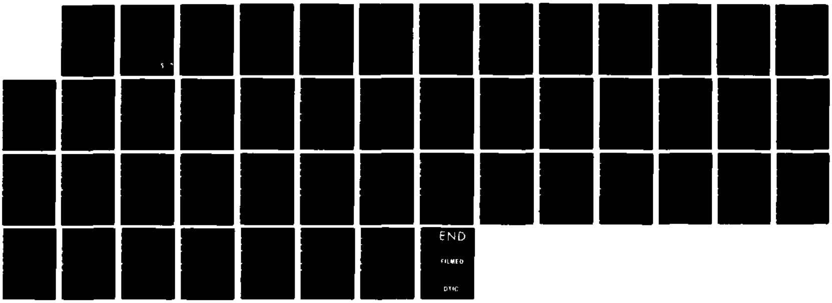
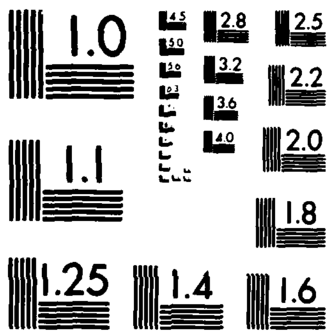
AD-A148 214   AN ECONOMIC EVALUATION OF ALTERNATIVE METHODS OF UTILIZING AVAILABLE LAND..(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA C A KODRES AUG 82 NCEL-TN-1642   1/1

UNCLASSIFIED   F/G 10/1   NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD-A148 214

TECHNICAL NOTE

TN NO: N-1642

TITLE: AN ECONOMIC EVALUATION OF ALTERNATIVE METHODS OF UTILIZING AVAILABLE LANDFILL GAS TO COGENERATE POWER AT NAS MIRAMAR

AUTHOR: C. A. Kodres

DATE: August 1982

SPONSOR: Chief of Naval Material

PROGRAM NO: S0371-01-141A

NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043

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METRIC CONVERSION FACTORS

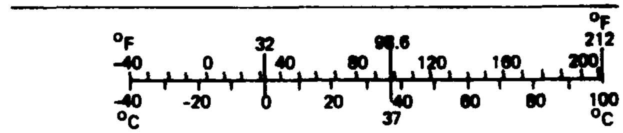
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: TN-1642

2. GOVT ACCESSION NO: AD-A145214 ~~DN987115~~

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): AN ECONOMIC EVALUATION OF ALTERNATIVE METHODS OF UTILIZING AVAILABLE LANDFILL GAS TO COGENERATE POWER AT NAS MIRAMAR

5. TYPE OF REPORT & PERIOD COVERED: Not final; Aug 1981 – Mar 1982

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): C. A. Kodres

8. CONTRACT OR GRANT NUMBER(s):

9. PERFORMING ORGANIZATION NAME AND ADDRESS: NAVAL CIVIL ENGINEERING LABORATORY, Port Hueneme, California 93043

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 64710N; S0371-01-141A

11. CONTROLLING OFFICE NAME AND ADDRESS: Chief of Naval Material, Washington, DC 20360

12. REPORT DATE: August 1982

13. NUMBER OF PAGES: 42

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cogeneration, waste heat recovery, sanitary landfill, landfill gas, ~~methane~~, energy conservation, alternate energy sources.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Naval Air Station at Miramar contains the largest active sanitary landfill in San Diego County. It is estimated that the anaerobic decomposition of the organic refuse in this fill is producing sufficient methane to completely satisfy the energy requirements of the base if some means can be found to efficiently utilize this gas as a fuel. An economic evaluation of alternative methods of employing the landfill gas is presented. Among the alternatives examined is the use of the methane as a gas turbine fuel to cogenerate both electricity and steam.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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Library Card

Naval Civil Engineering Laboratory
AN ECONOMIC EVALUATION OF ALTERNATIVE METHODS OF UTILIZING AVAILABLE LANDFILL GAS TO COGENERATE POWER AT NAS MIRAMAR, by C. A. Kodres

TN-1642 42 pp illus August 1982 Unclassified

1. Energy conservation 2. Methane I. S0371-01-141A

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

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INTRODUCTION

The Naval Air Station (NAS) at Miramar, California, contains the largest active sanitary landfill in San Diego County. It is anticipated that 730 acres will be filled by the end of 1982; an additional 870 adjacent acres have been proposed as an extension to the existing sites.

Anaerobic decomposition of the organic refuse in landfills generates a gas that is approximately 50% methane. It is estimated (Ref 1) that the completed Miramar fills are producing this landfill gas at about 1.9×10^5 ft^3/hr. If all the methane could be recovered, this would be equivalent to 100 MBtu/hr. The energy demand at the NAS, both electrical and thermal together, is about 45 MBtu/hr. Thus, much - possibly all - of the energy requirements at the base could be met by efficient utilization of the landfill gas.

It takes from 5 to 10 years of decomposition before methane is produced at rates sufficient to warrant the cost of extraction (Ref 2). The landfill's economic life then is between 20 and 25 years. The Miramar fill has been employed continuously for about 20 years, and different sections are in different stages of decomposition. Nevertheless, the landfill rate has been increasing, and most of the filled acreage is only a few years old. If the proposed fills are employed, the methane production rate is expected to equal or exceed the current 100 MBtu/hr rate for the next 22 years (Ref 1). This is about the life span of the equipment required to recover, process, and burn the gas to generate electricity and steam for the base.

The ratio of thermal to electrical loads experienced at Miramar is slightly greater than 1:1, suggesting that the use of the landfill gas as a gas turbine fuel for the cogeneration of both electricity and steam might be the optimum approach (Ref 3). This alternative, and others, have been examined, and the results of the study are presented in this report.

EVALUATION OF THE ALTERNATIVES

Scope

Comparisons of alternatives that would employ the landfill gas are made on the basis of economics. The dependent variable is the required annual cost of electricity and steam.

Real engines are being examined. Most of these engines, however, were designed to run on natural gas rather than medium-Btu landfill gas. The differences in performance have been accounted for; hardware problems have been considered but not appraised.

The economics and the hardware are, of course, coupled. Certainly the initial capital expenditure will vary, but of more consequence is the processing required of the landfill gas prior to its use as a fuel.

Engines capable of running on medium-Btu landfill gas straight out of the ground will have an economic advantage over engines requiring the gas to be purified.

Only the capacities of the Miramar fill have been considered. For instance, the moisture content or the presence of contaminants affect both the selection of hardware and the required degree of purification of the gas, but these characteristics have not been made a part of the study.

Estimates of the costs of landfill gas extraction and purification vary over a wide range. As a typical example, the Los Angeles Bureau of Sanitation calculates gas extraction to cost $0.60/MBtu, while extraction plus processing to pipeline grade costs about $2.73/MBtu (Ref 4). For this study, the landfill gas will be assumed to cost $1.35/MBtu (the actual cost of extracting, drying, and partial pressurization of gas produced at the Sheldon-Arleta fill near Los Angeles (Ref 2)).

Mathematical Modeling

Economic analyses of this type have a tendency to become lengthy. In addition to the large number of configurations to be investigated and the complexity of the engines themselves, the analyses involve examination of potential future conditions. The electrical and steam requirements must be included. Finally, the complicated rate structure of electricity sold and purchased by the utilities must be represented.

To shorten the duration of this study and others like it, a mathematical model was developed to simulate a facility cogenerating electricity and steam. Making minor modifications to fit individual alternatives, this model was used, exclusively, to provide the cost comparisons that follow.

COGENERATION MODEL

Gas Turbine

To achieve acceptable accuracy, real turbines must be examined; still, it would be advantageous to eliminate some of the lesser variables affecting performance. Consider, for example, the problem of interpolating through an Nth-order matrix to determine off-design conditions.

Two major assumptions were made to simplify performance calculations. First, it was assumed that losses to the environment were proportional to the generator output, $\dot{E}$,

$$\text{Losses to Environment} \sim (1 - \eta)\,\dot{E}$$

with the constant of proportionality, η, a characteristic efficiency of individual engines. The second assumption was to stipulate that the mass flow rate of air through the engine remains constant.

Figure 1 is a schematic illustrating the gas turbine cogeneration system. Applying conservation of energy to the overall turbine-generator,*

$$(\dot{M}_A + \dot{M}_F)\ C_{P,EXH}\ T_{EXH} + \dot{E} + (1-\eta)\ \dot{E} - \dot{M}_A\ C_{P,\infty}\ T_\infty$$

$$- \dot{M}_F \Delta H_F \;=\; 0 \qquad (1)$$

where $\dot{M}_A$ = mass flowrate of air

$\dot{M}_F$ = mass flowrate of fuel

C_P = specific heat

T_{EXH} = turbine exhaust temperature

$\dot{E}$ = generator output

T_∞ = ambient temperature

ΔH_F = heating value of fuel

With this approach, the performance of the system can be represented by the air flow rate and a relationship between fuel flow and generator output,

$$\dot{M}_F \;=\; f(\dot{E}) \qquad (2)$$

The assumptions perhaps need further elaboration. By utilizing real $\dot{M}_F$ versus $\dot{E}$ information, irreversibilities are built into the analyses. If losses to the "environment" can be accounted for, losses remaining are those that contribute to an increase in exhaust temperature. Knowledge of this temperature is fundamental to cogeneration studies.

Losses to the environment are the result of heat transfer (such as off the outer skin or into the lubrication oil) and power being diverted to auxiliaries (such as to the pumps). A direct correlation with power (generator) output can reasonably be assumed; losses to the environment amount to only a small percentage of the total power generated.

Turbine-generator sets operate at constant revolutions per minute in order to maintain a constant frequency output. If the blade geometry is fixed, the volumetric flow rate of air is nearly independent of loading. Unless inlet conditions vary appreciably, the air mass flow rate remains constant.**

---

* For a perfect gas and selecting a datum such that h = 0 when T = 0.
**This assumption is not valid for dual-shaft engines.

The typical accuracy of these assumptions is shown on Figure 2. Exhaust temperatures predicted by the model are being compared with manufacturers' specifications for several turbine-generator sets. Letting $\eta \sim 0.95$, the maximum error associated with predicted values of the turbine exhaust temperature is about 6%. The power lost to the environment ranges from 1.8% to 3.4% of the total power output.

Applying conservation of energy to the turbine exhaust, steam, and heat recovery boiler, respectively,

$$\dot{Q}_{STM} = K\ (\dot{M}_A + \dot{M}_F)\ C_{P,BLR}\ (T_{EXH} - T_{STACK}) \tag{3}$$

$$\dot{Q}_{STM} = \dot{M}_{STM}\ (h_{STM} - h_{SAT}) \tag{4}$$

$$\dot{Q}_{STM} = UA\Delta T_M \equiv UA \frac{(T_{EXH} - T_{STM}) - (T_{STACK} - T_{SAT})}{\ln\left(\dfrac{T_{EXH} - T_{STM}}{T_{STACK} - T_{SAT}}\right)} \tag{5}$$

where $\dot{Q}_{STM}$ = heat transferred from engine exhaust to steam

K = factor to account for flow loss between turbine and boiler

T_{STACK} = temperature of engine exhaust as it exits heat recovery boiler

h_{SAT} = enthalpy of feed water to heat recovery boiler

h_{STM} = enthalpy of steam exiting the heat recovery boiler

U = overall heat transfer coefficient of heat recovery boiler

A = heat transfer area of heat recovery boiler

ΔT_M = logarithmic mean temperature difference

Waste heat boiler heat transfer coefficients are assigned and are considered independent of loading. The resistance to heat transfer from the exhaust gases is the dominant resistance, and exhaust flow is nearly constant; the exhaust temperature is the only variable affecting heat transfer characteristics. It is easily demonstrated that, over the range of exhaust temperatures normally experienced, the influence of this variable is minor; e.g., if the turbine exhaust flows turbulently over a series of staggered tubes (Ref 6),

$$\hat{h}_{EXH} \propto k_{EXH}\ (\text{Reynolds No.})^{0.6}\ (\text{Prandtl No.})^{0.3}$$

where $\hat{h}_{EXH}$ = convective heat transfer coefficient

k_{EXH} = coefficient of thermal conductivity

Thus, the cogeneration process is represented by a system of five algebraic equations with the following six variables: $\dot{E}$, $\dot{M}_F$, T_{EXH}, T_{STACK}, Q_{STM}, and $\dot{M}_{STM}$. The final relationship required is the control mode of the turbine-generator. Three options are built into the model:

1. The turbine operates continuously at maximum output; therefore the electrical output, $\dot{E}$, is established.
2. The turbine-generator follows the electrical load of the facility; again, $\dot{E}$ is set.
3. The turbine follows the thermal (steam) load of the facility; here, the steam produced by the waste heat boiler, $\dot{M}_{STM}$, is established.

Equations 2 and 5 make the system nonlinear. A Newton-Raphson iteration is employed to obtain a solution.

Once the performance of the cogeneration system has been determined, the economics of the process becomes a matter of bookkeeping,

$$TC = CC + F + OM + P - R \tag{6}$$

where TC = total annual cost of providing electrical and thermal service to the base

CC = capital cost expenditure, including interest on funds during construction

F = fuel costs, including fuel to the auxiliary steam boiler

OM = operation and maintenance costs

P = cost of electricity purchased

R = revenue resulting from the sale of electricity or steam

References 3 and 5 describe the model in greater detail.

Diesel Cycle Engine

The model developed to simulate a diesel cycle engine cogenerating electricity and steam is analogous to the gas turbine model.

ALTERNATIVE METHODS OF UTILIZING LANDFILL

The geography of the NAS Miramar plays a major role in the evaluation of the alternatives. The landfill is located several miles from the working areas of the base, with the runways between the two areas (see Figure 3).

The following alternatives were examined:

1. Buying natural gas as a fuel for the cogeneration of electricity and steam. No landfill gas would be utilized.

2. Using landfill gas as a fuel to generate electricity only. The entire facility would be located at the landfill.

3. Generating electricity using landfill gas augmented with purchased natural gas. This alternative would be applicable when larger engines were used and the capacity of the fill was not sufficient to fuel them, or, perhaps, when the heating value of the landfill gas dropped below a level capable of sustaining the engines. Again, the entire facility would be located at the landfill.

4. Generating electricity using landfill gas and concurrently cogenerating electricity and steam with purchased natural gas. There would be separate facilities on the landfill and the base.

5. Piping landfill gas back to the base and using it as a fuel for the cogeneration of electricity and steam. This alternative would probably be preferable to the option of cogenerating at the landfill and piping steam to the base for utilization.

6. Piping landfill gas back to the base, augmenting it with purchased natural gas, and using it as fuel for the cogeneration of electricity and steam.

7. Selling the landfill gas. This could be done in several ways, depending upon the degree of purification (i.e., selling it straight out of the ground, partial purification, or purification to pipeline grade).

8. Selling the landfill gas and concurrently cogenerating electricity and steam on the base with purchased natural gas.

All alternatives investigated have included gas turbine configurations, but reciprocating engines employing the diesel cycle were also considered. This type of engine/generator is at least as efficient when only electricity is required. In addition, more reciprocating engines capable of running on a medium-Btu landfill gas are commercially available.

DISCUSSION OF ALTERNATIVES

A possibility not mentioned previously is to continue the current practice of buying electricity from San Diego Gas & Electric Co. and using purchased gas or, whenever available, waste fuel to generate steam. To evaluate this contingency, as well as to establish an economic baseline for all comparisons, "current" was defined as buying electricity and gas at the December 1981 prices and using only natural gas to fuel the boiler.

The annual costs of electricity and steam used for the comparisons that follow were calculated using Equation 6. With the NAS Miramar loads, cogeneration was found to be most economical when the engines were run at maximum power. Assumptions inherent in the analyses, loads, and energy prices are enclosed as appendices.

Initial capital investments have not been considered. An estimate of the economic importance of the initial investment can be acquired by using the equipment costs illustrated in Reference 3 and calculating the payback period of the alternative configurations. After examining the first alternative - cogeneration with purchased natural gas - this practice was discontinued. As shown on Figure 4, the initial capital costs are recovered within 2 or 3 years. Savings-to-investment ratios of alternatives utilizing the landfill would look even better.

Cogeneration with Purchased Natural Gas

Although straight cogeneration does not fare well in direct comparison to the other alternatives, it could still result in a sizable savings in energy costs. The potential of this alternative is illustrated by Figure 5, showing energy costs accumulated over the life of the equipment. Savings in the range of from $20 to 40 million are expected - on an initial investment of perhaps $5 million.

Since all fuel is being purchased, straight cogeneration is the alternative most sensitive to changes in the price of electricity and gas. This is indicated clearly by Figures 6 and 7. Change the relative escalation rates of the price of electricity or gas by a small percentage from the assumed values and this alternative becomes unfeasible.

Economically, this is the poorest alternative. In terms of hardware, however, it is the most favorable. The innate problems in extracting, transporting, and burning landfill gas do not have to be faced.

Generate Electricity Using Landfill Gas

A number of variables affect methane production, and accurately predicting the capacity of a landfill is difficult. The consumption of gas generated by landfills is, perhaps, best demonstrated by assuming the fill capacity to be a variable. This technique is employed in Figure 8. For convenience, the landfill sections completed and nearing completion have been given the geographical designations of south and north fills, respectively. Their estimated capacities are shown on this figure.

Figure 8 compares five engine-generator sets running on landfill gas. The left hand side of these curves marks the gas required to sustain the engines at idle, with no net power generation. The "knee" represents the gas consumption as maximum power is achieved. All engines shown on Figure 8 are capable of reaching maximum power on the landfill capacity estimated for the combined south and north fills.

Two observations are pertinent. First, the performances of the gas turbines and the reciprocating engines are equivalent. Without cogeneration, there is no economic advantage in selecting gas turbines for Miramar. Second, energy costs with this alternative and the purchased natural gas alternative are similar, but here there will probably be many additional hardware problems.

Landfill Gas Augmented with Purchased Gas

This is a poor alternative, even when the landfill gas is piped back to the base for cogeneration. The capacity of the landfill is sufficient to satisfy the energy requirements at Miramar. The engines examined for this alternative provide more energy than required at the base and require more gas than produced by the fills. Economically, they look favorable because the excess electricity being generated is assumed sold to San Diego Gas and Electric Co. - the NAS Miramar would go into the utilities business.

Regardless, the gain attributable to augmentation is small. One example is presented in Figure 9. If the entire capacity of the completed fills is available, augmentation of three 3,300-kW gas turbines results in an increased savings of perhaps 15%. Augmentation is also vulnerable to increases in the price of natural gas such as proposed by Figure 7.

Landfill Electricity Generation/Natural Gas Cogeneration

This alternative offers both the advantages and disadvantages of alternatives discussed previously. For the same number of engines, energy costs using this alternative compare closely with energy costs when all engine-generator sets are located at the landfill. In addition, it provides a hedge against the potentially excessive maintenance time required by landfill gas engines.

Pipe Landfill Gas to Base for Cogeneration

Energy costs with the landfill alternatives are compared in Figure 10. Piping the landfill gas across to the base results in an additional savings of about $30 million in energy costs over the life of the equipment.

In terms of total fuel consumption, this is the best alternative. The near one-to-one correlation between landfill methane production and the energy requirements at NAS has been mentioned previously. By piping the landfill gas back to the base for cogeneration of both electricity and steam, usage of the fill is optimized. As an example, one of the 7,400-kW turbine-generators, used as a parameter on Figures 8 and 10, would consume about 85% of the current fill capacity to generate 96% of the electricity and 98% of the steam required annually at the base.

The hardware problems associated with this alternative are the most severe; the problems of extracting and burning landfill gas as a fuel are increased further with the addition of the pipeline.

Selling the Landfill Gas

With purchased natural gas currently selling for $4.91/MBtu and expecting to pay about $2.73/MBtu to purify landfill gas to pipeline grade, the Miramar gas should sell for a net of approximately $2.00/MBtu.*

Direct sale is the safest means of profiting from the landfill gas.

---

*The sale price and the costs of processing will vary if different grades of gas are sold; however, to be competitive, the "net" will not deviate much from $2.00/MBtu.

Selling the Landfill Gas/Natural Gas Cogeneration

This alternative will save about $4 million a year with current utility costs, and it offers a hedge against future increased costs of both electricity and gas. If the price of electricity increases, the savings from cogeneration increases. Conversely, revenue from the sale of landfill gas can be expected to parallel any increase in the price of natural gas. The concept is illustrated, by example, in Tables 1 and 2.

SUMMARY

Table 3 is a comparison of annual costs of electricity and steam at the NAS Miramar with the different alternatives employed.

Based upon economics alone, piping the landfill gas around the airfield for cogeneration appears optimum; however, hardware must be considered when making the final selection. Alternatives involving several engines have the advantage of reliability. Engines cogenerating on purchased gas could possibly be converted to landfill gas when, in the future, additional sections of the fill have matured. Perhaps further thought should be given to future prices of electricity and gas. Selling the landfill gas while concurrently cogenerating with purchased natural gas is certainly the safest alternative.

Regardless, two conclusions are possible:

1. Several alternatives exist which could greatly decrease utility costs at NAS Miramar.

2. The landfill gas should be utilized.

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NOMENCLATURE

A	Heat transfer area of heat recovery boiler
CC	Capital cost expenditure, including interest on funds during construction
C_P	Specific heat
$\dot{E}$	Generator output
$\dot{E}_D$	Design generator output at full load
F	Fuel costs, including fuel to the auxiliary steam boiler
$\hat{h}_{EXH}$	Exhaust gas convective heat transfer coefficient
h	Enthalpy
K	Factor to account for flow loss between turbine and boiler
k_{EXH}	Coefficient of thermal conductivity of turbine exhaust gases
$\dot{M}$	Mass flow rate
OM	Operation and maintenance costs
P	Cost of electricity purchased
$\dot{Q}_{STM}$	Heat transferred from engine exhaust to steam
R	Revenue resulting from the sale of electricity
TC	Total annual cost of providing electrical and thermal service to the base
T	Temperature
U	Overall heat transfer coefficient of heat recovery boiler
ΔH_f	Heating value of fuel
ΔT_M	Logarithmic mean temperature difference

Subscripts

A	Air
BLR	Refers to engine exhaust while passing through heat recovery boiler
EXH	Refers to engine exhaust leaving the turbine
F	Fuel
SAT	Feed water entering the heat recovery boiler
STACK	Refers to engine exhaust leaving the heat recovery boiler
STM	Refers to steam leaving the heat recovery boiler
∞	Ambient

Table 1. Effect of the Price of Electricity on the Cogeneration Performance of a 7,400-kW Gas Turbine-Generator When Gas Prices Remain Constant

Electricity Energy Charge (¢/kW-hr)	Annual Utility Cost (million $) With Alternative			Utility Costs if Alternative Not Employed (million $)
	Revenue from Sale of Landfill Gas	Cost of Cogeneration	Net Cost of Alternative	
1.823	1.68	4.25	2.57	6.69
2.0	1.68	4.45	2.77	7.05
2.5	1.68	4.50	2.82	8.06
3.0	1.68	4.53	2.85	9.08

Table 2. Effect of the Price of Natural Gas on the Cogeneration Performance of a 7,400-kW Gas Turbine-Generator When Electricity Prices Remain Constant

Price of Natural Gas ($/MBtu)	Annual Utility Cost (million $) With Alternative			Utility Costs if Alternative Not Employed (million $)
	Revenue from Sale of Landfill Gas	Cost of Cogeneration	Net Cost of Alternative	
4.91	1.68	4.25	2.57	6.69
6.00	2.60	5.11	2.51	7.03
7.00	3.44	5.89	2.45	7.34
10.00	5.96	8.25	2.29	8.28

Table 3. A Comparison of Alternative Methods of Utilizing Available Landfill Gas to Generate Electricity and Steam at NAS Miramar

Alternative	Configuration[a]		Annual Cost of Electricity and Steam (million $)[b]
	Generate Only Electricity	Cogeneration	
Current (1981)			6.69
1. Cogeneration with purchased natural gas		1 x 3,300 kW GT[c]	5.39
		2 x 3,300	4.87
		1 x 7,400	4.25
		3 x 3,300	4.49
		1 x 10,150	4.92
2. Generate electricity using gas from north and south landfills (~ 3,200 std ft^3/min)	1 x 3,300 kW GT		5.21[d]
	2 x 3,300 kW GT		3.63
	1 x 7,400 kW GT		3.14
	2 x 2,500 kW recip[c]		4.55
	3 x 2,500 kW recip		3.29
3. Generate electricity using landfill gas (~ 3,200 std ft^3/min) augmented with purchased natural gas	3 x 3,300 kW GT		2.72
	1 x 10,150 kW GT		3.09
4. Generate electricity on landfill and concurrently cogenerate on base with purchased natural gas	1 x 3,300 kW GT	1 x 3,300 kW GT	3.80
	1 x 3,300	2 x 3,300	3.02
	1 x 3,300	1 x 7,400	2.36
	2 x 3,300	1 x 3,300	1.95
	1 x 7,400 kW GT	1 x 3,300 kW GT	1.43
	1 x 2,500 kW recip	1 x 3,300 kW GT	4.27
	1 x 2,500	2 x 3,300	3.52
	1 x 2,500	1 x 7,400	2.87
	2 x 2,500	1 x 3,300	2.97
	2 x 2,500	2 x 3,300	2.10
	2 x 2,500	3 x 3,300	1.64
	3 x 2,500	1 x 3,300	1.55
	3 x 2,500	2 x 3,300	0.68
5. Landfill gas (~ 3,200 std ft^3/min) piped to base for cogeneration		1 x 3,300 kW GT	4.07
		2 x 3,300	2.24
		1 x 7,400	1.73

continued

Table 3. Continued

Alternative	Configuration[a]		Annual Cost of Electricity and Steam (million $)[b]
	Generate Only Electricity	Cogeneration	
6. Landfill gas piped to base, augmented with purchased natural gas and used for cogeneration		3 x 3,300 kW GT 1 x 10,150	1.50 1.93
7. Selling landfill gas for net $2.00/MBtu (3,200 std ft^3/min)			5.01
8. Selling landfill gas for $2.00/MBtu and concurrently cogenerating on base with purchased natural gas		1 x 3,300 kW GT 2 x 3,300 1 x 7,400 3 x 3,300 1 x 10,150	3.53 3.19 2.57 2.81 3.24

[a]Auxiliary boiler, when required, fueled by natural gas only.

[b]Acquisition costs not included

[c]GT = gas turbine; recip = reciprocating engine

[d]Processing of landfill gas assumed to cost $1.35/MBtu.

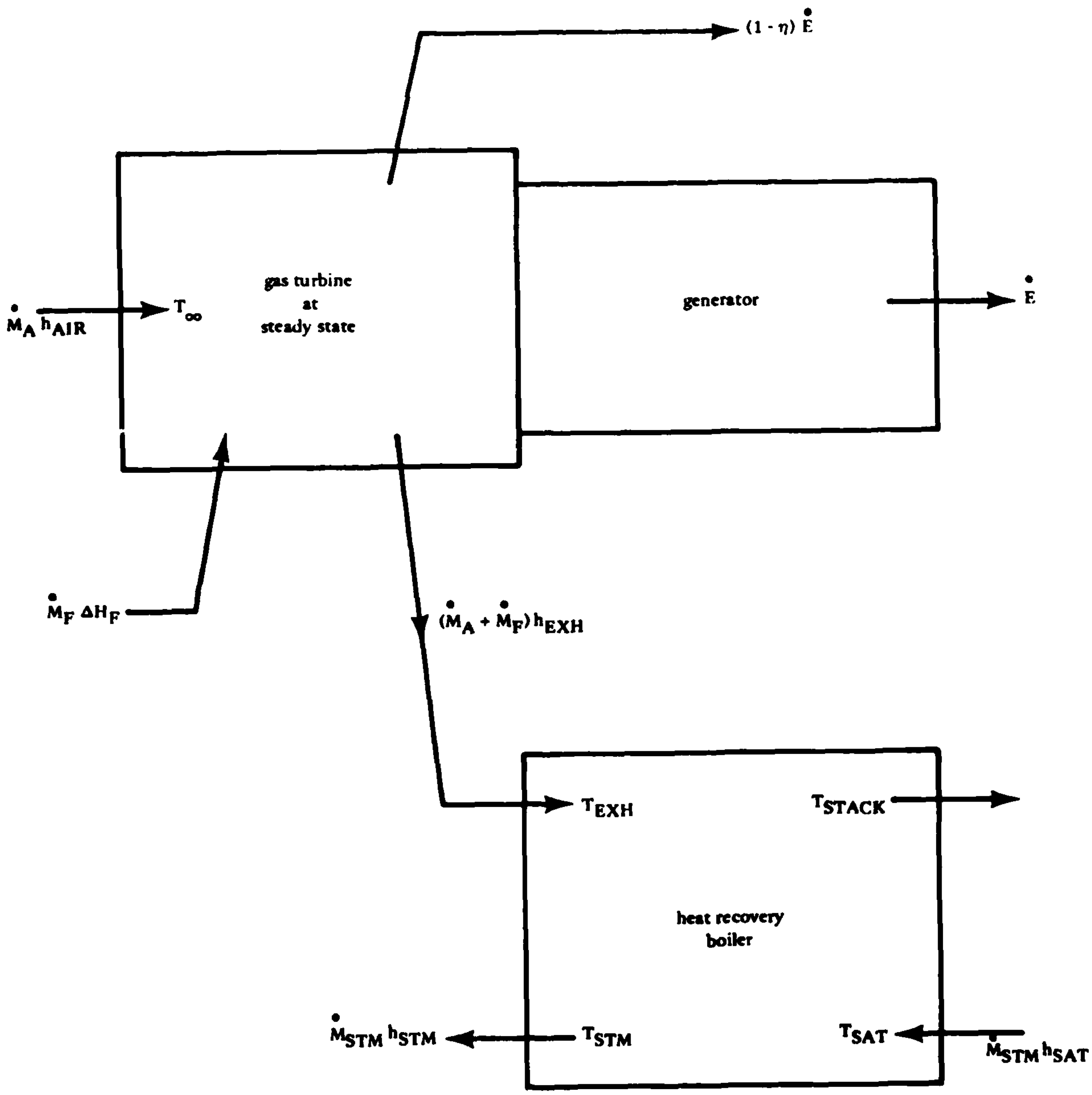

Figure 1. Gas turbine-generator waste heat cogeneration schematic.

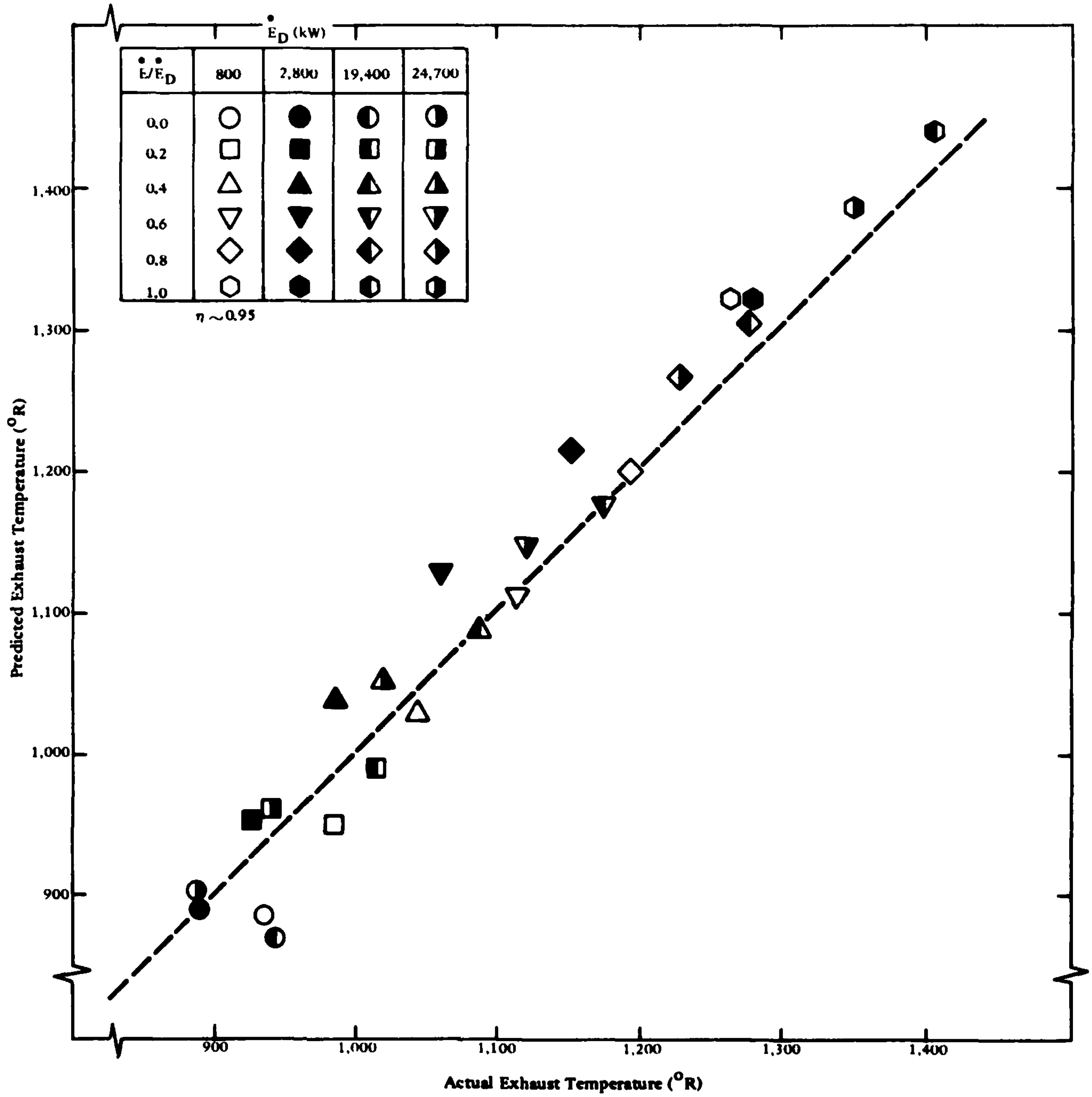

Figure 2. Comparison of predicted and actual gas turbine exhaust temperatures.

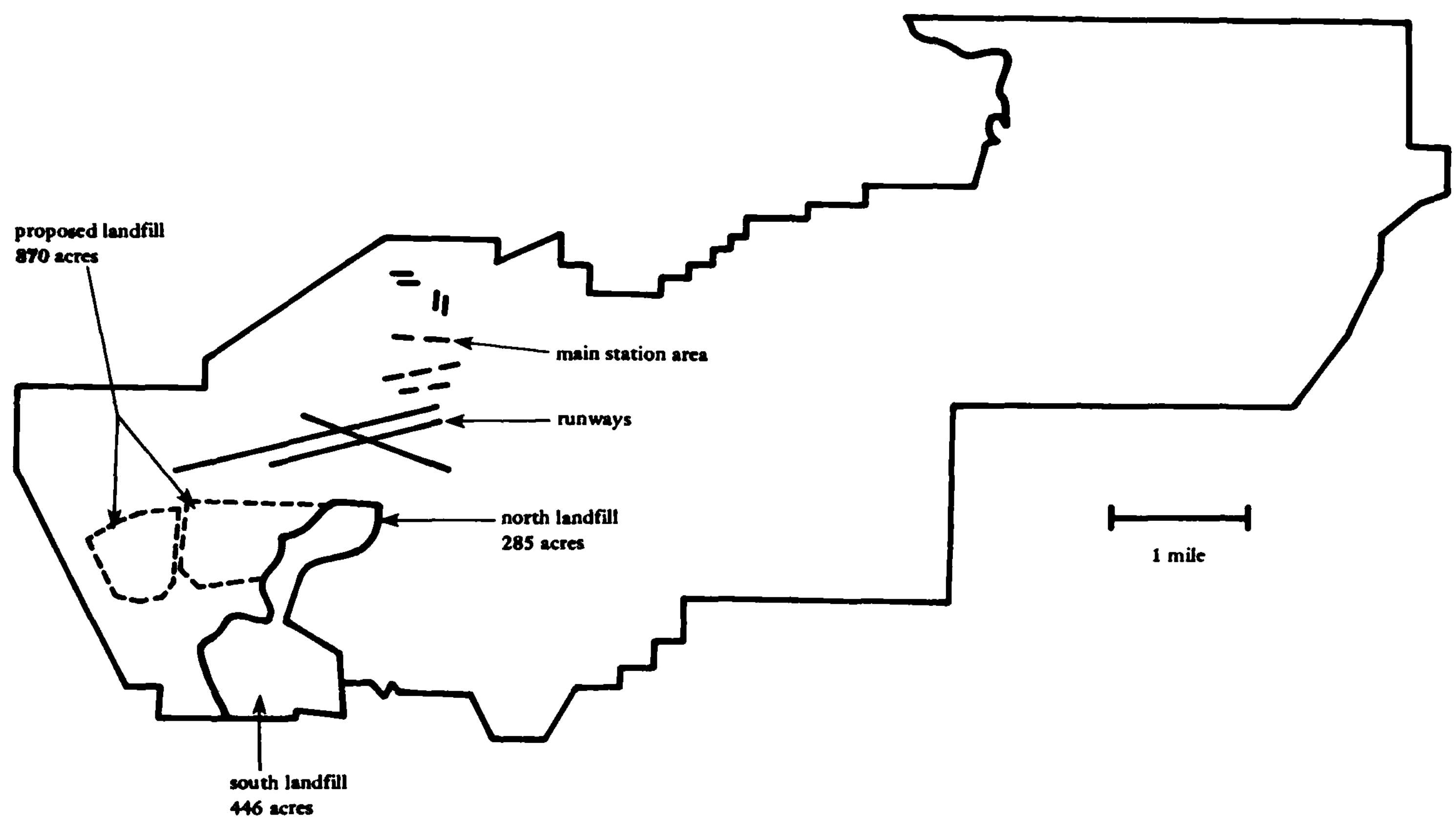

Figure 3. Naval Air Station, Miramar, San Diego, California.

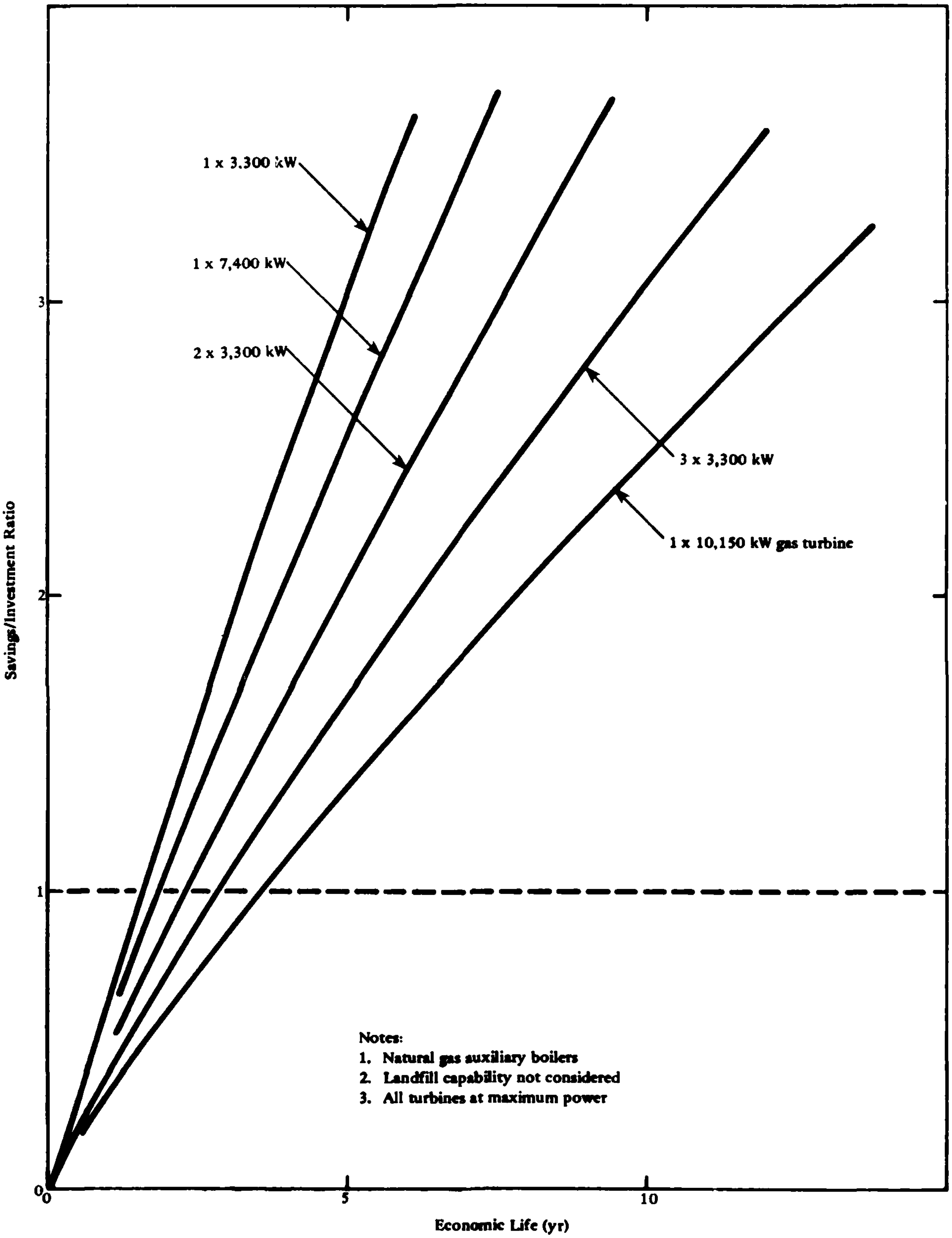

Figure 4. Savings-to-investment ratio of various cogeneration options for NAS, Miramar.

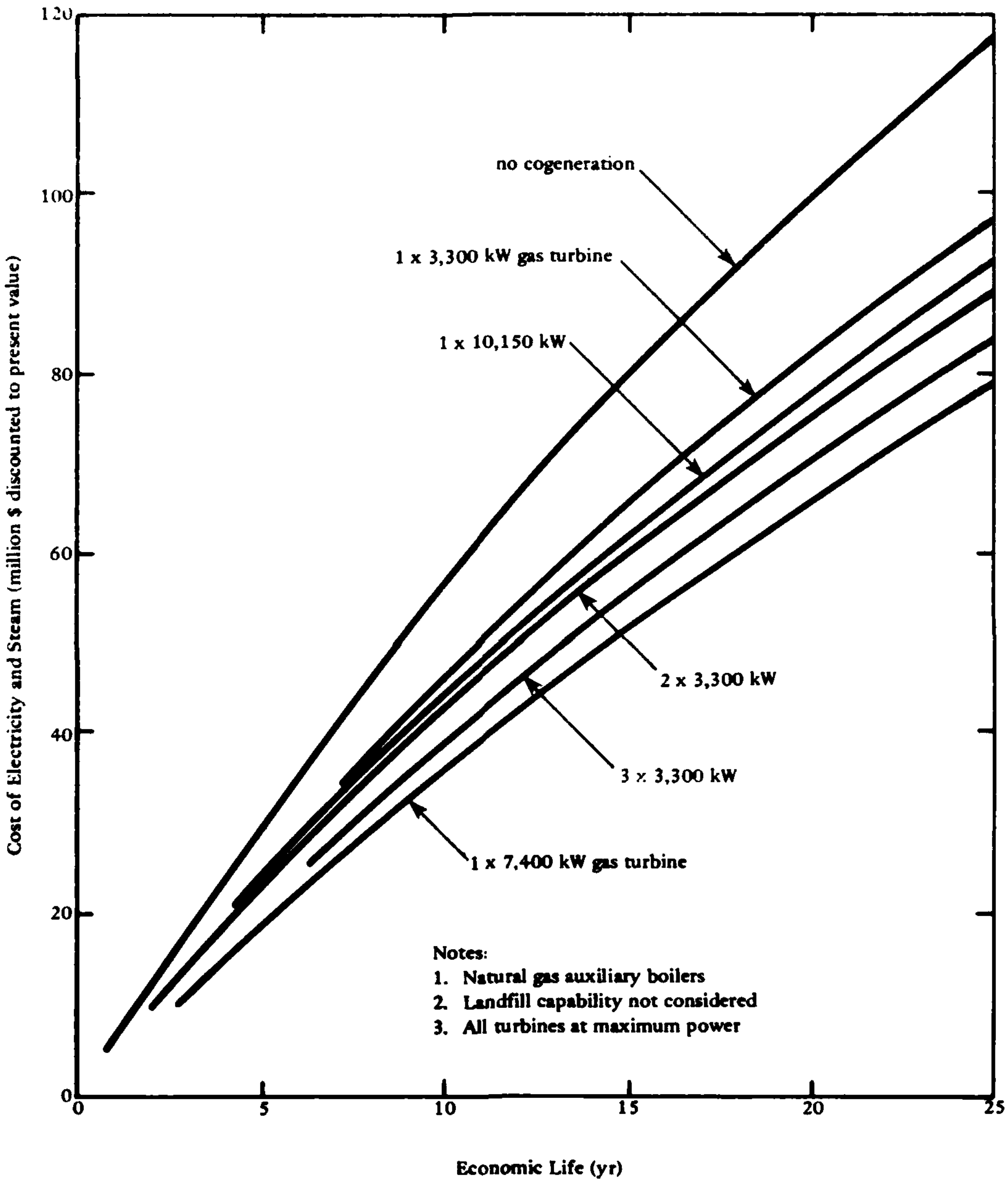

Figure 5. Accumulated energy costs of various cogeneration options, NAS Miramar.

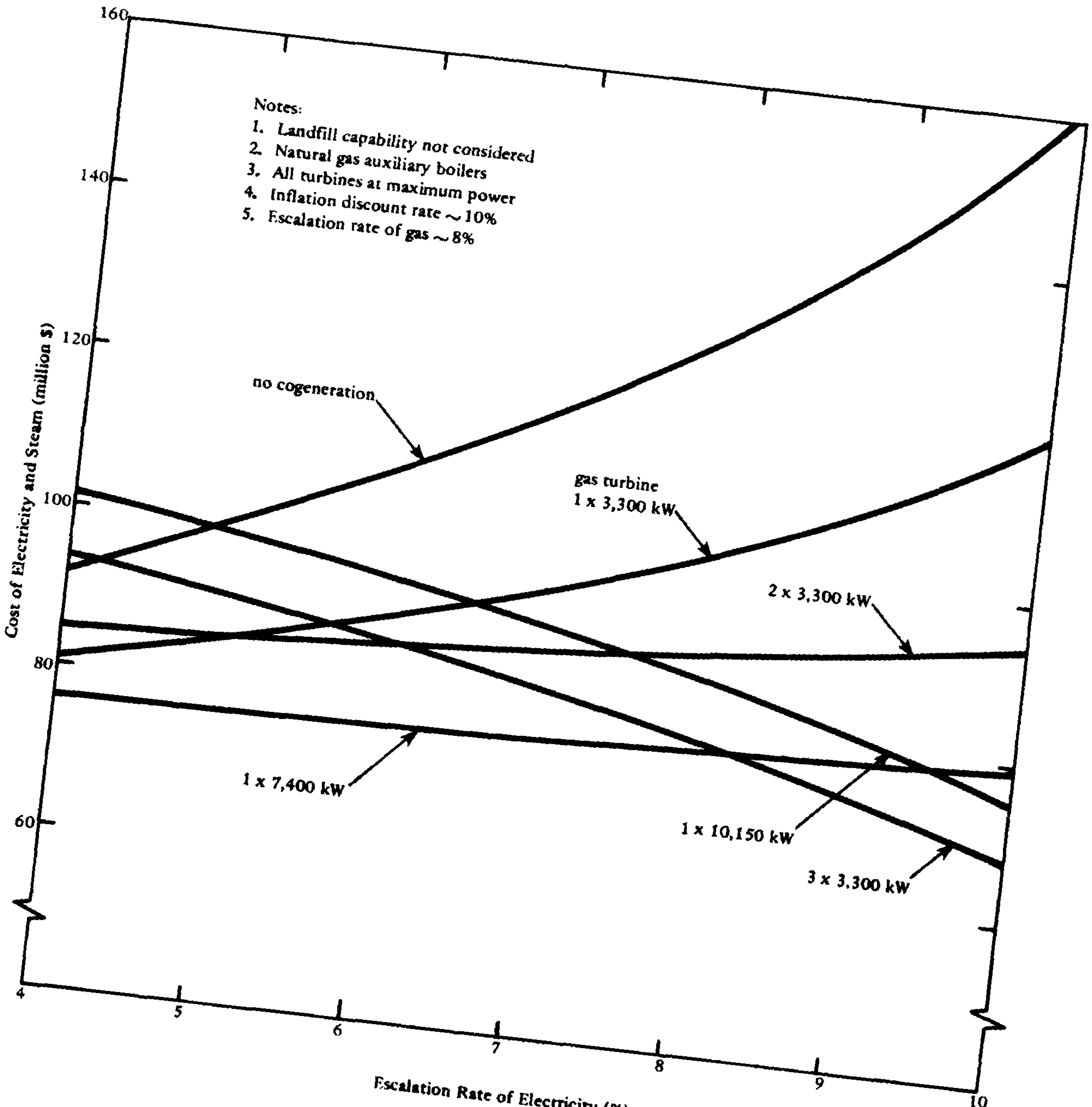

Figure 6. Effect of the cost of electricity on cogeneration costs accumulated over 25 years at NAS Miramar.

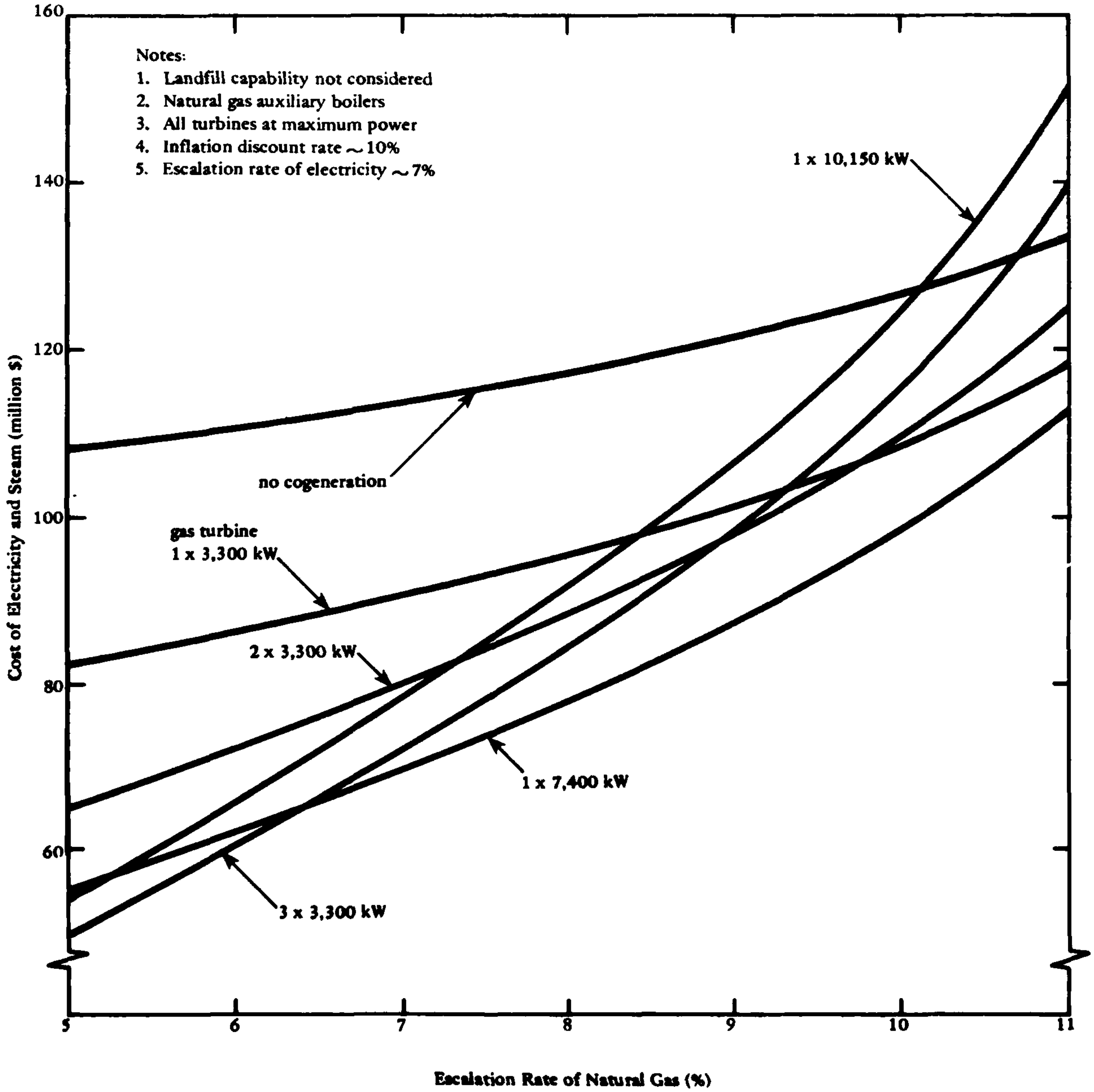

Figure 7. Effect of the cost of gas on cogeneration costs accumulated over 25 years at NAS Miramar.

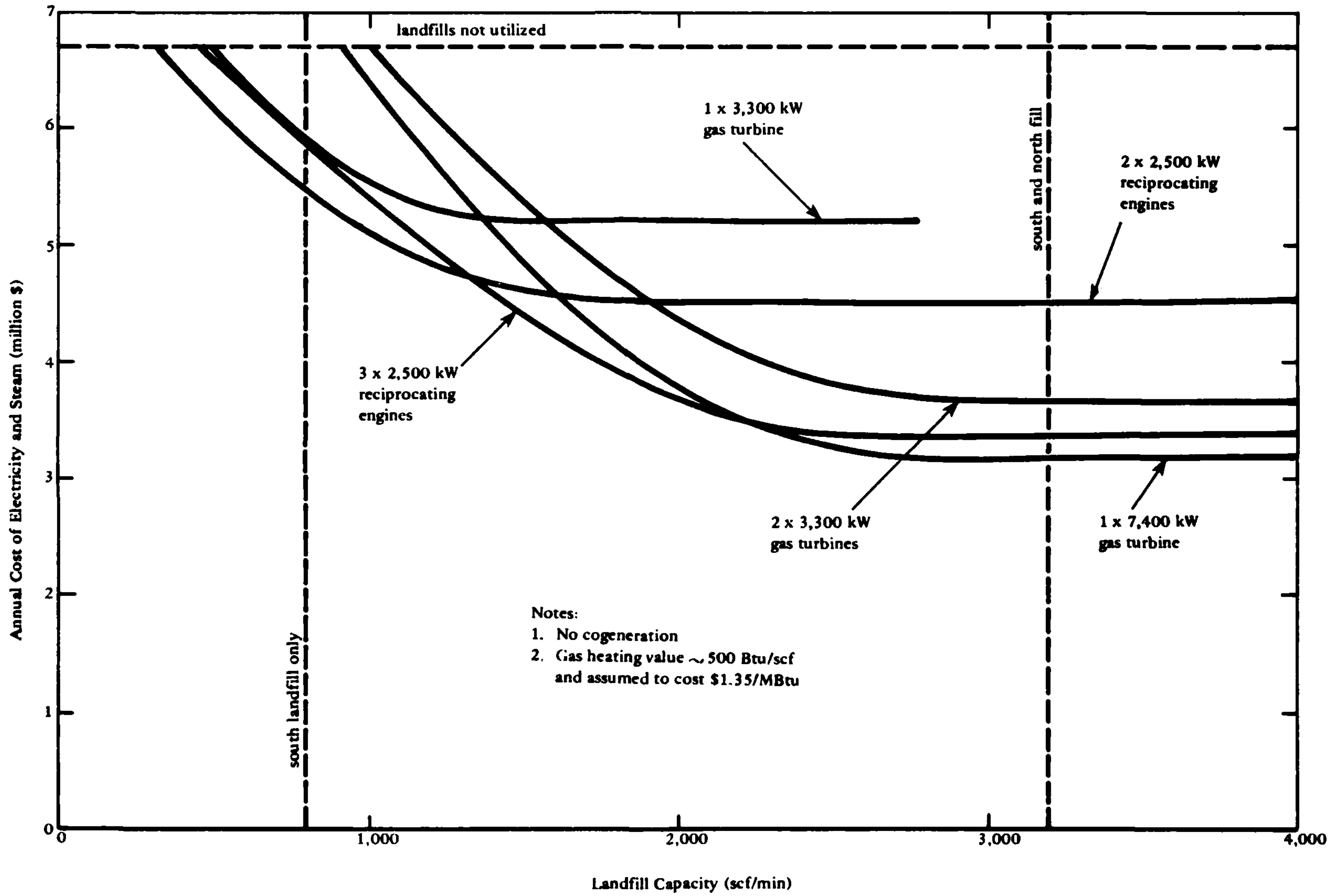

Figure 8. Energy costs at NAS Miramar when landfill gas is used to fuel various engine-generator configurations.

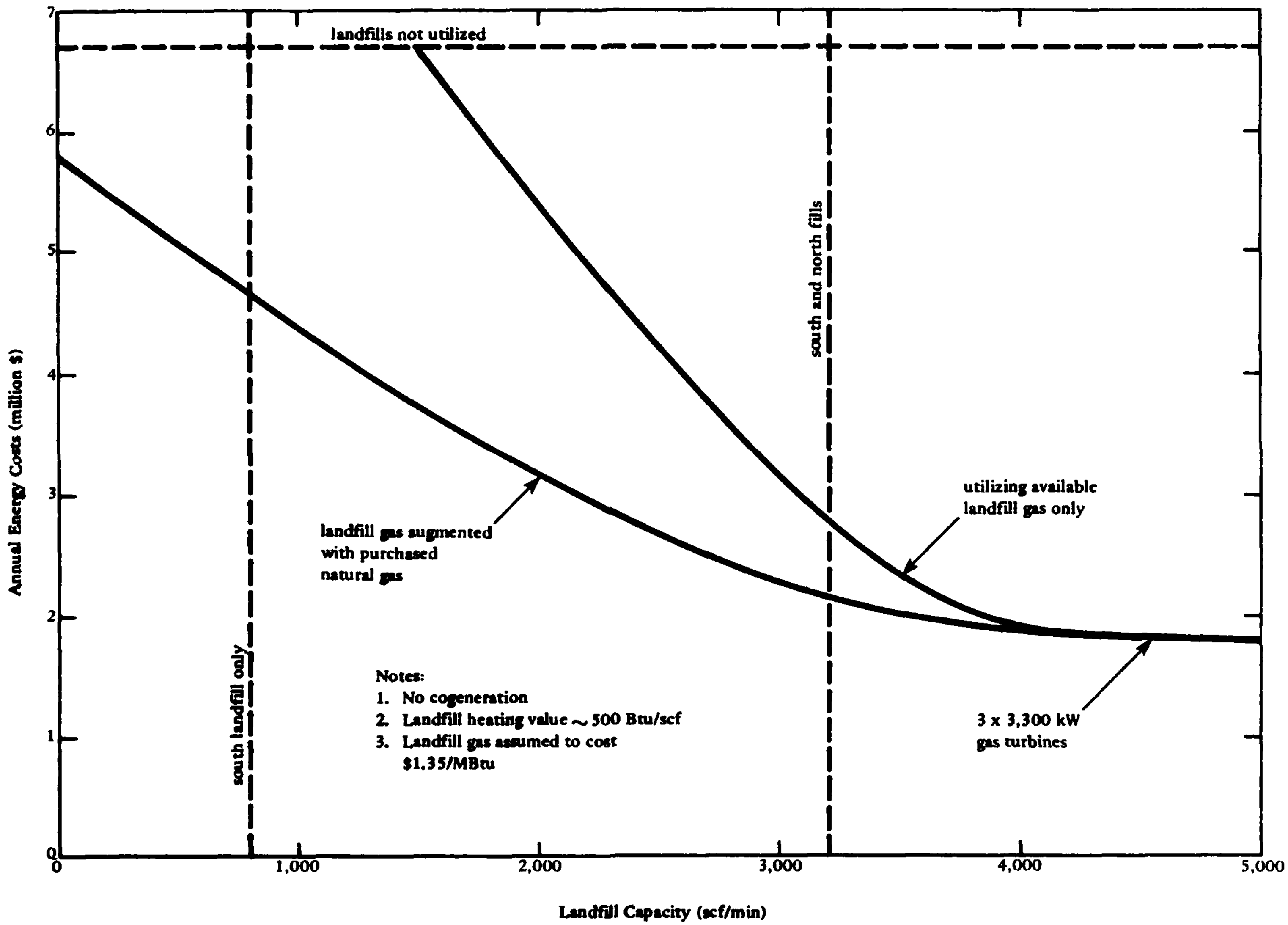

Figure 9. Economic advantage of augmenting landfill gas with purchased natural gas to fuel turbines generating electricity at NAS Miramar.

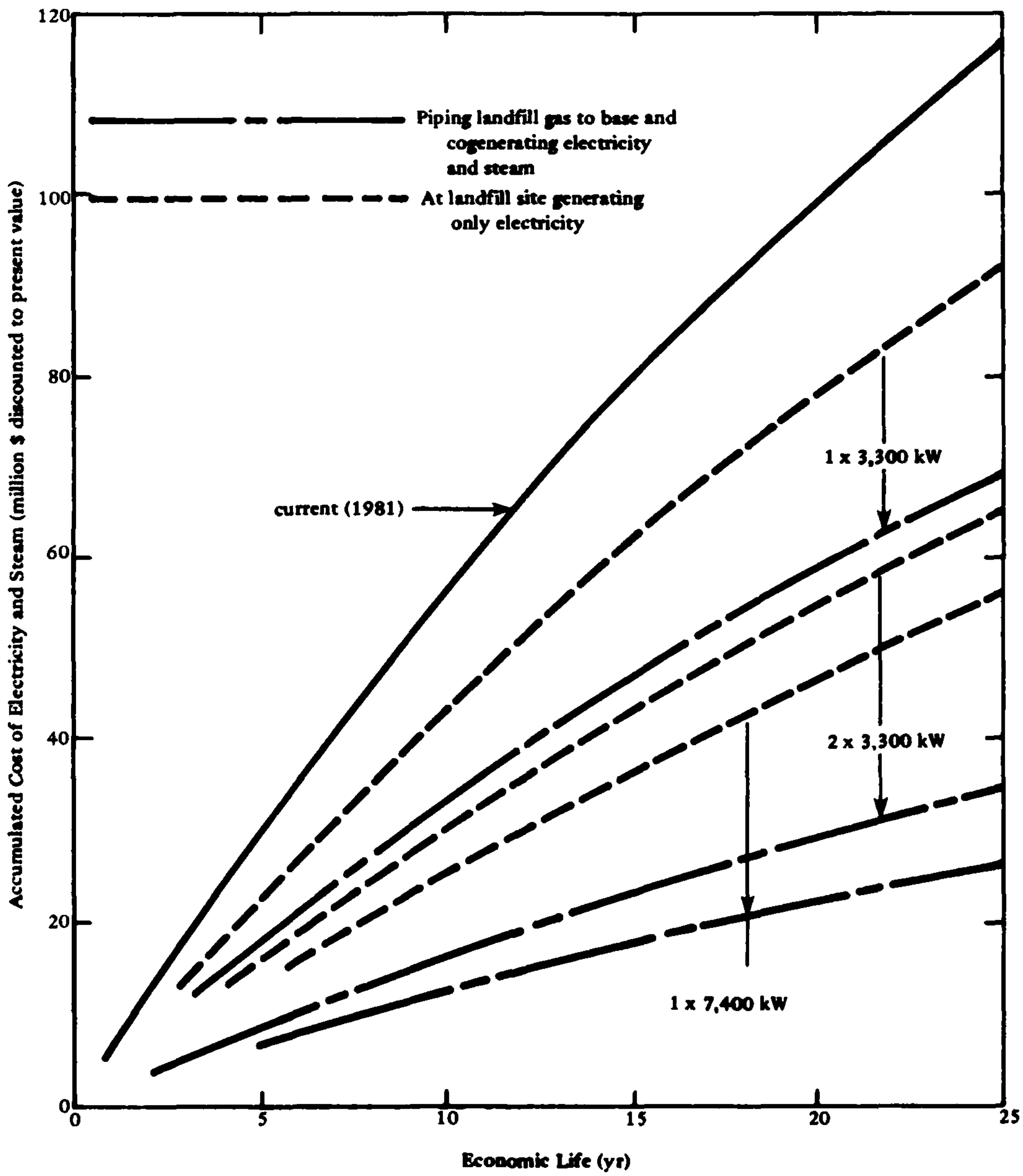

Figure 10. Economic advantage in piping landfill gas to NAS Miramar for gas turbine cogeneration.

Appendix A

ASSUMPTIONS INCLUDED IN ECONOMIC EVALUATION OF LANDFILL UTILIZATION AT THE NAVAL AIR STATION, MIRAMAR, CALIFORNIA

To avoid overwhelming the analyses, several variables were not considered or were given only limited consideration.

FUEL FOR AUXILIARY BOILER

It was assumed that the auxiliary steam boiler, when needed, would be fueled only with purchased natural gas. Currently, diesel fuel and, whenever available, waste JP-5 fuel are also being utilized; however, it is anticipated that the future supply of both will be greatly diminished.

At 1981 prices, steam for the base costs about $1.5M/yr when natural gas is used as the boiler fuel. This would be the approximate savings if waste fuel was burned exclusively. The difference is significant, particularly over a period of time such as illustrated by Figure A-1. If waste fuel is available, cogeneration is unnecessary and would appear economically unattractive compared to alternatives involving only the generation of electricity.

ELECTRICAL AND STEAM LOADS

Although these loads have a major effect on energy costs, neither has much influence on the relative advantages of the different alternatives. The effects of changing electrical and steam loads were examined once, for gas turbine cogeneration with purchased natural gas. The results are included as Figures A-2 and A-3.

PEAK ELECTRICITY DEMAND

Demand charges are fees that the utility charges to recover capital costs of installing equipment. These charges are based on the rate at which a customer draws electricity during the time of peak total demand in each billing period.

The demand charges will decrease when alternative means of generating electricity are utilized. As shown by Figure A-4, however, demand charges have only a minor influence on life cycle costs. For this reason, because future peak demand times can only be estimated, and because maintenance periods and other times when the generation/cogeneration equipment is inoperative would have to be considered, demand charges were set equal to a yearly average and assumed to remain constant.

ELECTRICITY SOLD TO UTILITY

For the same reasons, it was assumed that electricity generated in excess of base requirements would be sold to San Diego Gas and Electric Co., but that no specific capacity would be promised.

LANDFILL GAS HEATING VALUE

The heating value of the landfill gas was assumed to remain constant at 500 Btu/SCF. This is about the 50% methane expected for the Miramar fills (Ref 1).

Landfill gas heating value has a negligible effect on the costs of alternative configurations. Changes in heating value are reflected as a required change in fuel flow rate (examine Equation 1). The net effect on performance is only a few kilowatts.

PERFORMANCE OF LANDFILL GAS ENGINES

It is being implicitly assumed that all engines used in these analyses could be made to run on landfill gas and that only a change in fuel flow rate would change performance.

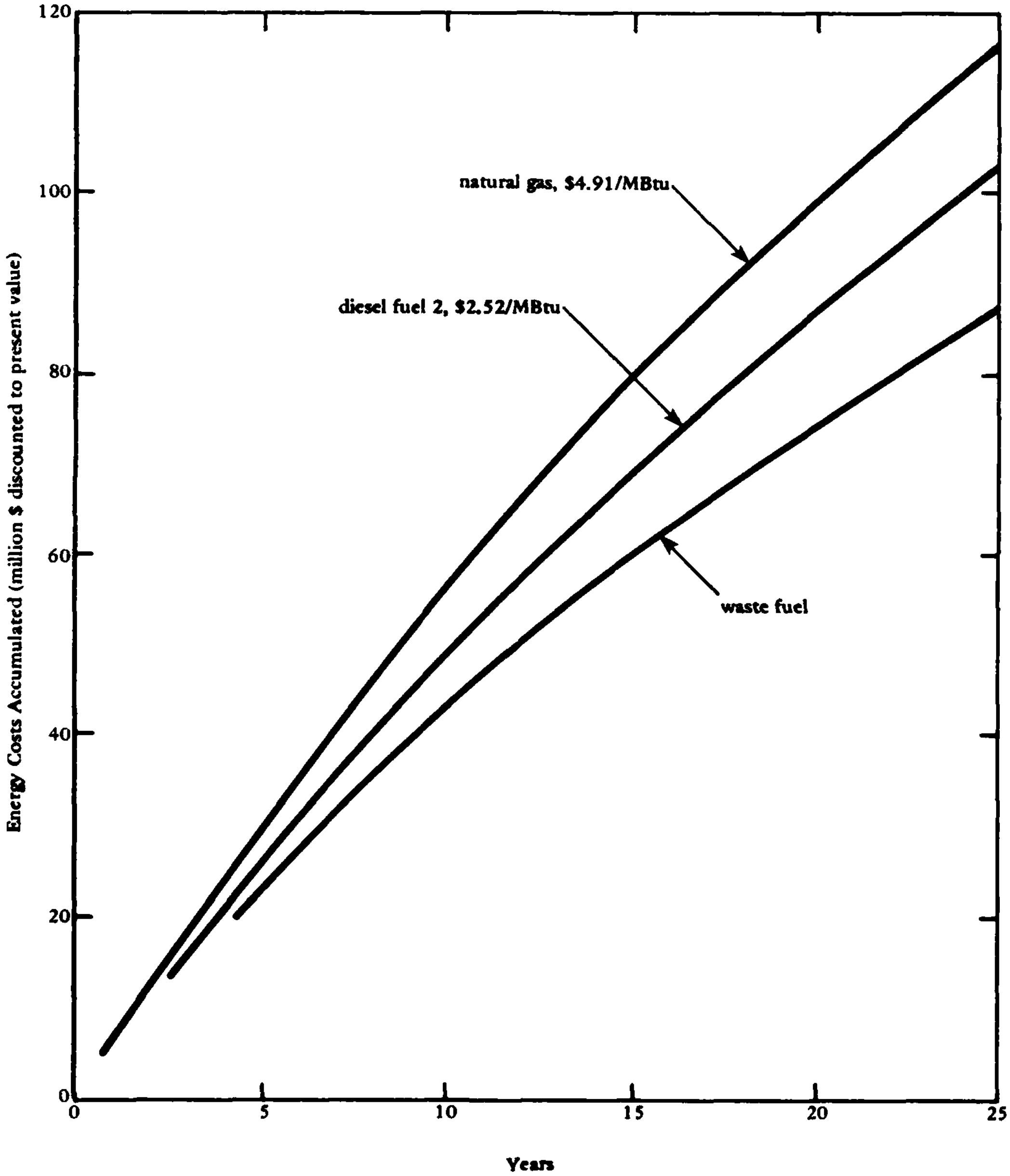

Figure A-1. Effect of the type of auxiliary boiler fuel on accumulated costs of electricity and steam at NAS Miramar.

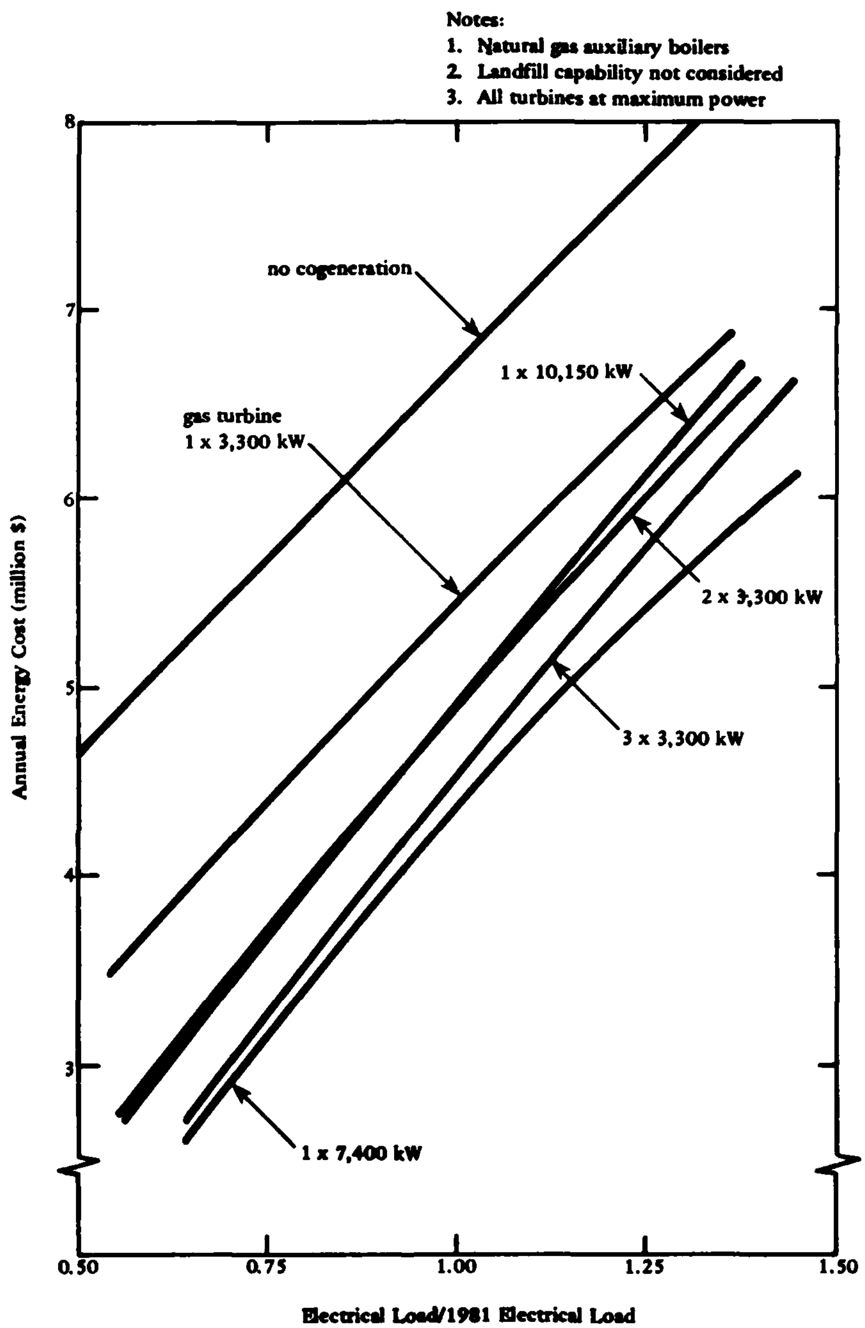

Figure A-2. Effect of electrical load on the economics of cogeneration at NAS Miramar.

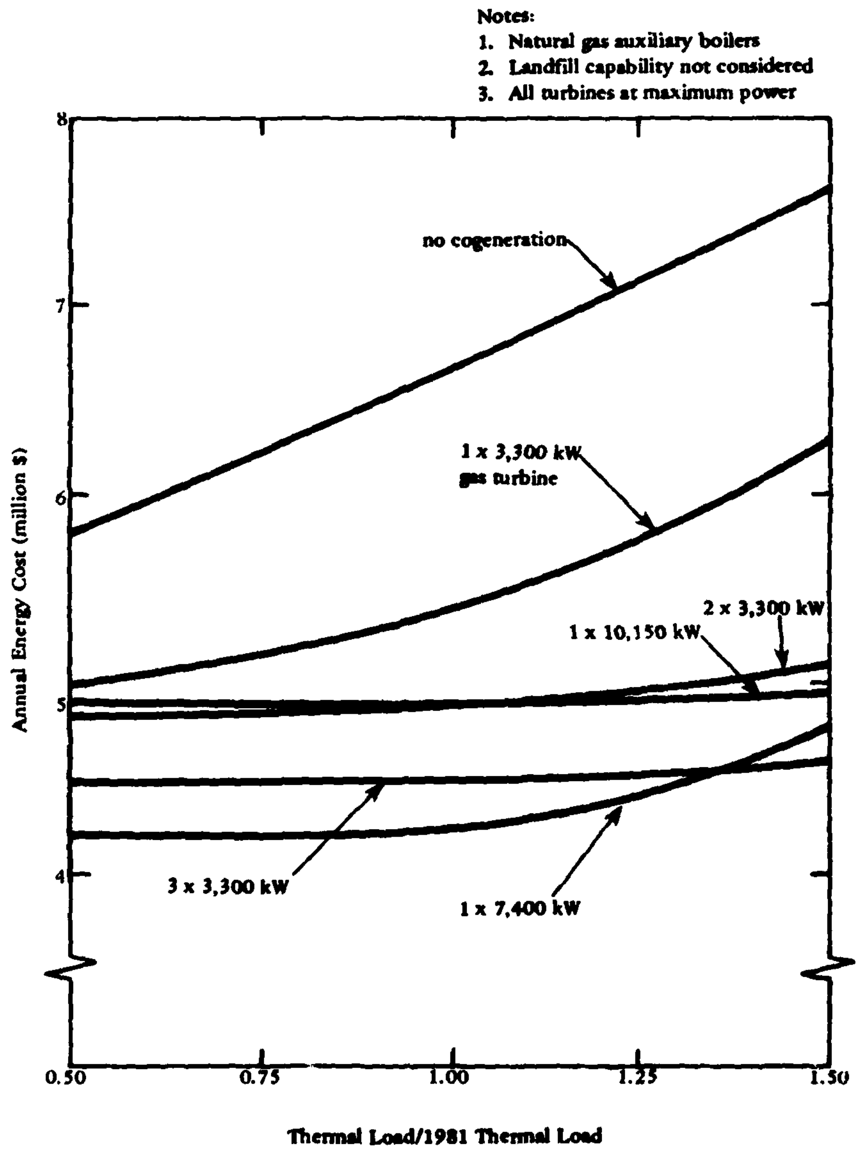

Figure A-3. Effect of steam load on the economics of cogeneration at NAS Miramar.

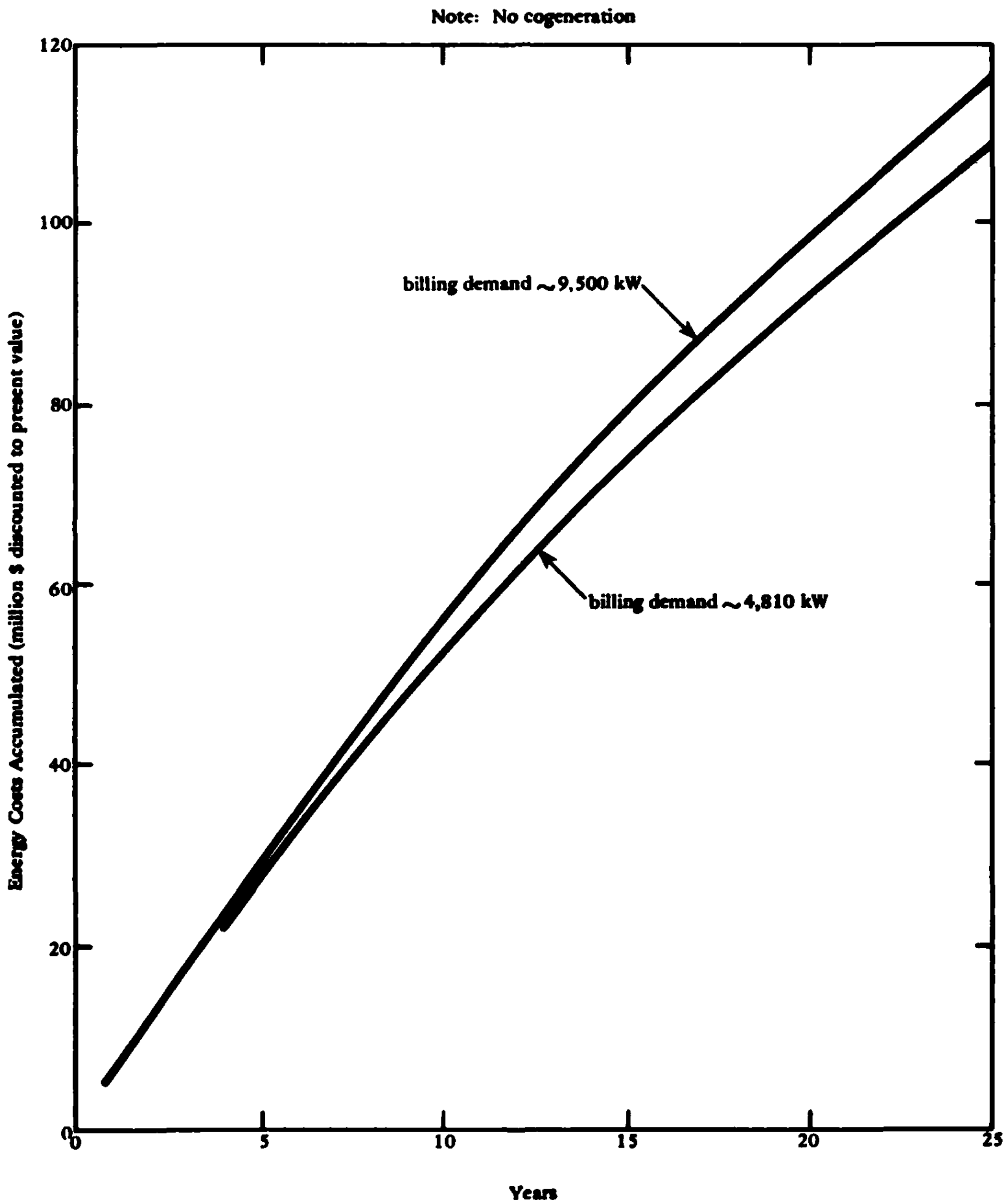

Figure A-4. Effect of electrical demand at utilities peak period on accumulated energy costs at NAS Miramar.

Appendix B

ELECTRICAL AND STEAM LOADS AT THE NAVAL AIR STATION, MIRAMAR, CALIFORNIA

Electrical and steam loads used as input to these analyses were recorded at NAS Miramar during the period October 1980 to September 1981. Two days were chosen to represent each month: one a typical workday, the second falling on a weekend or holiday.

ELECTRICAL LOADS

The disadvantage in using only two days to represent a month is the possibility that loads were recorded on days having unrepresentative weather conditions. To minimize the consequences if this should have occurred, recorded electrical loads were averaged over months normally experiencing the same range of temperatures (Ref 7). In this manner, seasonal loads were obtained:

1. Winter (Jan, Feb, Mar, Dec)
2. Spring (Apr, May, Nov)
3. Fall (Jun, Oct)
4. Summer (Jul, Aug, Sep)

Loads used in this study are shown on Figure B-1.

An indication of the accuracy of this procedure may be acquired by using these loads to calculate the monthly consumption of electricity and comparing these figures with recent billing summaries submitted by San Diego Gas and Electric Co. The comparison is good, as illustrated in Table B-1. Predicted electrical consumption approximates actual consumption to within a few percentage points.

STEAM LOADS

The same procedure was used to establish steam loads; here the entire period from June through October was combined. Steam loads used in the analyses are shown on Figure B-2.

Steam was "generated" in a saturated condition at 353°F. The existing boilers at the NAS were assumed retained for use as auxiliary boilers when waste heat was insufficient. These boilers have an efficiency of about 75%.

Table B-1. Comparison of Actual and Predicted Electricity Consumption at NAS Miramar

[Actual loads/costs have been adjusted to reflect billing periods and rate increases.]

Month	Mean Temperature (°F)	Electricity Consumed (MW-hr)			Cost of Electricity (million $)	
		Actual '79-'80	Actual '80-'81	Predicted	Actual '80-'81	Predicted
Oct	66	4,379	4,348	4,497	386	415
Nov	61	4,028	4,181	4,142	383	388
Dec	56	4,082	4,095	4,285	368	399
Jan	55	4,305	4,343	4,393	416	407
Feb	56	3,887	3,929	4,062	375	383
Mar	56	4,114	4,422	4,393	421	407
Apr	59	4,091	4,181	4,142	398	388
May	62	4,260	4,130	4,249	384	396
Jun	65	4,223	4,427	4,544	418	419
Jul	70	4,630	4,792	4,906	448	446
Aug	72	4,703	4,956	4,906	458	446
Sep	71	4,334	4,640	4,782	419	437
Total		51,033	52,444	53,301	4,869	4,931

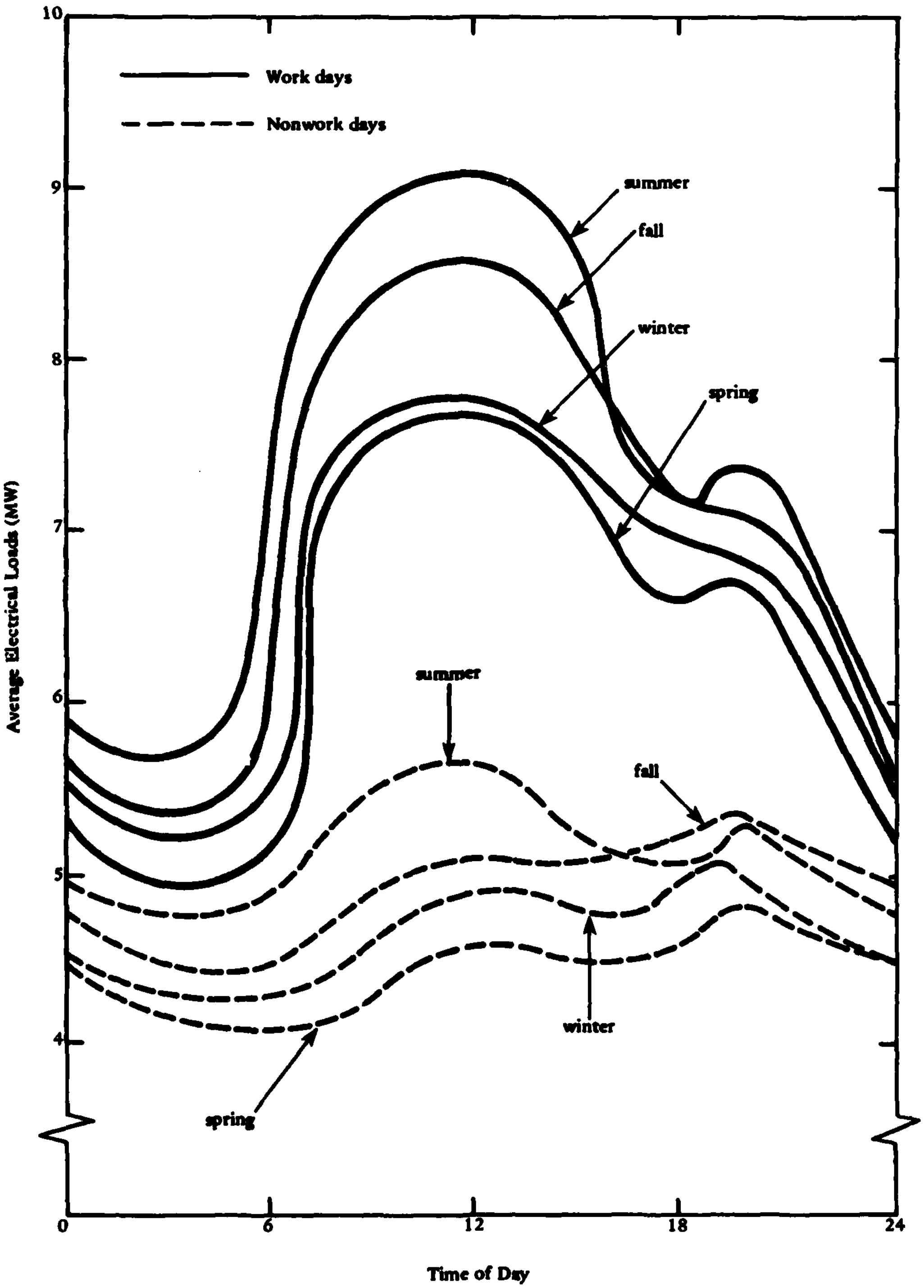

Figure B-1. Average electrical loads at NAS Miramar.

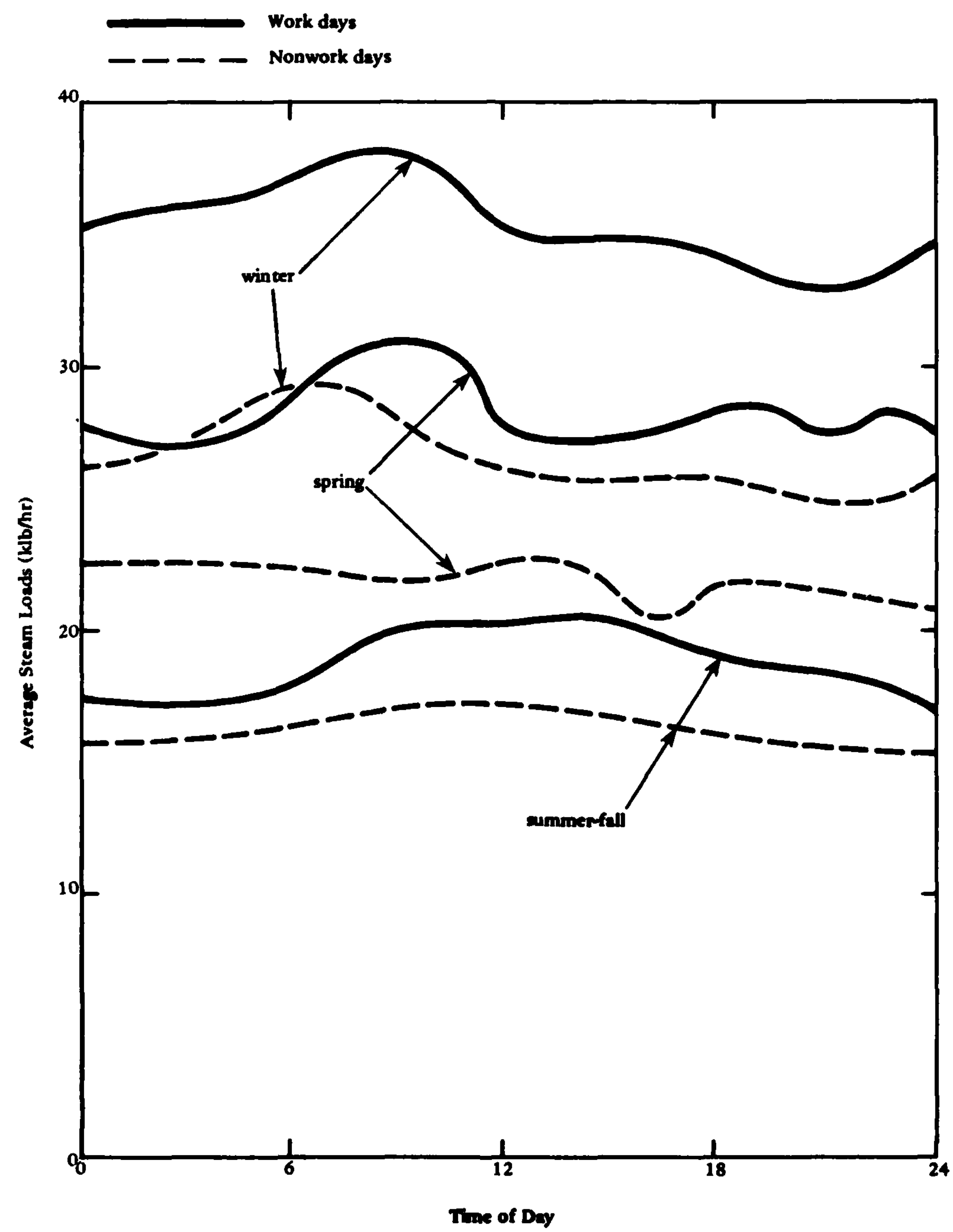

Figure B-2. Average steam loads at NAS Miramar.

Appendix C

UTILITY COSTS AT THE NAVAL AIR STATION, MIRAMAR, CALIFORNIA

COST OF PURCHASED ELECTRICITY (Ref 8)

Customer Charge $600.00

Peak Demand Charge for Customer Contribution
to Monthly System Peak $7.67/kW

Energy Charge:
On-Peak $0.01823/kW-hr
Semi-Peak 0.01323/kW-hr
Off-Peak 0.01073/kW-hr

Where time periods are defined as follows:

	May 1 - September 30	All Other
On-Peak	10 a.m. - 5 p.m. weekdays	5 p.m. - 9 p.m. weekdays
Semi-Peak	5 p.m. - 9 p.m. weekdays	10 a.m. - 5 p.m. weekdays
Off-Peak	9 p.m. - 10 a.m. weekdays Plus weekends & holidays	9 p.m. - 10 a.m. weekdays Plus weekends & holidays

Energy Cost Adjustment $0.06304/kW-hr

SALE PRICE OF EXCESS ELECTRICITY GENERATED (Ref 9)

Energy Charge $0.08468/kW-hr
(using a rate not time-of-day differentiated)

COST OF GAS

Purchased Natural Gas $4.91/MBtu
Processed Landfill Gas $1.35/MBtu

OPERATING AND MAINTENANCE COSTS (Ref 3)

Gas Turbines	$4.00/MW-hr
Reciprocating Engines	$13.00/MW-hr
Waste Heat Boilers	$1.00/klb steam
Auxiliary Boilers	$1.00/klb steam

INFLATION AND ESCALATION RATES

Inflation Discount Factor	0.10
Short-Term Escalation Rates (including landfill)	
Fuel	0.14
Electricity	0.13
Operating and Maintenance	0.077
Long-Term Escalation Rates	
Fuel	0.08
Electricity	0.07
Operating and Maintenance	0

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NAVSECGRUACT PWO, Adak AK; PWO, Edzell Scotland; PWO, Puerto Rico; PWO, Torri Sta, Okinawa
NAVSECSTA PWD - Engr Div, Wash., DC

NAVSHIPYD Code 202.4, Long Beach CA; Code 202.5 (Library) Puget Sound, Bremerton WA; Code 380, Portsmouth, VA; Code 382.3, Pearl Harbor, HI; Code 400, Puget Sound; Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; Code 453 (Util. Supr), Vallejo CA; Library, Portsmouth NH; PW Dept, Long Beach, CA; PWD (Code 420) Dir Portsmouth, VA; PWD (Code 450-HD) Portsmouth, VA; PWD (Code 453-HD) SHPO 03, Portsmouth, VA; PWO, Bremerton, WA; PWO, Mare Is.; PWO, Puget Sound; SCE, Pearl Harbor HI

NAVSTA Adak, AK; CO, Brooklyn NY; Code 4, 12 Marine Corps Dist, Treasure Is., San Francisco CA; Dir Engr Div, PWD, Mayport FL; Dir Mech Engr 37WC93 Norfolk, VA; Engr. Dir., Rota Spain; Long Beach, CA; Maint. Cont. Div., Guantanamo Bay Cuba; Maint. Div. Dir/Code 531, Rodman Panama Canal; PWD - Engr Dept, Adak, AK; PWD - Engr Div, Midway Is.; PWO, Keflavik Iceland; PWO, Mayport FL; SCE, Guam; SCE, Pearl Harbor HI; SCE, San Diego CA; SCE, Subic Bay, R.P.; Utilities Engr Off. Rota Spain

NAVSUBASE ENS S. Dove, Groton, CT

NAVSUPPACT CO, Naples, Italy; PWO Naples Italy

NAVSUPPFAC PWD - Maint. Control Div, Thurmont, MD

NAVSURFWPNCEN PWO, White Oak, Silver Spring, MD

NAVTECHTRACEN SCE, Pensacola FL

NAVTELCOMMCOM Code 53, Washington, DC

NAVWPNCEN Code 2636 China Lake; Code 3803 China Lake, CA; PWO (Code 266) China Lake, CA; ROICC (Code 702), China Lake CA

NAVWPNSTA (Clebak) Colts Neck, NJ; Code 092, Concord CA; Code 092A, Seal Beach, CA

NAVWPNSTA PW Office Yorktown, VA

NAVWPNSTA PWD - Maint. Control Div., Concord, CA; PWD - Supr Gen Engr, Seal Beach, CA; PWO, Charleston, SC; PWO, Seal Beach CA

NAVWPNSUPPCEN Code 09 Crane IN

NCTC Const. Elec. School, Port Hueneme, CA

NCBC Code 10 Davisville, RI; Code 15, Port Hueneme CA; Code 155, Port Hueneme CA; Code 156, Port Hueneme, CA; Code 25111 Port Hueneme, CA; Code 430 (PW Engrng) Gulfport, MS; Code 470.2, Gulfport, MS; NEESA Code 252 (P Winters) Port Hueneme, CA; PWO (Code 80) Port Hueneme, CA; PWO, Davisville RI; PWO, Gulfport, MS

NMCB FIVE, Operations Dept; THREE, Operations Off.

NOAA (Dr. T. Mc Guinness) Rockville, MD; Library Rockville, MD

NRL Code 5800 Washington, DC

NROTC J.W. Stephenson, UC, Berkeley, CA

NSC Code 54.1 Norfolk, VA

NSD SCE, Subic Bay, R.P.

NSWSES Code 0150 Port Hueneme, CA

NUSC Code 131 New London, CT; Code 5202 (S. Schady) New London, CT; Code EA123 (R.S. Munn), New London CT; Code SB 331 (Brown), Newport RI

OFFICE SECRETARY OF DEFENSE OASD (MRA&L) Dir. of Energy, Pentagon, Washington, DC

ONR Code 221, Arlington VA; Code 700F Arlington VA

PACMISRANFAC HI Area Bkg Sands, PWO Kekaha, Kauai, HI

PHIBCB 1 P&E, San Diego, CA

PMTC Pat. Counsel, Point Mugu CA

PWC CO Norfolk, VA; CO, (Code 10), Oakland, CA; CO, Great Lakes IL; CO, Pearl Harbor HI; Code 10, Great Lakes, IL; Code 105 Oakland, CA; Code 110, Great Lakes, IL; Code 110, Oakland, CA; Code 120, Oakland CA; Code 120C, (Library) San Diego, CA; Code 154, Great Lakes, IL; Code 200, Great Lakes IL; Code 400, Great Lakes, IL; Commanding Officer, Subic Bay; Code 400, Pearl Harbor, HI; Code 400, San Diego, CA; Code 420, Great Lakes, IL; Code 420, Oakland, CA; Code 424, Norfolk, VA; Code 500 Norfolk, VA; Code 505A Oakland, CA; Code 600, Great Lakes, IL; Code 610, San Diego Ca; Code 700, Great Lakes, IL; Library, Guam; Library, Norfolk, VA; Library, Pearl Harbor, HI; Library, Pensacola, FL; Library, Subic Bay, R.P.; Util Dept (R Pascua) Pearl Harbor, HI; Utilities Officer, Guam

SPCC PWO (Code 120) Mechanicsburg PA

TVA Smelser, Knoxville, Tenn.; Solar Group, Arnold, Knoxville, TN

U.S. MERCHANT MARINE ACADEMY Kings Point, NY (Reprint Custodian)

USAF REGIONAL HOSPITAL Fairchild AFB, WA

USCG (Smith), Washington, DC; G-MMT-4/82 (J Spencer)

USDA Forest Service Reg 3 (R. Brown) Albuquerque, NM

USNA Ch. Mech. Engr. Dept Annapolis MD; ENGRNG Div, PWD, Annapolis MD; Energy-Environ Study Grp, Annapolis, MD; Environ. Prot. R&D Prog. (J. Williams), Annapolis MD; Mech. Engr. Dept. (C. Wu), Annapolis MD; NAVSYSENGR Dept, Annapolis, MD

USS FULTON WPNS Rep. Offr (W-3) New York, NY

ARIZONA Kroelinger Tempe, AZ; State Energy Programs Off., Phoenix AZ

AUBURN UNIV. Bldg Sci Dept, Lechner, Auburn, AL

BERKELEY PW Engr Div, Harrison, Berkeley, CA

BONNEVILLE POWER ADMIN Portland OR (Energy Consrv. Off., D. Davey)

BROOKHAVEN NATL LAB M. Steinberg, Upton NY

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CORNELL UNIVERSITY Ithaca NY (Serials Dept, Engr Lib.)
DAMES & MOORE LIBRARY LOS ANGELES, CA
DRURY COLLEGE Physics Dept, Springfield, MO
FLORIDA ATLANTIC UNIVERSITY Boca Raton, FL (McAllister)
FOREST INST. FOR OCEAN & MOUNTAIN Carson City NV (Studies - Library)
GEORGIA INSTITUTE OF TECHNOLOGY (LT R. Johnson) Atlanta, GA; Col. Arch, Benton, Atlanta, GA
HARVARD UNIV. Dept. of Architecture, Dr. Kim, Cambridge, MA
HAWAII STATE DEPT OF PLAN. & ECON DEV. Honolulu HI (Tech Info Ctr)
IOWA STATE UNIVERSITY Dept. Arch, McKrown, Ames, IA
WOODS HOLE OCEANOGRAPHIC INST. Woods Hole MA (Winget)
KEENE STATE COLLEGE Keene NH (Cunningham)
LEHIGH UNIVERSITY Bethlehem PA (Linderman Lib. No.30, Flecksteiner)
LOUISIANA DIV NATURAL RESOURCES & ENERGY Div Of R&D, Baton Rouge, LA
MAINE OFFICE OF ENERGY RESOURCES Augusta, ME
MISSOURI ENERGY AGENCY Jefferson City MO
MIT Cambridge MA (Rm 10-500, Tech. Reports, Engr. Lib.); Cambridge, MA (Harleman)
MONTANA ENERGY OFFICE Anderson, Helena, MT
NATURAL ENERGY LAB Library, Honolulu, HI
NEW HAMPSHIRE Concord NH (Governor's Council on Energy)
NEW MEXICO SOLAR ENERGY INST. Dr. Zwibel Las Cruces NM
NY CITY COMMUNITY COLLEGE BROOKLYN, NY (LIBRARY)
NYS ENERGY OFFICE Library, Albany NY
OAK RIDGE NATL LAB T. Lundy, Oak Ridge, TN
POLLUTION ABATEMENT ASSOC. Graham
PURDUE UNIVERSITY Lafayette, IN (CE Engr. Lib)
CONNECTICUT Hartford CT (Dept of Plan. & Energy Policy)
SCRIPPS INSTITUTE OF OCEANOGRAPHY LA JOLLA, CA (ADAMS)
SEATTLE U Prof Schwaegler Seattle WA
SRI INTL Phillips, Chem Engr Lab, Menlo Park, CA
STATE UNIV. OF NEW YORK Fort Schuyler, NY (Longobardi)
STATE UNIV. OF NY AT BUFFALO School of Medicine, Buffalo, NY
TEXAS A&M UNIVERSITY W.B. Ledbetter College Station, TX
UNIVERSITY OF CALIFORNIA Energy Engineer, Davis CA; LIVERMORE, CA (LAWRENCE LIVERMORE LAB, TOKARZ); UCSF, Physical Plant, San Francisco, CA
UNIVERSITY OF DELAWARE Newark, DE (Dept of Civil Engineering, Chesson)
UNIVERSITY OF FLORIDA Dept Arch., Morgan, Gainesville, FL
UNIVERSITY OF HAWAII HONOLULU, HI (SCIENCE AND TECH. DIV.)
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TRW SYSTEMS REDONDO BEACH, CA (DAI)
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WESTINGHOUSE ELECTRIC CORP. Annapolis MD (Oceanic Div Lib, Bryan); Library, Pittsburgh PA
WM CLAPP LABS - BATTELLE DUXBURY, MA (LIBRARY)
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FISHER San Diego, Ca
KETRON, BOB Ft Worth, TX
KRUZIC, T.P. Silver Spring, MD
LAFKIN Seattle, WA
BROWN & CALDWELL Saunders, E.M./Oakland, CA
T.W. MERMEL Washington DC
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