ENERGY CONSERVATION IN COAL CONVERSION

Energy Conservation Potential in Heat Recovery Techniques

A Case Study

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ABSTRACT

In this study, we looked at replacing certain heat exchangers with Organic Rankine Cycles. In each case, we determined the cost of generating power and then from this tabulation of capital investment for power generation, feasibility of replacement on a unit-by-unit basis was determined.

The results show that 18 heat exchangers reject sufficient heat to warrant ORC usage, with potential electric generation of 36 MW or a 17% increase of the inplant power generation of 210 MW.

Cost estimates indicate the capital investment required to be approximately $1000/KW with a potential reduction of $300/KW for mass produced units.

Based on the results of this analysis it is recommended that ORC manufacturers be engaged to further engineer and incorporate Organic Rankine Cycles into the Oil/Gas design.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

In our initial energy study, we developed a number of methods by which energy can be conserved in inefficient coal conversion plants.[10] Currently, our objective is to apply the procedures we have learned to more near term, efficient and highly engineered plants. The commercial concept Oil/Gas Complex designed by Ralph M. Parsons Company has been selected as the next candidate to be evaluated. This design has a high thermal efficiency of 77%.[11]

The purpose of this particular study is to investigate the feasibility of replacing certain heat exchangers with an organic rankine cycle. For each case, the cost of generating electric power is to be determined and then from this tabulation of capital investment for power generation, the feasibility of replacement on a unit-by-unit basis will be determined.

2. H_x Suitability for ORC

Every heat exchanger in the Oil/Gas Complex has been evaluated for its suitability of being replaced by an organic rankine cycle to produce shaft work. As shown in Figure 1, the ORC can perform essentially the same function as a heat exchanger but the exit temperature of the second stream cannot be the same, ($T_4 \neq T_4'$) since work is extracted.

In evaluating heat exchangers, there are three reasons why a heat exchanger may be rejected as a potential candidate: (1) the exchanger's operation is important to the downstream process and therefore a temperature change in any stream cannot be afforded or (2) the incoming temperature of the process stream is too low to warrant ORC usage or (3) the unit is too small.

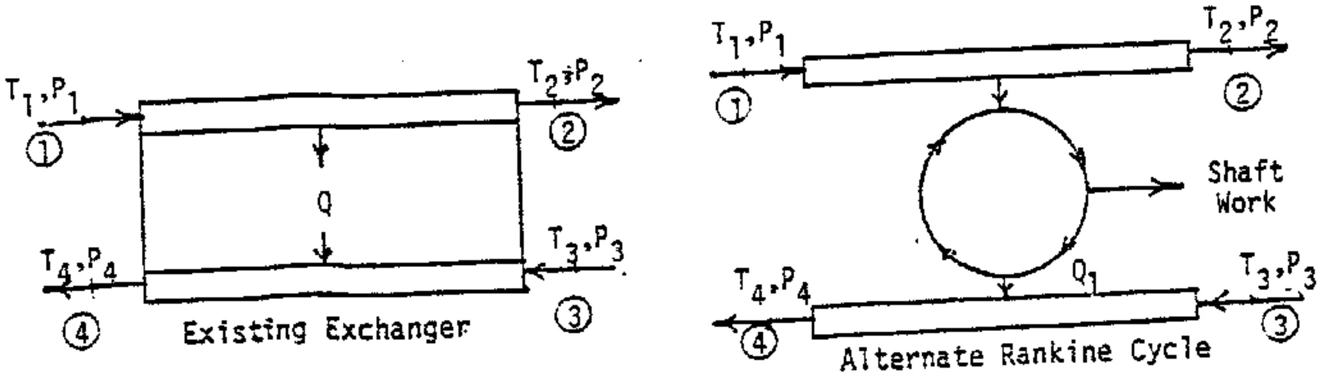


FIGURE 1.

COMPARISON OF ORC AND H_x

3. Organic Rankine Cycle

In many areas in the Oil/Gas complex, air coolers and water coolers are used to cool process streams. In some cases the coolers are used independently and in others they are used in series as shown in Figure 2A. Normally, the air cooler cools the stream to 120°F, then the water cooler cools the stream to 100°F. The inlet temperature of the air coolers vary throughout the plant from 550°F-200°F. It is these schemes which are proposed for replacement by the Rankine Cycle design in Figure 2B, in this report.

The Rankine Cycle design in Figure 2B utilizes an organic working fluid to produce shaft power through a reciprocating or turbine type expander. The air cooler and/or water cooler is replaced by the boiler of Figure 2B keeping inlet and exit states of the process stream constant. Therefore, the waste heat which was previously lost to the atmosphere is used as a heat source for the Rankine Cycle in which some of this heat is converted to mechanical energy in the expander while the remaining is rejected in the condenser to the cooling tower.

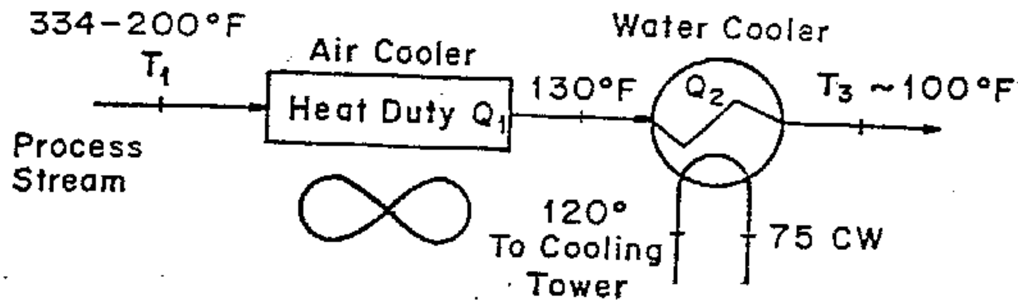


FIGURE 2A. PRESENT DESIGN

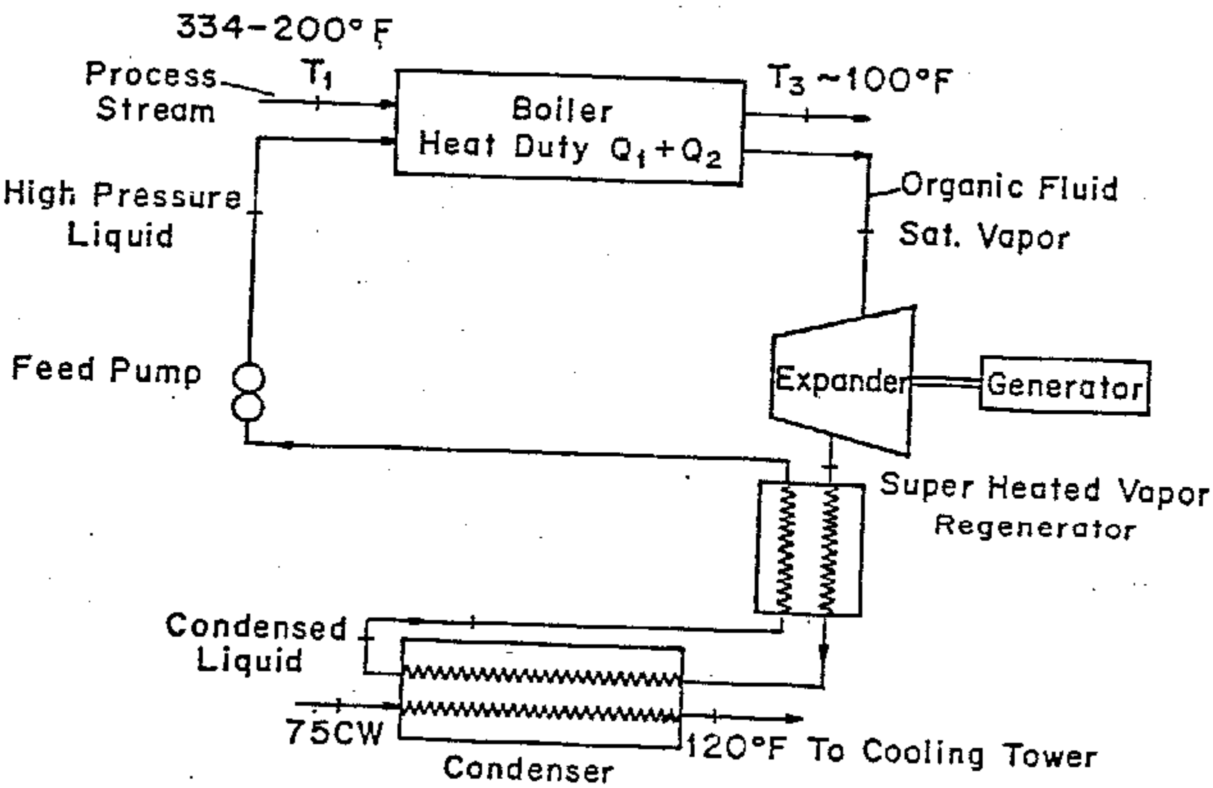


FIGURE 2B. ALTERNATIVE DESIGN ORGANIC RANKINE CYCLE

To date, only AFI Energy Systems is in a position to market Organic Rankine Cycles as low level waste heat recovery systems in the 200-400°F temperature range.[17] AFI Energy Systems is a joint venture of: Allied Chemical, Foster Wheeler and Ishikawajima Hauma (IHI) of Japan.

A demonstration 500 KW Organic Rankine Cycle system shown in Figure 3 is being constructed at the Allied Chemical facility at Claymont, Delaware and will be operating in early 1978.[8] This plant incorporates a turbine and associated technology which has been commercially applied in Japan since 1968 in a 3800 KW Organic Rankine Cycle. This system shown in Figure 4 has provided over 70,000 hours of continuous operation with no major problems.[18]

The AFI systems are being offered for sale on a turnkey, fixed price basis in four nominal sizes: 500 KW, 1000 KW, 2000 KW, and 4000 KW. Delivered costs are approximately $1000/KW.[17]

AFI's current market thrust is toward retrofitting the ORC to waste heat sources in existing plants. These systems utilize liquids or condensable vapors as a heating source. AFI feels economics are not yet justified for installation of an ORC when using gas as a heating source because of a much larger heat transfer area required in the boiler. A three-year AFI study indicated that there is a huge potential application in the following areas: chemical plants, refineries, chemical processes, and areas where there is excess process steam.[17]

Figures 5 and 6, furnished by AFI, have been used to estimate the ORC power output potential of heat exchangers with a liquid or condensable vapor as a heat source. Samples are shown in the figures.

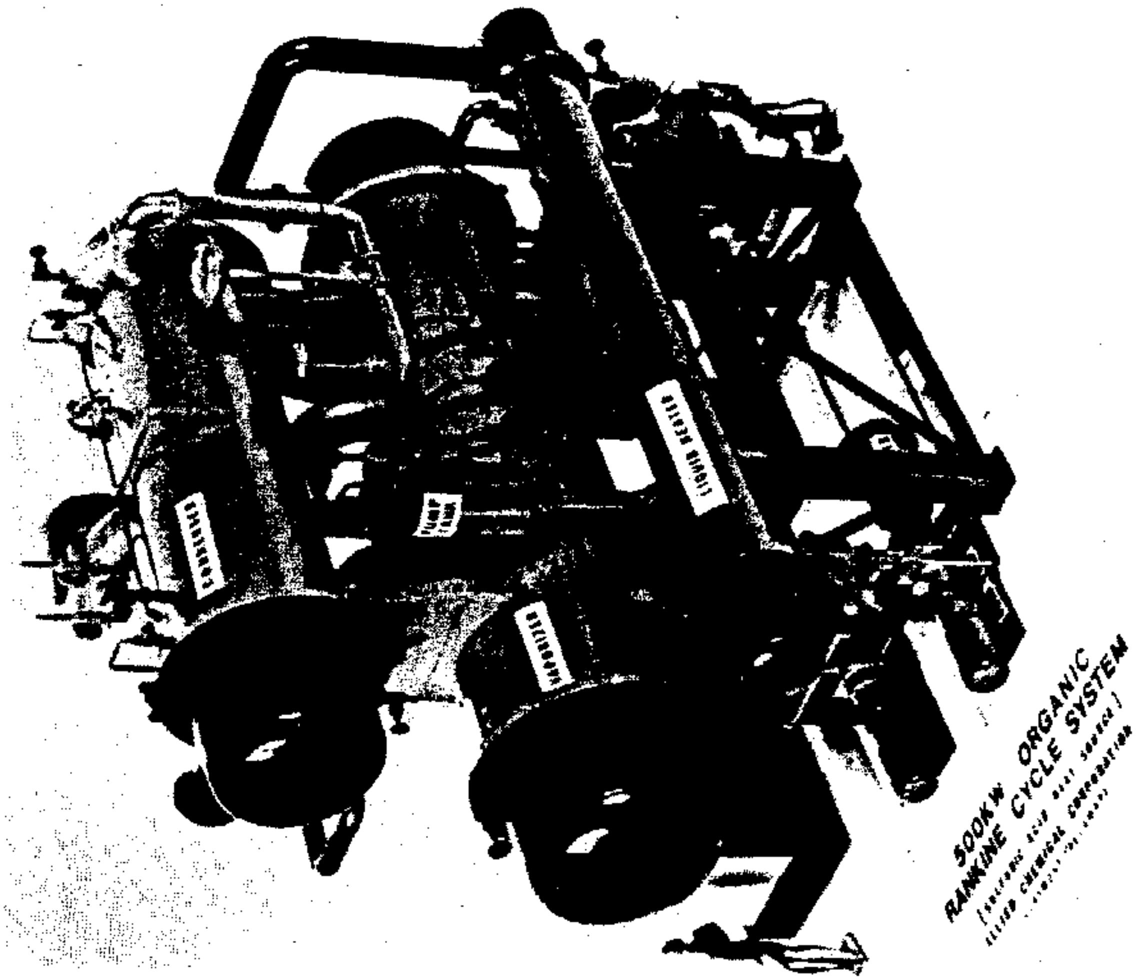


FIGURE 3

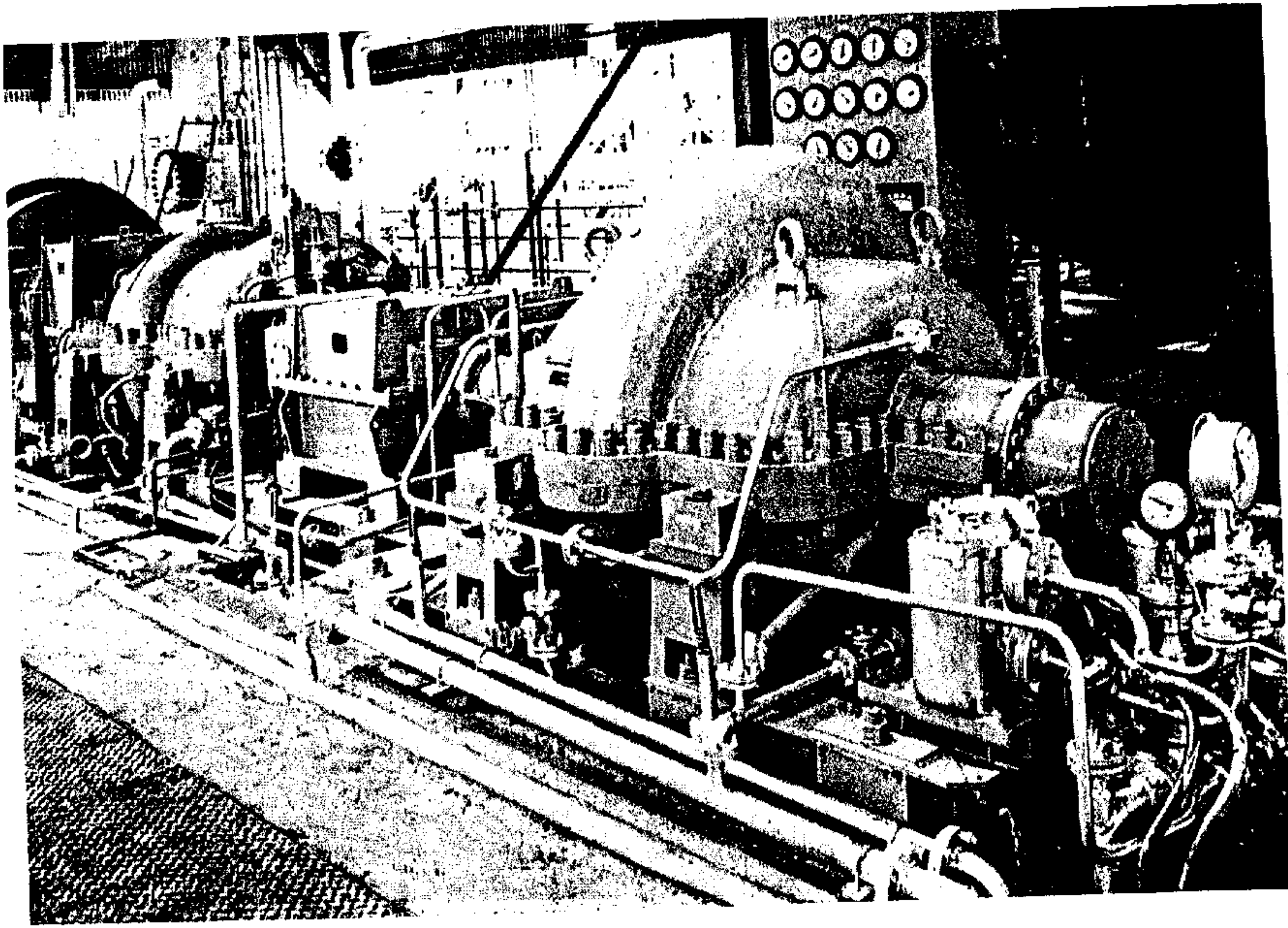
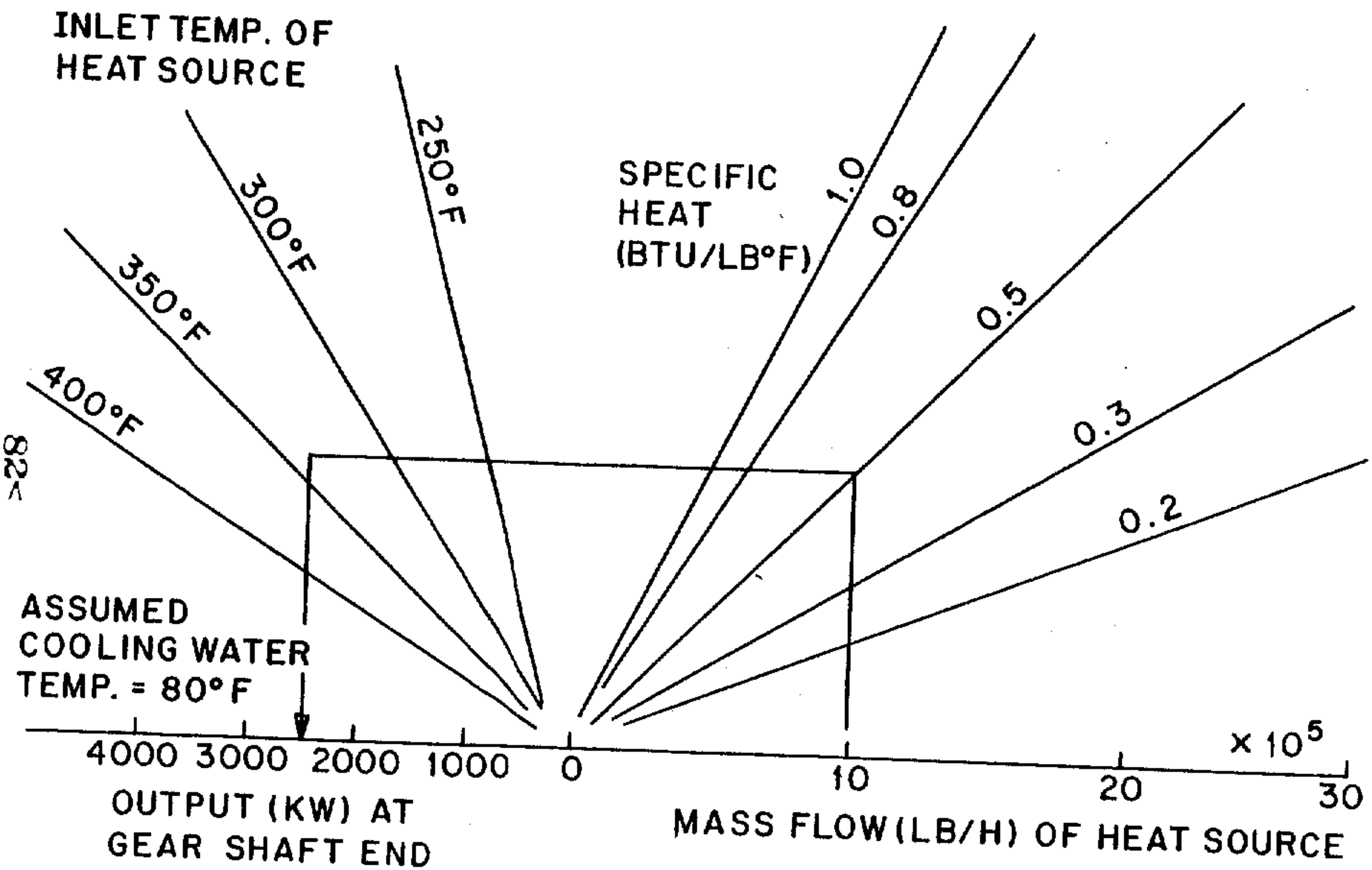
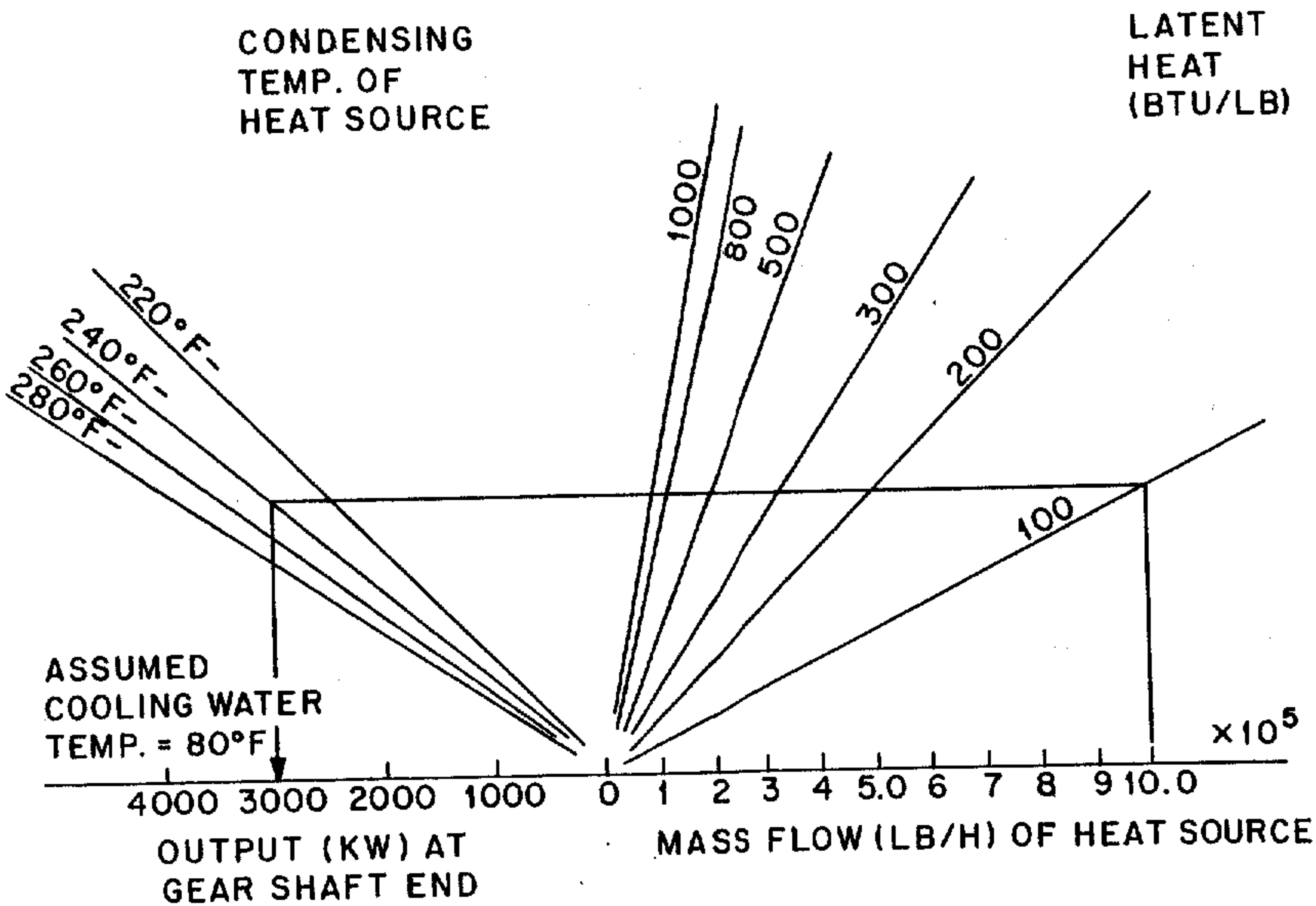


FIGURE 4
3800KW ORGANIC RANKINE CYCLE SYSTEM



RECOVERED OUTPUT FROM LIQUID HEAT SOURCE

Fig. 5



RECOVERED OUTPUT FROM CONDENSABLE HEAT SOURCE

Fig. 6

Table I shows the results of the power estimates. As can be seen in the table, this analysis indicates that 6 MW of power can be generated using AFI's hardware.

Our analysis of all heat exchangers in the Oil/Gas Complex shows that most of the rejected waste heat is removed from gas streams. Currently AFI does not market systems which can use this heat source, but this is because their market thrust is toward retrofitting in existing installations rather than application at the design stage of a new plant. When looking at the economics of the ORC in a new design, credit must be taken for the heat exchanger which would have otherwise been needed to remove the heat. This credit will make the ORC utilizing a gas heat source economically attractive.

Barber-Nichols Engineering Company (Refs. 6 and 7) has constructed a generalized curve showing the evaluation of Rankine Cycle efficiency with maximum cycle temperature for various working fluids as shown in Figure 7. It is on this curve that output power has been made for the ORC system utilizing a gas as a heat source. Sample calculations are given in Appendix A. All results are shown in Table II. The results of Table II show that by incorporating an ORC in every potential gas stream over 30 megawatts of power can be generated.

4. Cost Analysis

Only a rough figure of $1000/KW for the ORC systems has been obtained through personal conversations with a representative of Allied Chemical.[17] Installation costs have been kept at a minimum because of a modular installation approach and is estimated to be 20% of the capital

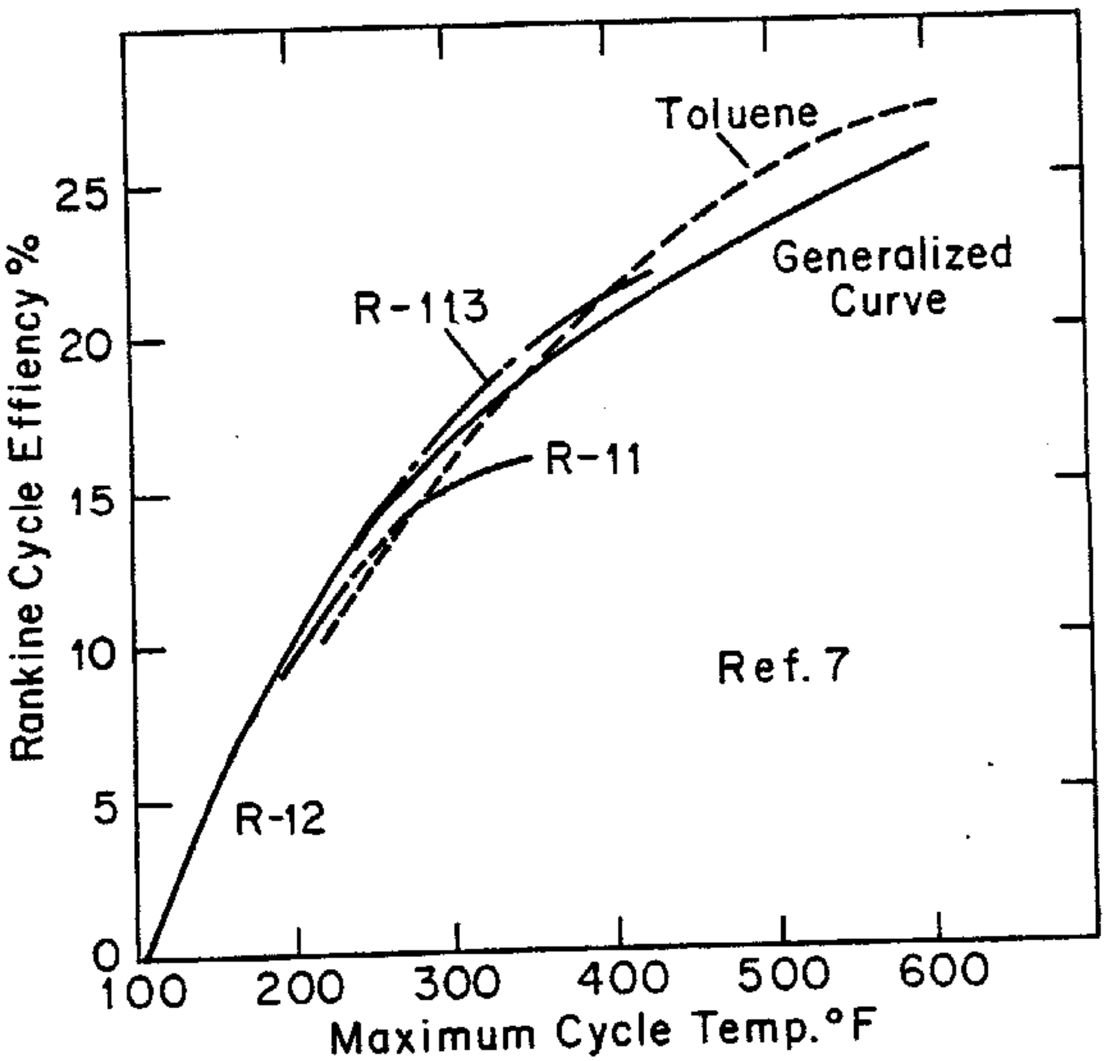


FIGURE 7. RANKINE CYCLE EFFICENCY

Table I - Output Potential-AFI Energy Systems

Item	Description	Specific Heat BTU/lb-°F	Mass Flow lb/hr	Temp. of Source °F	Output KW	Costs $/KW	Costs $
12-1301	slurry vapor condenser air	0.45	46,340	450	500	1200	600,000
12-1302	slurry vapor water condenser	0.45	44,500	260	1900	1200	2,280,000
12-1307(8)	Hp separator liquid coolers	0.41	224,740	300	500	1200	600,000
13-1301	dried vapor cooler	0.65	74,000	460	900	1200	1,080,000
14-1308	naptha air cooler	0.65	199,600	280	600	1200	720,000
14-1314	fuel oil air cooler	0.45	942,413	300	1400	1200	1,680,000
16-1307(8)	product coolers	0.57	106,500	270	500	1200	600,000
				TOTAL	6300 KW	1200	$7,560,000
				Heat Exchanger Costs		--	$1,843,500
				Net Investment		--	$5,716,500
				Or Installed Cost of		--	$ 910/KW

Table II - Power Output-Barber and Nichols

Item	Description	Mass Flow lb/hr	Temp. of Source °F	Power Generated KW
12-1305	Hp separator vapor air cond.	605,700	300	5400
16-1303	effluent air cooler	325,350	280	900
17-1304	amine cond.	153,500	230	2500
18-1303	methanation comp. 1st stage discharge	294,300	290	1300
18-1304	methanation comp. 2nd stage intercooler	294,300	250	900
18-1308	methanation effluent air cooler	305,314	305	2200
18-1315	SNG comp. 1st stage discharge intercooler	277,295	235	800
21-1302(3)	shift gas coolers	2,019,162	260	8200
24-1307(8)	fuel gas coolers	2,213,382	300	7900
			TOTAL	30,100

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investment.[17] The installed cost is therefore approximately $1200/KW for systems utilizing a liquid or condensable vapor heat source. The capital investment required, shown in Table I, is 7.5 million dollars. The total replacement heat exchanger cost was found to be 1.8 million dollars. Taking the heat exchanger costs as a savings the net investment is 5.7 million dollars or $910/KW. It is assumed that the same cost will be realized with ORC's utilizing gas as a heat source when credit is taken for the replacement heat exchangers.

Figure 8 presents cost curves which were extrapolated from cost curves given in Reference 6. These curves forecast the installed costs of Rankine Cycles for production units. The costs for the Rankine system include all the components necessary to produce shaft power and, in addition, the generator and associated controls to result in electrical power generation. The additional cost to the cooling tower because of larger cooling requirements are not given in this figure.

These curves assume a 100% installation cost and a 6% escalating rate from 1976. From this figure, the installed cost of replacement Rankine Cycles was estimated based on the cycle output and maximum cycle temperature. The cost estimates are given in Table III. Sample calculations are given in Appendix B of the report.

Table III is a summary of the results of the ORC feasibility analysis for all heat exchangers in the Oil/Gas Design. This table gives the feasibility of replacement in column one and the type of feasible exchangers in column two. Column three gives the estimated power output of each replacement cycle. The estimated installed costs are given in columns four and five, column 4 is AFI's estimated costs and column 5 is

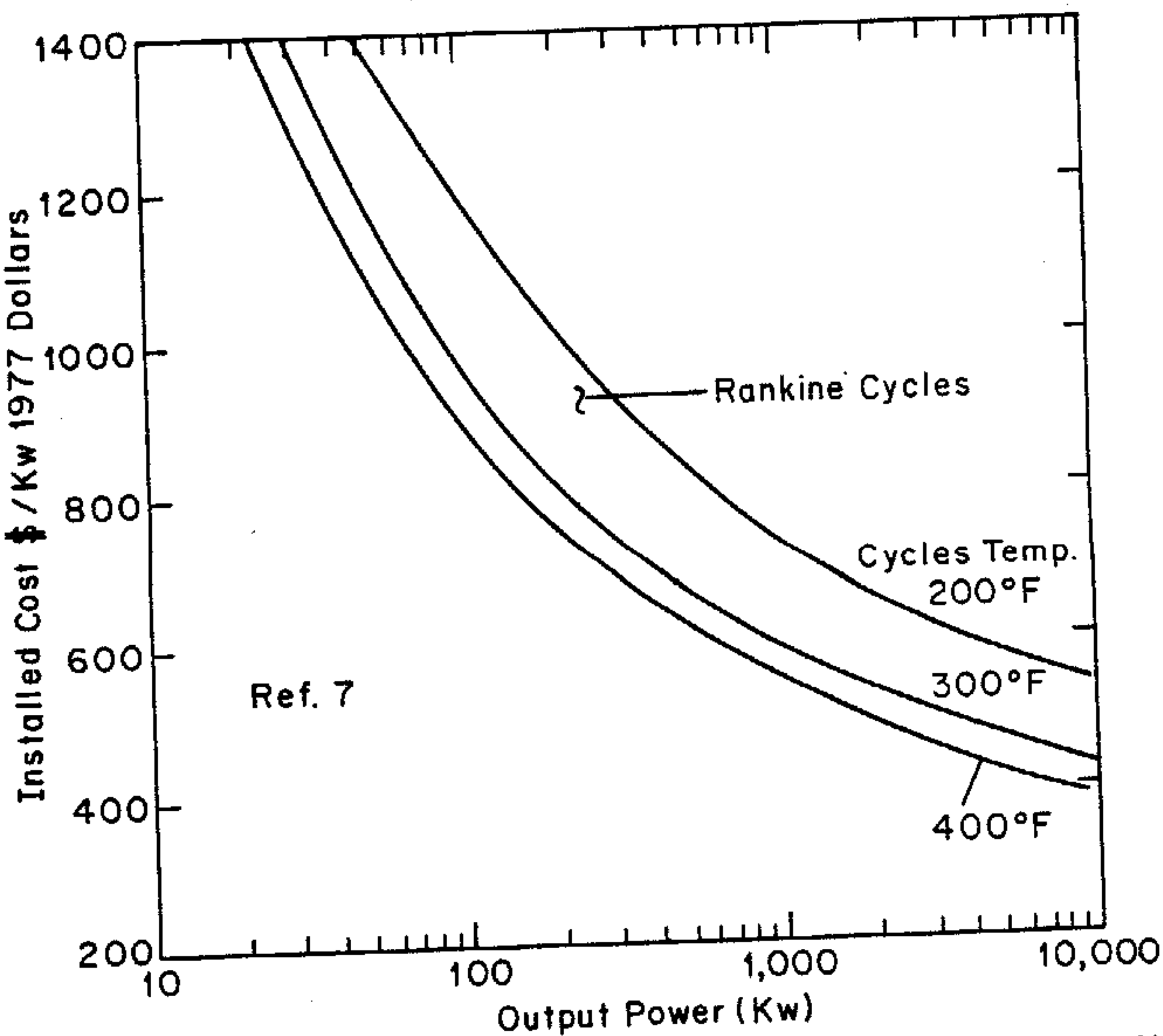

FIGURE 8. ESTIMATED INSTALLED COSTS FOR RANKINE CYCLES

Table III - Summary of ORC Analysis

Item	Description	Feasibility	Type	Power Generated KW	Installed Costs AFI ($/KW)	B & N	Remarks
12-1301	slurry vapor air condenser		steam-air	500	1200	725	
12-1302	slurry vapor water condenser		steam-air	1900	1200	650	
12-1310 12-1340	Hp separator slurry feed exchangers	rejected					Process Hx
12-1370		rejected					Process Hx
12-1313	Hp separator slurry OH cond. Hx	rejected					Process Hx
12-1314	Hp separator slurry steam gen.	rejected					Process Hx
12-1303	Hp separator vapor Feed Gas Hx	rejected					Process Hx
12-1304	Hp separator OH vapor steam gen.	rejected					Process Hx
12-1305	Hp separator OH vapor air condenser		gas-air	5400		500	
12-1306	Hp separator OH liq. steam gen.	rejected					Process Hx

Table III - Summary of ORC Analysis

Item	Description	Feasibility	Type	Power Generated KW	Installed Costs ($/KW) AFI	Installed Costs ($/KW) B & N	Remarks
12-1307	Hp separator OH liq. air cooler		Liquid-air	500	1200	625	Process Hx
12-1308	Hp separator OH liq. water cooler						+12-1307
12-1309	Hp separator OH Cond. H_2O cooler	rejected					Temp. too low
12-1315	Hp flash vapor steam generator	rejected					Process Hx
12-1316	Hp flash vapor air condenser	rejected					Output too low
12-1317	Hp flash vapor water condenser	rejected					Output too low
12-1318	1st IP flash vapor steam generator	rejected					Process Hx
12-1319	1st IP flash vapor air condenser	rejected					Output too low
12-1320	2nd IP flash vapor steam generator	rejected					Process Hx
12-1321	2nd IP flash vapor air condenser	rejected					Output too low
12-1322	LP flash vapor air condenser	rejected					Output too low
12-1324	LP vent gas condenser	rejected					Output too low

Table III - Summary of ORC Analysis

Item	Description	Feasibility	Type	Power Generated KW	Installed Costs AFI ($/KW)	Installed Costs B & N	Remarks
13-1301	Dried vapor cooler		liquid-air	900	1200	580	
13-1302	Recycle wash oil preheater	rejected					Process Hx
13-1601	Drier WHB #1	rejected					Process Hx
13-1602	Drier WHB #2	rejected					Process Hx
14-1305	Hy. Dist. PA/ Lt. Dist. Reboiler	rejected					Process Hx
14-1301	Hy. Dist. PA Feed Exchanger	rejected					Process Hx
14-1302	Hy. Dist. PA Steam generator	rejected					Process Hx
14-1307	Fract. OVHD/ Steam generator	rejected					Process Hx
14-1303	Lt. Dist. PA Steam generator	rejected					Process Hx
14-1306	Fract. Bottoms/ Hy. Dist. reboiler	rejected					Process Hx
14-1401	Main Fact. charge furnace	rejected					Process Hx
14-1304	Fract. Bottoms/ Feed exchanger	rejected					Process Hx
14-1308	NAPHTHA air cooler		liquid air	600	1200	675	

Table III - Summary of ORC Analysis

Item	Description	Feasibility	Type	Power Generated KW	Installed Costs AFI ($/KW)	Installed Costs B & N	Remarks
14-1315	ATM. Bottoms/ 600 psig steam gen.	rejected					Process Hx
14-1312	Fuel oil/150 psig steam generator	rejected					Process Hx
14-1313	Fuel oil/150 psig steam generator	rejected					Process Hx
14-1314	Fuel oil air cooler		liquid-air	1400	1200	590	
14-1309	OVHD. vapor interm. air cooler	rejected					Temp. too low
14-1310	OVHD. vapor air cooler	rejected					Temp. too low
16-1302	Charge heater	rejected					Process Hx
16-1301	Feed-effluent exchanger	rejected					Process Hx
16-1303	Effluent air cooler		gas-air	900		650	
16-1304	Stabilizer feed-bottoms exchanger	rejected					Process Hx
16-1307	Product air cooler		liquid-air	500	1200	725	
16-1304	Stabilizer OVHD air cooler	rejected					Output too low
16-1308	Product water trim cooler		liquid-H_2O				+16-1307

Table III - Summary of ORC Analysis

Item	Description	Feasibility	Type	Power Generated KW	Installed Costs AFI ($/KW)	Installed Costs B & N	Remarks
16-1306	Stabilizer reboiler	rejected					Process Hx
19-1301	Feed effluent Hx	rejected					Process Hx
19-1302	Effluent cooler	rejected					Output too low
17-1301	Gas/Gas Hx	rejected					Process Hx
17-1302	Amine cooler	rejected					Process Hx
17-1303	Amine exchanger	rejected					Process Hx
17-1304	Amine condenser		gas-air	2500		610	
17-1305	Amine reboiler	rejected					Process Hx
17-1306	Amine reclaimer	rejected					Process Hx
18-1301	Regeneration heater	rejected					Process Hx
18-1302	Regeneration cooler	rejected					Temp. too low
18-1303	Methanation comp. 1st stage discharge		gas-H_2O	1300		620	
18-1304	Methanation comp. 2nd stage discharge intercooler		gas-H_2O	900		710	
18-1305	Methanation feed/effluent fix	rejected					Process Hx
18-1401	Methanation start-up heater	rejected					Process Hx

Table III - Summary of ORC Analysis

Item	Description	Feasibility	Type	Power Generated KW	Installed Costs AFI ($/KW)	Installed Costs B & N	Remarks
18-1306	Methanation circulating oil boiler	rejected					Process Hx
18-1308	Methanation effluent air cooler		gas-air	2200		570	
18-1311	Polish methanator feed/effluent Hx	rejected					Process Hx
18-1402	Polish methanator start-up heater	rejected					Process Hx
18-1313	Polish methanator air cooler	rejected					Output too low
18-1315	SNG compressor 1st stage discharge intercooler		gas-H_2O	800		780	
18-1316	SNG comp. 2nd stage discharge cooler	rejected					Output too low
18-1314	Deethanizer comp. 1st stage discharge intercooler	rejected					Output too low
18-1317	Deethanizer cond.	rejected					Temp. too low
18-1318	Deethanizer reboiler	rejected					Process Hx
18-1319	Depropanizer cond.	rejected					Output too low
18-1320	Depropanizer reboiler	rejected					Process Hx

Table III - Summary of ORC Analysis

Item	Description	Feasibility	Type	Power Generated KW	Installed Costs ($/KW) AFI	Installed Costs ($/KW) B & N	Remarks
18-1321	Debutanizer cond.	rejected					Temp. too low
18-1322	Debutanizer re-boiler	rejected					Process Hx
20-1301	Steam superheater	rejected					Process Hx
20-1302	Oxygen preheater	rejected					Process Hx
20-1303	Quench water air cooler	rejected					Temp. too low
20-1601	Steam boiler	rejected					Process Hx
21-1601	170 psia waste heat boiler	rejected					Process Hx
21-1301	Boiler feed water preheater	rejected					Process Hx
21-1602	40 psia waste heat boiler	rejected					Process Hx
21-1603	25 psia waste heat boiler	rejected					Process Hx
21-1302	Shift gas air cooler		gas-air	8200		520	
21-1303	Shift gas water trim cooler		gas-H_2O				+21-1302
24-1301	Quench water air cooler	rejected					Temp. too low

Table III - Summary of ORC Analysis

Item	Description	Feasibility	Type	Power Generated KW	Installed Costs ($/KW) AFI	Installed Costs ($/KW) B & N	Remarks
24-1302	Air/fuel gas HX #1	rejected					Process Hx
24-1303	Fuel gas-1200 psi steam generator	rejected					Process Hx
24-1304	Air/fuel gas HX #2	rejected					Process Hx
24-1305	Fuel gas-150 psi steam generator	rejected					Process Hx
24-1306	Fuel gas-25 psi steam generator	rejected					Process Hx
24-1307	Fuel gas air cooler		gas-air	7900		490	
24-1308	Fuel gas water cooler		gas-H_2O				+24-1307
26-1302	Reboiler	rejected					Process Hx
26-1351	Solution Hx	rejected					Process Hx
26-1352	Solution cooler	rejected					Process Hx
26-1353	NH_3 stripper condenser	rejected					Process Hx
26-1354	NH_3 stripper cooler	rejected					Process Hx
26-1355	NH_3 stripper reboiler	rejected					Process Hx
26-1356	NH_3 condenser	rejected					Process Hx

Table III - Summary of ORC Analysis

Item	Description	Feasibility	Type	Power Generated KW	Installed Costs ($/KW) AFI	Installed Costs ($/KW) B & N	Remarks
32-1311	Condenser	rejected					Process Hx
32-1312	Condenser	rejected					Process Hx
32-1313	Condenser	rejected					Process Hx
32-1315	Condenser	rejected					Process Hx
32-1316	Condenser	rejected					Temp. too low
32-1317	Condenser	rejected					Temp. too low
12-1323	LP flash vapor air condenser	rejected					Potential too low
Total 110 Hx			Total	36,400	1200	560	
18-Used		Less Hx Investment		-12,040,260	910	230	
		Plus Cooling Tower Costs		+ 2,300,000	985/KW	300/KW	

98^

the estimated costs from Reference 7. The last column gives reasons for rejection of heat exchanger replacement.

The total results shown in page 27 of the table indicates that 36 megawatts of power can be generated. The costs for the ORC is estimated to be around $1200/KW using AFI's data and $560/KW using the data from Reference 7. When credit is taken for the replaced heat exchangers and an adjustment made for the increased cooling tower costs the AFI estimate drops to $985/KW and $300/KW for Reference 7 costs.

Although the AFI estimates indicate the current costs of ORC for waste heat utilization, the costs from Reference 7 indicate the potential costs of the ORC given the appropriate demand. Given this range it is therefore necessary to perform a return on investment sensitivity analysis to demonstrate the potential ROI for various investment costs and selling prices.

4.1 <u>DCF Sensitivity Analysis</u>

A discounted cash flow analysis has been performed on varying sizes of ORC for different investment costs and electricity exporting rates and the results are shown in Figures 9 and 10. Figure 9 assumes a $.025/KW-hr exporting rate escalating 8% per year for 10 years. Figure 10 assumes a $.01/KW-hr exporting rate escalating 6% per year for 10 years. Assumptions used for the basis of this analysis are in accordance with the Gas Cost Guidelines used in the Oil/Gas Complex and are shown in Appendix B.[11]

The cost curves of Figure 8 were used as a basis for this analysis. The capital investment was taken directly from Figure 8 for curve B in Figure 9 (B and C), the most optimistic curve. The capital investment for the pessimistic outlook, curves (A and D) was assumed to be a 100%

increase in the curve of Figure 7. This analysis does take credit for replacement heat exchangers.

The expected ROI for two ORC manufacturers is also given in the figure. One is AFI at $985/KW and the other is Sundstrand Corporation, a 600 KW waste heat recovery ORC utilizing heat source temperatures above 550°F. The Sundstrand systems installed cost is $800/KW, with a mass production projection of $400/KW.

5. Discussion of ORC

The results and conclusions presented here concerning Organic Rankine Cycles are not necessarily (restricted) to coal conversion plants but can be expanded to any inudstry in which low level heat is being wasted.

By replacing air coolers and water coolers with Organic Rankine Cycles, waste heat can be utilized to produce useful electrical or shaft power. All ORC presented in this report are within the realm of technological development of Rankine Cycles. In addition to AFI Energy Systems and Sundstrand's experience, many other U.S. firms have applied considerable effort to the development of Organic Rankine Cycles for various applications. Table IV, not intended to be an all inclusive list, gives a summary of some of the companies working on ORC.

Most applications of the Organic Rankine Cycle are of a prototype nature at the present time and therefore costs are substantially higher than the estimates presented here. In some cases the costs are as high as $2000/KW-$3000/KW, but all manufacturers forecast price declines given the appropriate demand. AFI's and Sundstrand's cycles

Table IV

	Manufacturer	Type of Fluid	Type of Expander	Type of Application	Expander Inlet °F/PSIA	Rated Power Hp
1.	Aerojet-Liquid Rocket	AEF-78	Turbine	Automobile	650/1000	74.9
2.	Barber-Nichols	R-113	Turbine	Solar Cooling	200/57	2.7
3.	Barber-Nichols	R-113	Turbine	Solar Irrigation	920/221	25.0
4.	Fairchild-Hiller	FC-75	Turbine	Total Energy Plant	428/206	25.34
5.	Kinetics	R-113	Rotary	Automobile	375/355	47.0
6.	Kinetics	R-114	Rotary	Solar Cooling	200/180	7.5
7.	Ormat	MCB	Turbine	Power Pack	variable	3.0
8.	Sundstrand Aviation	CP-25	Turbine	Total Energy Plant	825/195	134.1
9.	Sundstrand Aviation	Dowtherm A	Turbine	Power Pack	700/7	8.0
10.	Sundstrand Aviation	Tolvene	Turbine	Waste Heat Recovery	550/300	900
11.	Thermo-Electron	Fluorinol 85	Turbine	Automobile	600/700	145.5
12.	Thermo-Electron	Fluorinol 85	Turbine	Gas turbine bottoming plant	600/700	
13.	Thermo-Electron	Fluorinol 85	Turbine	Diesel engine bottoming plant	600/700	1,000
14.	United Aircraft	R-113	Turbine	Solar Cooling	200-375/70-340	4.3
15.	United Aircraft	R-114	Turbine	Solar Cooling	250-275/250-400	8.0

are currently being sold at reasonable costs with satisfactory rates of return given today's electricity costs.

These efforts and the efforts of numerous other companies indicate the cost estimates presented here are certainly within the time frame necessary for use in coal conversion plants.

6. Conclusions

Based on estimates and results presented in this report, the following conclusions are drawn:

1. The Organic Rankine Cycle is an energy effective to air and water cooled systems operating at temperatures above 200°F. In the Oil/Gas Complex 36 megawatts of electricity can be produced in an energy effective manner through recovery of the waste heat of air and water coolers.
2. Incorporating Organic Rankine Cycles into coal gasification designs will generate demand to lower production costs and, therefore, enable the ORC to become cost effective in a variety of other industries where waste heat is available. On a national level the energy savings potential is incredible.

7. Recommendations

This report is a preliminary analysis which pinpoints 18 heat exchangers throughout the Oil/Gas Complex, in which the rejected heat is sufficient to generate over 36 MW of power via Organic Rankine Cycles. It is therefore recommended that current manufacturers be contacted and steps taken to further engineer and incorporate Organic Rankine Cycles into the Oil/Gas design.

8. References

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Appendix A

Sample Calculations

Rankine Cycle Power Output

The High pressure Separator vapor air condenser (12-1305) is used as an example in these calculations to illustrate the method used in determining possible power output of the ORC.

Data

Heat Source Temp:	300°F
Heat Transfer:	123.3×10^6 BTU/Hr.
Mass Flow:	605,700 Lbm/Hr.

Assumptions

1. Boiler, regeneration and condenser have an effectiveness of 80%.

Sample Calculations

The heat transfer in the boiler is 123.3×10^6 BTU/Hr.

$$QB = 123.3 \times 10^6 \text{ BTU/Hr.}$$

Assuming boiler effectiveness of 80% the maximum cycle temperature is about 270°F.

$$T_{max} = 270°F.$$

Using the generalized curve of Figure #7, the Rankine cycle efficiency is 15%.

$$y = 15\%$$

Multiplying the heat source from the boiler with the cycle efficiency gives the power output of the cycle.

$$P = yQ_B = .15 \times 123.3 \times 10^6$$

$$= 18.5 \times 10^6 \text{ BTU/Hr.}$$

$$= 5{,}420 \text{ KW}$$

$$= 7{,}275 \text{ Hp}$$

Appendix B

1. Cost Analysis

The replacement rankine cycle for the air cooled system (12-1305) is used as an example for the cost analysis presented in this paper.

The installed cost of replacement rankine systems is estimated from the curves of Figure 8 using the estimated power output and cycle temperature calculated in Appendix A.

$$P_{out} = 5{,}400 \text{ KW}$$

$$T_{max} = 270°F.$$

From Figure 8 the installed cost is found to be \$500/KW

$$IC = \$500/KW$$

Since the total output possible is 5,400 KW the total installed cost is easily found.

$$(IC)_T = \$500/KW \times 5400$$
$$= \$2{,}700{,}000$$

Additional cost resulting from enlarging cooling tower capacity is estimated from data given in Reference 10.

Cooling Tower Costs = \$76,400

Heat exchanger costs were obtained from Reference 13.

Hx Costs = \$540,350

The net cost is found by adding the ORC installed cost plus the cooling tower costs minus the heat exchanger costs.

$$\text{Net Cost} = \$2{,}700{,}000 + 76{,}400 - 540{,}350$$
$$= \$2{,}236{,}050$$

or \$415/KW

2. DCF - Sensitivity Analysis

A discounted cash flow analysis was performed for various capital investments and rates of electricity. The following is the assumptions used in constructing the curves of Figures 9 and 10.

All Curves

1. 20 year project life
2. Double-Declining Balance Depreciation
3. 48% federal income tax
4. $.003/KW-hr operation and maintenance costs
5. 8400 Hrs/year operating

Curve A - Pessimistic outlook

1. Capital Cost based on 100% increase of Fig. 8 with credit taken for replacement Heat Exchanger
2. Exporting rate for electric power is $.01/KW-hr escalating at a rate of 6% per year for 10 years

Curve B - Optimistic Outlook

1. Capital Cost based on Fig. 8 with credit taken for replacement Heat Exchanger
2. Exporting rate for electric power is $.025/KW-hr escalating at a rate of 8%/year for 10 years

Curve C

1. Capital Costs based on Fig. 8 with credit taken for replacement exchanger
2. Exporting rate of $.01/KW-hr escalating at a rate of 6%/year for 10 years

Curve D

1. Capital Costs based on 100% increase of Fig. 8 with credit taken for replacement exchanger
2. Exporting rate of $.025/KW-hr escalating at a rate of 8%/year for 10 years.

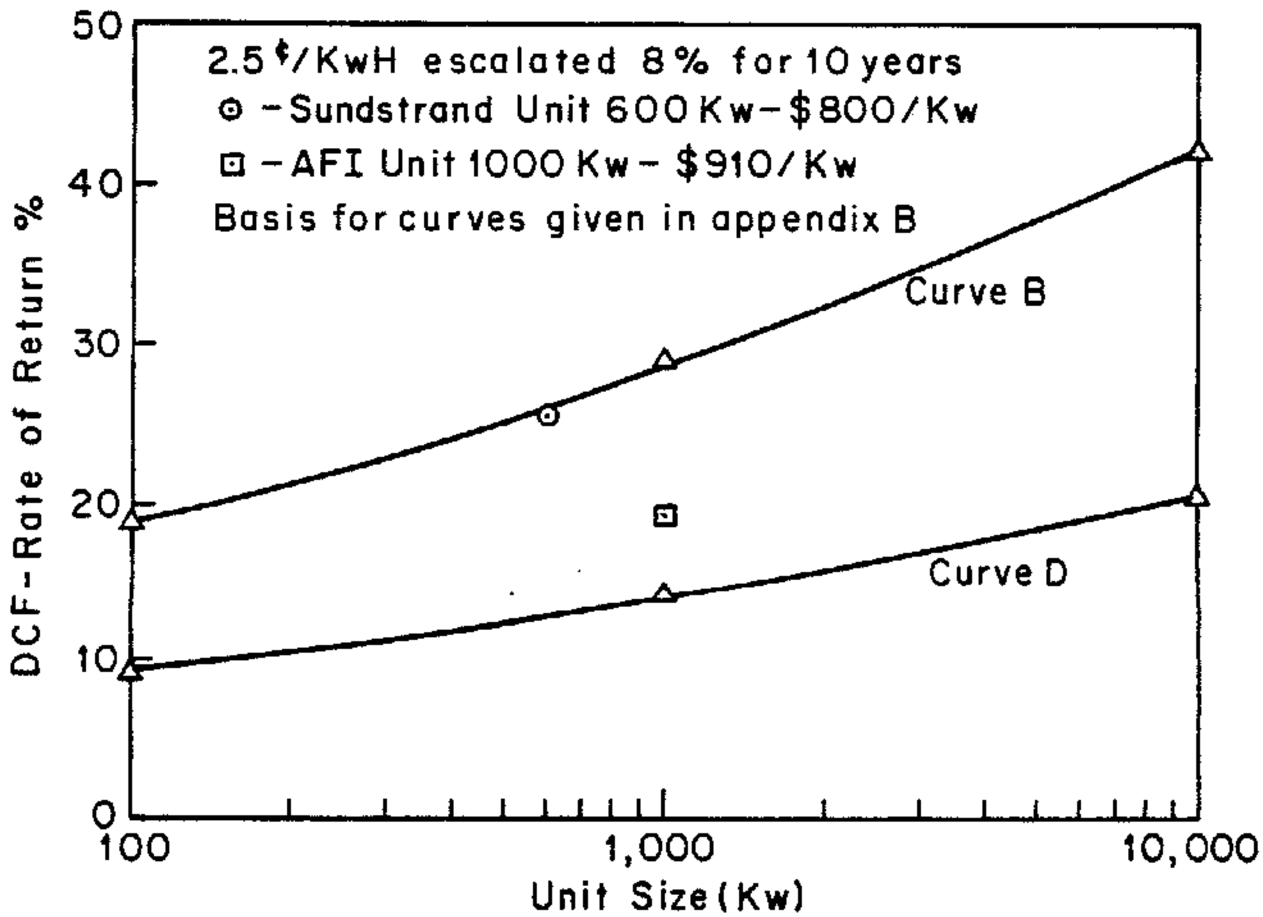

FIGURE 9. RATE OF RETURN VS CYCLE SIZE

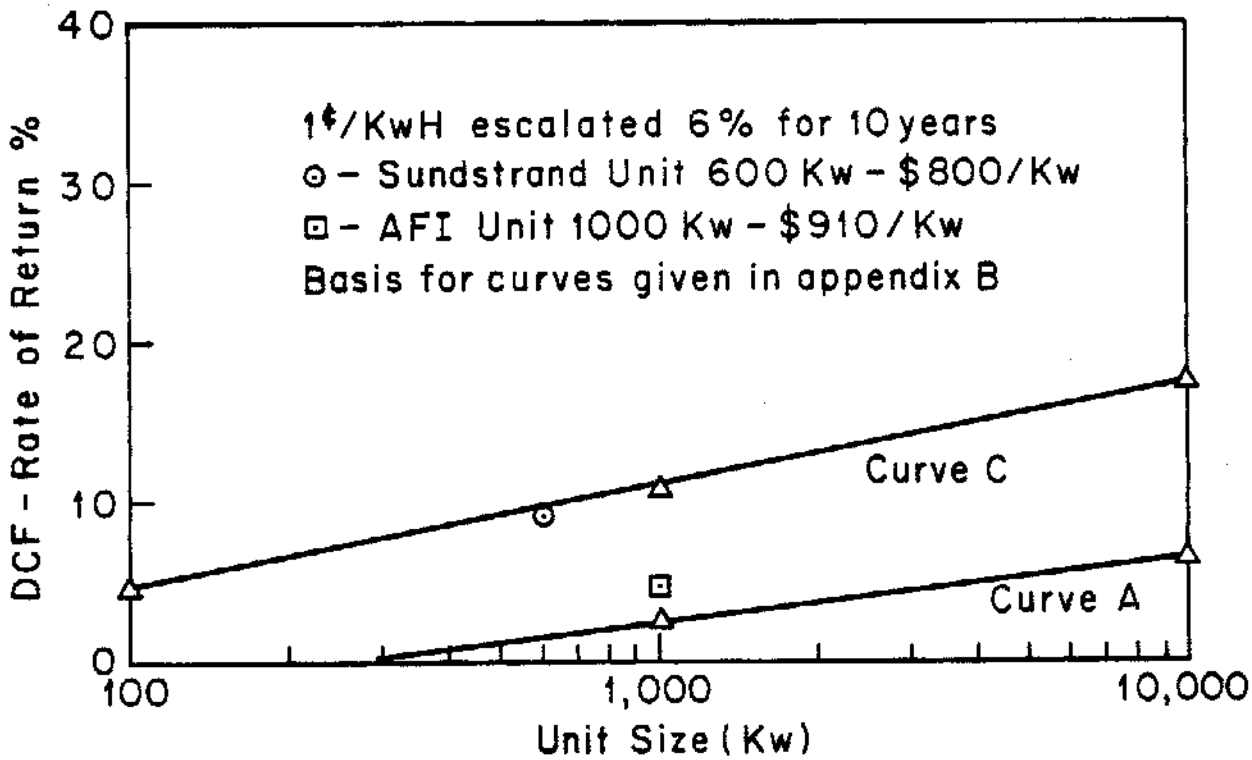

FIGURE 10. RATE OF RETURN VS CYCLE SIZE