initial cost estimating relationships. The Small Coal Plant Data Base resulted from a 1984-85 effort for the U.S. Army Construction Engineering Research Laboratory analyzing fuel-burning technologies.[2]

The final data base, shown in Fig. 2, is miscellaneous data from other government owned heating plants such as the Department of Energy's K-25, Y-12, and X-10 plants.

2.2 Data Analyses

After initial data base construction individual data was analyzed, sorted, and in a number of cases corrected. There were two primary types of corrections:

1. Missing data: A number of data points were missing for both performance and cost. In most cases cost data was estimated by

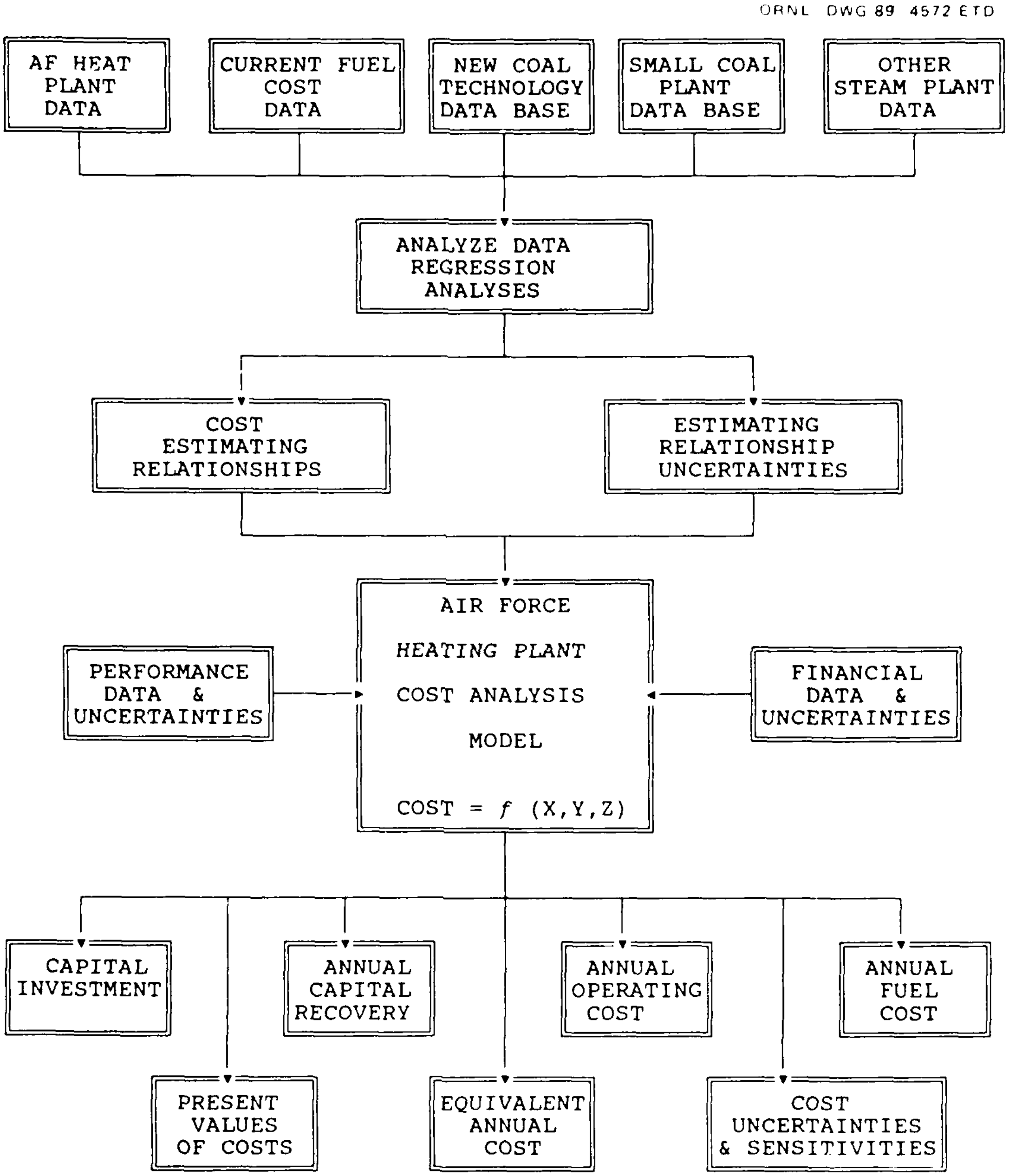

Fig. 2. Model Development.

Table 1. Coal price and transportation cost data

Coal price data					Transportation cost data		
Heat content (Btus/lb)	FOB price ($/ton)	FOB price ($/Mbtus)	Ash content (%)	Sulfur content (%)	Transport mileage	Transport cost ($/ton)	Transport cost ($/ton-mi)
12300	28.00	1.14	13.00	2.00	588	15.31	0.02604
12500	30.00	1.20	10.00	1.00	581	17.02	0.02929
12500	27.00	1.08	15.00	3.00	663	11.44	0.01725
12600	32.00	1.27	10.00	2.00	928	15.39	0.01658
12800	28.00	1.09	9.00	2.50	329	8.95	0.02720
12300	26.00	1.06	13.00	3.00			
13000	27.60	1.06	10.00	3.00			
13000	30.00	1.15	9.00	2.50			
11000	26.50	1.20	14.00	2.60			
11200	22.00	0.98	15.00	3.40			
11800	22.50	0.95	11.00	3.00			
12000	30.00	1.25	10.00	0.70			
12500	28.50	1.14	12.00	1.50			
11900	32.50	1.37	12.00	1.10			
12200	31.00	1.27	13.00	1.60			
13000	27.50	1.06	10.00	1.00			
13000	31.00	1.19	9.00	0.70			
11000	25.00	1.14	14.00	3.60			
12300	30.50	1.24	10.00	2.50			
10500	24.50	1.17	13.00	3.50			
11700	29.50	1.26	9.00	2.50			
10500	24.25	1.15	12.00	3.00			
11000	16.50	0.75	12.00	3.50			
11300	25.00	1.11	9.00	2.50			

Table 1. (continued)

	Coal price data					Transportation cost data		
	Heat content (Btus/lb)	FOB price ($/ton)	FOB price ($/Mbtus)	Ash content (%)	Sulfur content (%)	Transport mileage	Transport cost ($/ton)	Transport cost ($/ton-mi)
	9500	22.50	1.18	15.00	4.00			
	12000	31.50	1.31	13.00	1.60			
	12500	36.50	1.46	10.00	0.75			
	11700	28.00	1.20	12.00	4.50			
	12300	29.00	1.18	11.00	4.50			
	13000	39.50	1.52	9.00	0.70			
	10700	20.00	0.93	9.00	0.50			
	11600	24.00	1.03	9.00	0.50			
	10000	25.00	1.25	11.00	0.50			
	8100	6.25	0.39	6.00	0.50			
	10500	23.00	1.10	9.00	0.60			
	11500	26.00	1.13	9.00	0.60			
	8600	9.75	0.57	8.00	0.70			
	9300	12.00	0.65	6.00	0.40			
Mean	11557.89	26.01	1.11	10.82	2.00	617.80	13.62	0.02327
Standard deviation	1246.54	6.58	0.22	2.30	1.27	214.43	3.32	0.00592
Minimum	8100	6.25	0.39	6.00	0.40	329	8.95	0.01658
Maximum	13000	39.50	1.52	15.00	4.50	928	17.02	0.02929

Source: *Coal Week*, December 23, 1985.

weighted averages for the same type of plant. Missing data in the performance category was developed through expert opinion combined with engineering judgement.

2. Conflicting data: In a number of cases data for the same place or technology was not reported consistently from year-to-year or from one data base to another (both cost and performance). Again data corrections were supplied through expert opinion combined with engineering judgement.

2.3 Regression Analyses

Multiple-variable regression analysis was used to determine the principal cost drivers and the cost estimating relationships. The regression analyses considered two basic models:

1. The linear relationship:

$$DVj = A + B1 \cdot IV1 + B2 \cdot IV2 + \ldots + Bi \cdot IVi$$

where:

DVj is the jth dependent variable.

A is the linear intercept point and the Bs are the model parameters for each of the selected independent variables (IVs).

2. The non-linear relationship:

$$DVj = A \cdot [IV1^{B1}] \cdot [IV2^{B2}] \cdot \ldots \cdot [IVi^{Bi}]$$

The primary decision parameter used to determine which cost estimating relationship was best and which independent variables to include in the model was the amount of improvement in the regression coefficient; the SAS R-SQUARE procedure,[3] which examines all possible combinations of independent variables. The regression coefficient R-SQUARE is a measure of how much dependent variable data variation can be accounted for by the model. In general, the larger the value of R-SQUARE the better the model's fit.

3. COST ANALYSIS MODEL

After completion of the regression analyses, the results were examined, verified, and preliminary cost estimating relationships established. The next step was to construct models for each heating plant cost parameter (labor, material, etc.) based on the two models shown in the preceding section.

The basic model for each cost element is of the form:

$$\text{COST} = \alpha + \beta \cdot (\text{BC})^{\Phi} + \Gamma \cdot (\text{BC}\cdot\text{CF}) + \sigma \cdot (\text{BC/EF})^{\Omega}$$

where:

BC = Total heating plant output capacity in millions of Btus/h.
CF = Capacity Factor or demand/available.
EF = Boiler efficiency or heat out/heat in.

The following are the cost elements that make up the Heating Plant Cost Analysis Model. The numerical examples are for a conventional stoker coal fired plant. Follow-on work will modify individual inputs and parametric relationships to account for site and fuel technology specifics such that each site and technology at that site will ultimately be represented by its own individual life cycle cost model.[11,12]

3.1 Development Cost

Development costs are those expenditures required to develop a particular process. Development costs were simply an input for this study. Future studies may estimate these costs as a function of the capital investment required.

3.2 Capital Cost

Capital costs are the cost of construction and the engineering costs required for that construction. Engineering costs are estimated to be 20% of the construction estimate. Capital costs are adjusted on a size basis with an average stoker coal cost estimating relationship of 0.46. For example, a 200 MBtu/hour plant will cost about 40% more than a 100 MBtu/h plant. The capital costs and models shown in this report use scaling factors for a packaged shell stoker replacement boiler in an existing Air Force central heating plant.

Thus:

$$\text{Capital Cost} = \Sigma\ \text{CI}^{\text{SF}} + \text{INDIRECTS} + \text{CONTINGENCY}$$

where:

CI = Capital cost items (site work, baghouse, fuel handling, etc.)
SF = CI scaling factors. For a stoker plant $0.40 \leq SF \geq 0.80$ with a weighted average of 0.46.[2]

A more detailed discussion of the development of heating plant cost estimating equations can be found in Ref. 15. Site and technology specific capital costs can be found in Ref. 12.

3.3 Operating and Maintenance (O&M) Costs

O&M costs are the annual sum of capital equipment maintenance costs (often assumed to be a percentage of the capital investment), direct labor, fuel, other material, and utilities. For the private investment case return on investment (capital and operating), insurance and taxes (local and federal) are included in the O&M category.

3.3.1 Fuel costs

Fuel costs include the cost of transportation as a function of both rate and distance. The factors which determine the cost of fuel are the fuel price, the demand, heating plant efficiencies, and heating content of the fuel. Thus:

$$FD = 4175/(HC \cdot EF) \cdot (CF \cdot BC)$$
$$TR = TM \cdot MI$$
$$FUEL\ COST = (FP + TR) \cdot FD \text{ in k\$}$$

where:

FD = Fuel Demand in ktons/year
HC = Fuel Heat Content in Btus/lb
TR = Transportation Cost in k$/ktons
TM = Transportation Distance in miles
MI = Transportation Rate in $/ton-mile
FP = Fuel Price in $/ton

3.3.2 Fuel inflation

Shown in Table 2 are the indices for coal, oil, and gas used in these analyses. All examples in this report use the "nominal" values of Table 2. Because the LCC analyses are very sensitive to the assumed fuel escalation rates (when comparing one fuel to another), three separate fuel escalation rates will be examined in the follow-on studies.[11,12]

One set of fuel escalators are currently mandated to be used in Department of Defense (DOD) energy dependent economic analyses.[4] These DOD escalators are based on DOE's "Annual Energy Outlook 1986" report.[13] This report tabulates fuel escalation projections for ten regions of the

Table 2. Fuel escalation scenarios

Fuel	Escalation rate (%/year) 1988 through 1989	1990 through 1994	1995 through 1999	2000 and beyond
	Nominal values case			
Gas	3.89	8.87	5.77	5.77
Oil	4.86	7.87	4.16	4.16
Coal	1.16	2.31	1.19	1.19
	AEO 1987 case			
Gas	2.28	4.70	5.49	2.75
Oil	0.17	4.16	5.55	2.77
Coal	1.46	1.76	1.61	0.81

United States. For these analyses it was assumed that the average of these rates was applicable.

A second fuel escalation scenario was developed from the updated "Annual Energy Outlook 1987".[14] This set of escalators are designated "AEO 1987" and lie about midway between the "Nominal Values" and the third inflation scenario of zero fuel inflation. A more detailed analysis of these rates are contained in the ranking study.[12]

3.3.3 Labor costs

Labor costs are the direct labor costs including fringes for a 21 shifts per week operation. Thus:

$$LC = SM \cdot [5.55 \cdot (BC)^{0.18}] \cdot LR$$

where:

LC = Labor Cost in annual k$
LR = Labor Rate in k$ per year
SM = Supervision Multiplier

3.3.4 Utilities cost

Utilities required (including bag house) for the heating plant operation are assumed to be a function of the plant size and operating capacity. Thus for a coal fired plant based on previous work:[2]

$$UC = CF \cdot BC \cdot KW \cdot KP$$

where:

UC = Utilities Costs in k\$/year
KW = kWh used at full capacity in kWh/BC
KP = kWh price in k\$/kWh

3.3.5 Non-fuel materials costs

Non-fuel materials are those materials other than fuel required to operate the heating plant. Included in these categories is the cost of bag house operations.

Thus for a coal fired plant based on previous work:[2]

$$MT = 70.8 \cdot BC^{0.36}$$

where MT = Other Material Costs.

3.3.6 Ash disposal cost

The annual cost of ash disposal for coal fired plants is a function of the unit cost of disposal, fuel usage, and ash content of the fuel. Thus:

$$AD = UD \cdot AC \cdot FD$$

where:

AD = Ash Disposal Costs in k\$/year
UD = Unit Disposal Cost in \$/ton
AC = Ash Content in %

3.3.7 Maintenance costs

Maintenance costs are those annual costs required to maintain the heating plant. Maintenance costs also include the cost of replacement parts. Based on historical data, annual maintenance costs required for the heating plant operation are assumed to follow the standard "bathtub" reliability curve as shown in Fig. 3. The first three years of operation show the standard early or infant failure rate which has a high of about 17% of the capital costs. The most likely 9.55% constant rate is reached between year two and three with an uncertainty range of 3 to 10%. After 15 years of operations maintenance costs start increasing to a high of about 20% of the capital cost.

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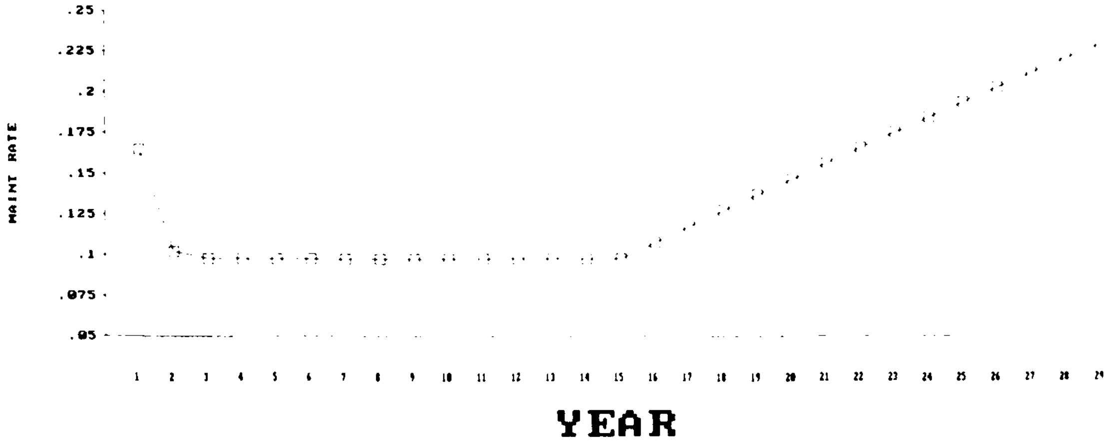

Fig. 3. Annual Maintenance Rate.

3.4 Private Investment

Several options may consider a privately owned and operated heating plant. The following assumptions can be used for these cases.

3.4.1 Return on investment

A Return on Investment (ROI) of 15 to 30% on the capital investment.

The private investment option does not require Air Force capital expenditures.

The contractor's capital investment is recovered using the standard Capital Recovery algorithm over the assumed plant life.

The private contractor received the same ROI for 60 days of operating cost expenditures (i.e., 60 days of working capital).

3.4.2 Taxes and insurance

Local property taxes and insurance are assumed to be 2% of the initial investment for the privately owned and operated plant. The local taxes and insurance for the privately owned plant were assumed to be paid out of the return on investment. For a government owned facility the change in facility investment is assumed to not effect the local in lieu of tax obligations. Income taxes are based on the 1986 Tax Reform Act rates shown in Table 3. The Heating Plant was assumed to be in the 15-year Property Class and was depreciated over 15 years using the sum-of-the-years' digits method. Taxable income was assumed to be the ROI

Table 3. 1986 Tax Reform Act rates

Taxable income (k$)	Rates (%)
0 < TI < 50	15.00
50 < TI < 75	25.00
75 < TI < 100	34.00
100 < TI < 335	39.00
335 < TI	34.00

on both capital and working capital and was treated as a negative cost (an income to the government) in the cash flows.

3.5 Figures-of-Merit

The following figures-of-merit are proposed as decision cost parameters for the Air Force heating plant analyses. All figures-of-merit reflect both Air Force and Federal Government costs. The difference between government and Air Force figures-of-merit is that the government figures take credit for income taxes paid by a private heating plant contractor-operator.

Five figures-of-merit are used for these example analyses.

3.5.1 Total cost

Total cost is the sum of all capital recoveries, development costs, and thirty years of operating costs. In the case of private investment the annual capital recovery cost is charged for each of the first 30 years.

3.5.2 Capital cost

Capital cost is the sum of all AIR FORCE capital expenditures over the life of the project (assumed to be 30 years for this study). In the case of private investment that capital cost is zero.

3.5.3 Annual operating cost

Annual operating costs are all costs required for normal operation of the heating plant, including fuel costs. Return on Investment of 60 days of operating costs is also part of this category.

3.5.4 Present value of cost

Present Value of Cost is the annual total cost stream, discounted at the 10% OMB recommended rate,[5] over the life of the project. This 10% discount rate accounts for the Federal Government's cost of capital.

3.5.5 Equivalent annual cost

The Equivalent annual cost algorithm used in this study was one proposed by Scott Lummer[6] for use in evaluating Investment alternatives with unequal lives under inflation. Even though the lives of all of the study options were the same, this figure-of-merit is useful in comparing the alternatives with an uncertain inflation rate. The basic algorithm states that:

Equivalent Real Annual Costs =
Present Value of Costs / Present Worth Factor

where the present worth factor is based on the equivalent interest rate (r) and

$$r = (1 + \text{discount rate}) / (1 + \text{inflation rate}) - 1.$$

The ultimate figure-of-merit used in the ranking studies[12] is the Benefit/Cost Ratio of:

Oil or Gas Present Value LCC/Coal Present Value LCC

for each of the sites and for each coal fired technology.

4. TYPICAL RESULTS

This section gives an overview of some typical results obtained using the methodology and models described in the preceding sections. This section first looks at the base or most likely case for a typical stoker coal fired heating plant. The remainder of this section looks at both single variable and multi-variable sensitivities analyses about the base case.

4.1 Base Case

Table 4 summarizes the base or most likely cost model input values for a government owned and operated stoker coal fired heating plant, the expected range of those values, and type of distribution for that range. Table 5 shows the appropriate output values for the Table 4 inputs. Table 6 shows the cash flows over the economic study life in constant, discounted, as spent, and discounted as spent dollars.

Table 4. Cost model input

Type plant: Stoker Case: Conventional coal

Parameter	Most likely value	Dimension	Expected distribution	Expected range
Development cost	0			
Boiler capacity	200	MBtu/h	Triangle	100 to 500
Boiler efficiency	76	%	Triangle	70 to 79
Capacity factor	72	%	Triangle	55 to 75
Coal price	20	$/ton	Triangle	6.26 to 39.5
Transportation cost	0.02	$/mile	Triangle	0.0166 to 0.293
Transportation distance	500	Miles	Constant	
Heat content	7600	Btus/lb	Triangle	7600 to 13,000
Ash content	7	%	Triangle	6 to 15
Ash disposal cost	10	$/ton	Triangle	6 to 14.5
Labor cost	35	$K/year	Triangle	29.4 to 40.0
Plant life	30	Years	Constant	
Discount rate	10	%	Constant	
Inflation rate	0	%	Triangle	0 to 8
Return on investment	0	%	Triangle	10 to 40
Real interest rate	10	%		
Maintenance factor	9.75	%	Triangle	3 to 13
Input dollars	1989	FY		
Project start year	1990	FY		
Depreciation life	15	Years		
Electric rate	0.05	$/kWh		

Table 5. Most likely cost of Stoker coal case

Cost element	Most likely ($K)
Development	0
Capital	5,620
Average annual operating and maintenance	5,511
Fuel	3,442
Labor	670
Non-fuel material	477
Utilities	184
Ash disposal	76
Maintenance	661
Average annual return on investment	0
Average annual local tax and insurance	0
Average annual federal tax	0
Figures-of-merit	
Total cost - Government	183,226
Total cost - Air Force	183,226
Capital cost	5,620
Annual operating	5,511
Total present value - Government	51,915
Total present value - Air Force	51,915
Equivalent annual - Government	5,507
Equivalent annual - Air Force	5,507

Tables 4, 5, and 6 make up the conventional coal model. Changing the Table 4 input values will automatically change the output values of Tables 5 and 6 when this program is Run in Ashton-Tate's Framework II.®

Shown in Table 5 are the costs resulting from the application of most likely conventional coal values from Table 4. Table 6 shows the cash flows for the Table 5 values.

4.2 Single Variable Sensitivities

Figures 4 and 5 show the results of two conventional coal single variable sensitivity studies. The single variable study or technique is the most useful method for determining which input parameter has the highest economic leverage on a specific figure-of-merit.

Table 6. Stoker coal cash flows, $K

Cost element	1990	1991	1992	1993	1994	1995	1996	1997	1998
Development	0								
Capital investment	5,620	0							
Capital recovery	0	596	596	596	596	596	596	596	596
Operations % maintenance	0	5,774	5,423	[illegible]	5,398	5,398	5,398	5,398	5,398
Fuel	0	3,442	3,442	3,442	3,442	3,442	3,442	3,442	3,442
Labor	0	670	670	[illegible]	670	670	670	670	670
Non-fuel material	0	477	477	477	477	477	477	477	477
Utilities	0	184	184	184	184	184	184	184	184
Ash disposal	0	76	76	76	76	76	76	76	76
Maintenance	0	925	573	550	548	548	548	548	548
R O I	0	0	0	0	0	0	0	0	0
Local tax	0	0	0	0	0	0	0	0	0
Federal tax	0	0	0	0	0	0	0	0	0
Government total - 89 $	0	6,371	6,019	5,996	5,994	5,994	5,994	5,994	5,994
Air Force total - 89 $	0	6,371	6,019	5,996	5,994	5,994	5,994	5,994	5,994
Discount factor	0.91	0.83	0.75	0.68	0.62	0.56	0.51	0.47	0.42
Government discount total	0	5,265	4,522	4,095	3,722	3,384	3,076	2,796	2,542
Air Force discount total	0	5,265	4,522	4,095	3,722	3,384	3,076	2,796	2,542
Fuel escalated - 89 $	0	3,603	3,686	3,771	3,858	3,904	3,951	3,998	4,045
Inflation factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Government with escalated fuel total	0	6,532	6,263	6,325	6,411	6,456	6,503	6,550	6,597
Air Force with escalated fuel total	0	6,532	6,263	6,325	6,411	6,456	6,503	6,550	6,597
Government with escalated fuel	0	5,398	4,706	4,320	3,980	3,644	3,337	3,056	2,798
Air Force with escalated fuel	0	5,398	4,706	4,320	3,980	3,644	3,337	3,056	2,798

Table 6. (continued)

Cost element	1999	2000	2001	2002	2003	2004	2005	2006	2007
Development									
Capital investment									
Capital recovery	596	596	596	596	596	596	596	596	596
Operations % maintenance	5,398	5,398	5,398	5,398	5,398	5,398	5,398	5,398	5,398
Fuel	3,442	3,442	3,442	3,442	3,442	3,442	3,442	3,442	3,442
Labor	670	670	670	670	670	670	670	670	670
Non-fuel material	477	477	477	477	477	477	477	477	477
Utilities	184	184	184	184	184	184	184	184	184
Ash disposal	76	76	76	76	76	76	76	76	76
Maintenance	548	548	548	548	548	548	548	548	548
R O I	0	0	0	0	0	0	0	0	0
Local tax	0	0	0	0	0	0	0	0	0
Federal tax	0	0	0	0	0	0	0	0	0
Government total - 89 $	5,994	5,994	5,994	5,994	5,994	5,994	5,994	5,994	5,994
Air Force total - 89 $	5,994	5,994	5,994	5,994	5,994	5,994	5,994	5,994	5,994
Discount factor	0.39	0.35	0.32	0.29	0.26	0.24	0.22	0.20	0.18
Government discount total	2,311	2,101	1,910	1,736	1,578	1,435	1,304	1,186	1,078
Air Force discount total	2,311	2,101	1,910	1,736	1,578	1,435	1,304	1,186	1,078
Fuel escalated - 89 $	4,094	4,142	4,192	4,241	4,292	4,343	4,395	4,447	4,500
Inflation factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Government with escalated fuel total	6,646	6,694	6,744	6,793	6,844	6,895	6,947	6,999	7,052
Air Force with escalated fuel total	6,646	6,694	6,744	6,793	6,844	6,895	6,947	6,999	7,052
Government with escalated fuel	2,562	2,346	2,149	1.968	1,802	1,651	1,512	1,385	1,268
Air Force with escalated fuel	2,562	2,346	2,149	1.968	1,802	1,651	1,512	1,385	1,268

Table 6. (continued)

Cost element	2008	2009	2010	2011	2012	2013	2014	2015	2016
Development									
Capital investment									
Capital recovery	596	596	596	596	596	596	596	596	596
Operations % maintenance	5,398	5,398	5,398	5,398	5,398	5,398	5,398	5,398	5,398
Fuel	3,442	3,442	3,442	3,442	3,442	3,442	3,442	3,442	3,442
Labor	670	670	670	670	670	670	670	670	670
Non-fuel material	477	477	477	477	477	477	477	477	477
Utilities	184	184	184	184	184	184	184	184	184
Ash disposal	76	76	76	76	76	76	76	76	76
Maintenance	548	548	548	604	650	715	769	823	877
R O I	0	0	0	0	0	0	0	0	0
Local tax	0	0	0	0	0	0	0	0	0
Federal tax	0	0	0	0	0	0	0	0	0
Government total - 89 $	5,994	5,994	5,994	6,050	6,106	6,161	6,216	6,270	6,323
Air Force total - 89 $	5,994	5,994	5,994	6,050	6,106	6,161	6,216	6,270	6,323
Discount factor	0.16	0.15	0.14	0.12	0.11	0.10	0.09	0.08	0.08
Government discount total	980	891	810	743	682	626	574	526	482
Air Force discount total	980	891	810	743	682	626	574	526	482
Fuel escalated - 89 $	4,553	4,608	4,662	4,718	4,774	4,831	4,888	4,946	5,005
Inflation factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Government with escalated fuel total	7,105	7,160	7,214	7,326	7,438	7,550	7,662	7,774	7,886
Air Force with escalated fuel total	7,105	7,160	7,214	7,326	7,438	7,550	7,662	7,774	7,886
Government with escalated fuel	1,162	1,064	975	900	831	766	707	652	602
Air Force with escalated fuel	1,162	1,064	975	900	831	766	707	652	602

Table 6. (continued)

Cost element	2017	2018	2019	2020	Total ($M)
Development					0
Capital investment					6
Capital recovery	596	596	596	596	18
Operations % maintenance	5,780	5,832	5,884	5,935	165
Fuel	3,442	3,442	3,442	3,442	103
Labor	670	670	670	670	20
Non-fuel material	477	477	477	477	14
Utilities	184	184	184	184	6
Ash disposal	76	76	76	76	2
Maintenance	930	982	1,034	1,085	20
R O I	0	0	0	0	0
Local tax	0	0	0	0	0
Federal tax	0	0	0	0	0
Government total - 89 $	6,376	6,428	6,480	6,531	183
Air Force total - 89 $	6,376	6,428	6,480	6,531	183
Discount factor	0.07	0.06	0.06	0.05	
Government discount total	442	405	371	340	52
Air Force discount total	442	405	371	340	52
Fuel escalated - 89 $	5,065	5,125	5,186	5,248	133
Inflation factor	1.00	1.00	1.00	1.00	
Government with escalated fuel total	7,999	8,111	8,224	8,337	213
Air Force with escalated fuel total	7,999	8,111	8,224	8,337	213
Government with escalated fuel	555	511	471	434	58
Air Force with escalated fuel	555	511	471	434	58

Figure 4 graphically depicts the ROI affect on the Total Cost figure-of-merit. The zero ROI represents the government financed case. The other cases represent priviate financing.

Figure 5 demonstrates the boiler capacity affect on required capital investment.

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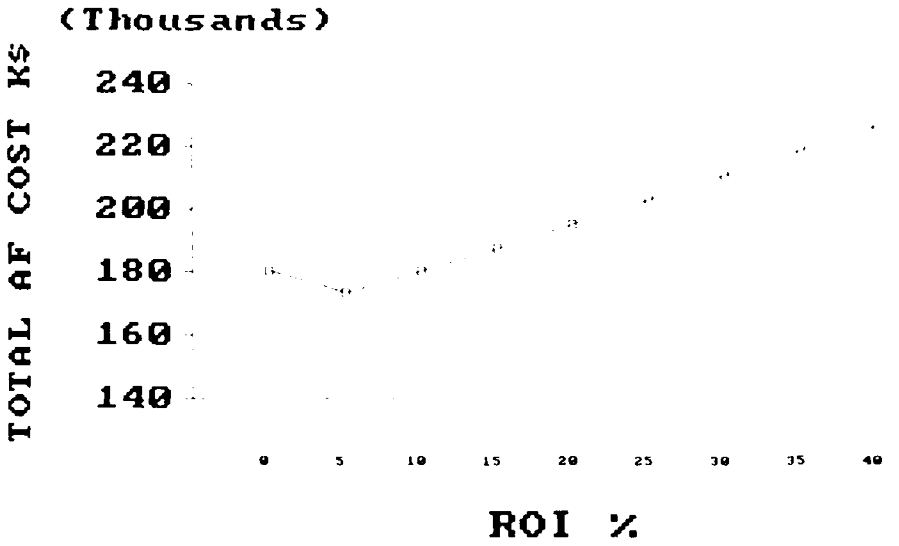

Fig. 4. Total Air Force Cost as a Function of ROI.

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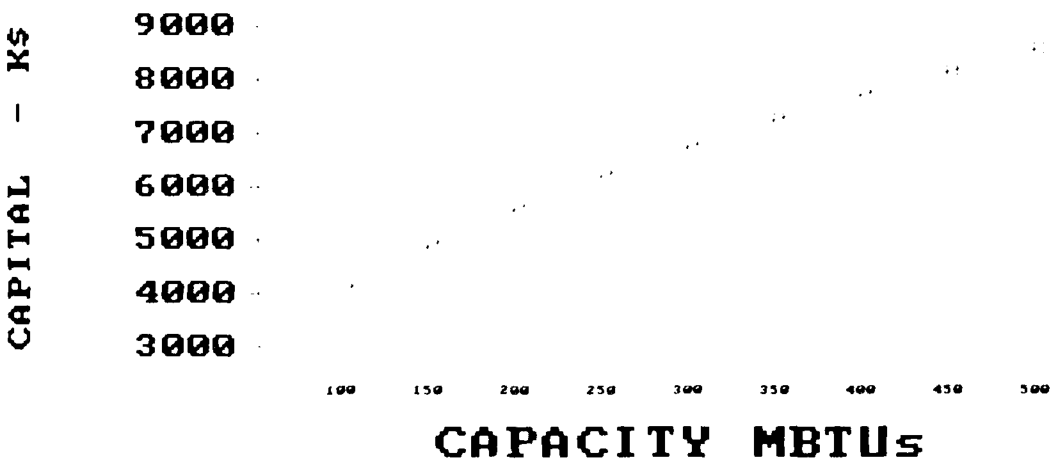

Fig. 5. Capital as a Function of Boiler Capacity.

4.3 Multi-Variable Sensitivities

The next step in this procedure was to examine the interaction of the various input uncertainties. It is very misleading to examine the so-called "best" and "worst" cases and call the result the range of possible outcomes. The probability of the best or worst occurring may be in the order of 1 in a billion in even moderately complex systems. What must be defined is the probability of the various results given the input uncertainties. The uncertainties of the results should be stated as a degree of confidence in the results. For example, a 50% confidence that the total cost will be $150 million or less and a 90% confidence the total will be less than $300 million. This study used simulation as the means of estimating the uncertainties of the figures-of-merit.

Uncertainty analysis requires that the economic figures-of-merit (outcomes) be derivable from a set of performance and economic inputs. These inputs may or may not have uncertainty associated with them. Mathematical models that simulate the process and the associated investments and costs are the primary method used to determine the range of possible outcomes for a particular option.

The key to this process is the selection of the most likely value, the range of that value and a probable distribution of the value for each uncertain input. This analyses requires expert opinion along with the use of conventional forecasting techniques. Simultaneous selection of values for the uncertain inputs within the specified range at the assumed frequency of occurrence is accomplished with a Monte Carlo sampling technique. For each set of randomly selected input values, a figure-of-merit is calculated; this process is repeated until a statistically significant figure-of-merit probability distribution emerges. This method constitutes a means of performing multi-variable sensitivity studies (MVSS).

Simulation is the term often applied to the use of probabilistic methods, such as Monte Carlo, used in conjunction with a system or process model. It is the model that "simulates" the system. The model is a subroutine that is called by the driver for each iteration. Driver software are sometimes called "simulators" even though their algorithms do not model any system.

At this point the question: Why simulation? should be answered:

> If the relationships which make up the model are simple enough, it may be possible to use standard mathematical method (such as algebra, calculus, or probability theory) to obtain an analytic solution. However, most real-world systems are too complex and the relationships are too interrelated to be evaluated analytically, and these models must be studied by means of simulation. An example of this is the complex relationship between discount rate, inflation rate, return on investment, and time that was used in this study.

The Monte Carlo driver used in this study was developed by ORNL's Kent A. Williams[7,8] and modified by the author. This driver and the associated Fortran process and cost models have been used extensively, with outstanding results, for a number of risk and uncertainty analyses.

With even very accurate and comprehensive models, the quality of the output depends entirely on the accuracies of the inputs. Determination of the "correct" input values and range of those values are best estimated by experts in the areas in question. Estimating methods that use collective expert opinion (such as Delphi techniques) are very useful for this task.

The triangular probability distribution for inputs is especially useful because its parameters are easily defined and understood by managers. This distribution is defined in terms of an optimistic end point, a pessimistic end point, and a most likely value (mode). An additional advantage of the triangular distribution is that it can be used to approximate more complex distributions such as the normal, lognormal, Weibull, and Poisson and still be easily understood.

However, input distributions are not limited to the triangular. Distribution that were available and considered for this study were: constant, triangle, normal, log-triangle, log-normal, trapezoidal, and uniform. The assumed distribution and its parameters for each input variable are shown in Table 5 in Sect. 4.1.

See Refs. 9 and 10 for addition detail on the use of uncertainty analysis in decision making.

Table 7 shows the figures-of-merit distributions as well as the 50% and 95% confidence intervals which result from the input uncertainties shown in Table 4. Figure 6 shows the resulting distribution for Total Cost as a function of probability of occurrence.

Table 7. Conventional coal figures-of-merit uncertainties

Figures-of-merit	Mean ($M)	σ ($M)	Confidence cost	
			<50%	<95%
Total cost	261	77	250	401
Capital cost	5.88	0.80	5.82	7.32
Annual operating	7.08	2.11	6.78	10.83
Total PV	76	23	73	119
Equivalent annual	5.07	1.76	4.82	8.25

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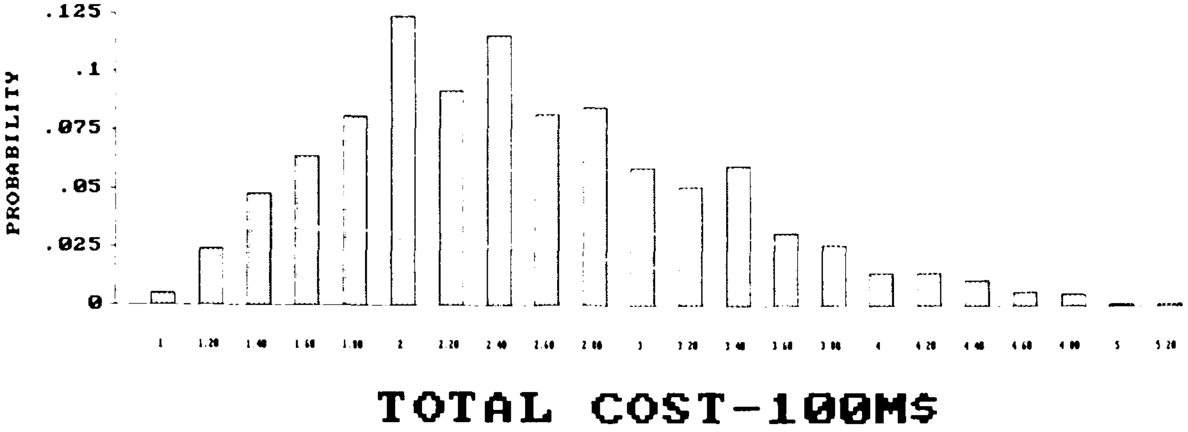

Fig. 6. Total Cost Probabilities.

5. CONCLUSIONS

The single, most significant conclusion reached in the course of this project is that a methodology in which systematic analyses of historical cost and performance data coupled with input from experts can be used to predict life cycle costs of Air Force heating plants.

The following are some specific conclusions and recommendations:

1. Life cycle cost should be used as part of any formal technology evaluation cycle.

2. All proposed design changes should be subject to a cost benefit analysis as part of the approval process.

3. The CERs developed over the course of the project should be examined and critiqued by heating plant operators, designers, system analysts, and component suppliers.

4. The CERs developed during this project should be evaluated and updated as additional information becomes available.

5. The heating plant cost model developed during this project should be expanded and updated as part of the on going Air Force heating plant upgrade program.

6. The data base developed during this project should be continually evaluated and updated as additional information becomes available.

7. The coal, gas, and oil price inflators form the bases of all long term analyses. These indices are probably the most uncertain of all the inputs and as such should be analyzed extensively for there affect on all cost benefit analyses.

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