TRI-STATE SYNFUELS COMPANY
Indirect Coal Liquefaction Plant
Western Kentucky

FLUOR ENGINEERS AND CONSTRUCTORS, INC.
Contract 835504

PROCESS DEVELOPMENT STUDY NO. 5

AIR/WATER COOLING BREAKPOINT

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1.0 Introduction

1.1 Background

For a project of this magnitude it is important that the selection of air-cooled versus water-cooled heat exchangers is accomplished in an objective manner, particularly in the temperature ranges for which either air or water cooling will work with given process, space, and coolant limitations. Generally, air-cooled exchangers are judged to perform best with a minimum air to process temperature differential of 40° to 50°F. Water-cooled exchangers are specified so that the tubes do not become hot enough to adversely affect the cooling water. Between these extremes either air or water cooling will frequently meet the criteria limitations. The relative cost of air cooling is no longer as expensive as it once was, and is becoming even less expensive with increasing power and water costs.

1.2 Purpose

The purpose of this study, as defined in the attached scope of work (Appendix 1), is to determine the differential between the ambient air and process exit temperatures where air cooling becomes more economical than water cooling for a selected set of process conditions. The economics of air and water cooling for these process conditions will be analyzed for sensitivity to capital and energy costs and developed such that the calculations can be modified for other process conditions to provide a guideline for exchanger selections. As such, the methods used in this study will apply to those situations where either air or water cooling are suitable for the particular process conditions and cost is the critical factor in the selection.

1.3 Scope of Work

This study was initiated to determine the economic transition temperature from air-cooled to water-cooled exchangers. The scope of work is accomplished by comparative analysis of air and water cooling systems as follows:

- A Lurgi gas stream is cooled assuming four process temperature differentials, all starting at 345°F and ending at 255°F, 200°F, 145°F and 115°F respectively. The four services are cooled in an air-cooled exchanger case and in a water-cooled exchanger case.

1.3 Scope of Work (Continued)

- Four pairs of specifications were prepared for the exchangers, one pair for each of the temperature differentials. Each pair of specifications covered an air-cooled and water-cooled exchanger with identical duties. For each exchanger, vendor costs were developed from which the installed capital cost (sell price) was established. Air and water conditions were based on published weather data for Owensboro, Kentucky with dry bulb air temperature at 96°F and the cooling tower water temperature at 85°F. These temperatures correspond to the present Tri-State Design Criteria.

- Installed capital costs for forced draft cooling towers and for pumps were developed on an incremental cost basis. For the base case, energy costs were calculated at a constant $0.055/Kwh and added to the operating and maintenance costs. These costs were then converted to an equivalent annualized cost (present worth) using an assumed cost of capital of 17 percent and a 25 year plant life. To establish the sensitivity of the analysis to the assumption of 17 percent for Tri-State's cost of capital, results at 12 percent and 23 percent interest were also developed. To establish the sensitivity of the analysis to cost of energy with power costs at $0.055/Kwh, results were developed for the 17 percent cost of capital case at power costs of $0.035/Kwh and $0.075/Kwh.

2.0 Summary

On the basis of installed capital cost alone, the air-cooled heat exchangers are several times more expensive than water-cooled exchangers in identical service. The cost ratios range from 3.96 to 2.89 for process exit temperatures of 255 °F and 115 °F respectively. On the other hand, water cooling suffers a substantial penalty for cooling tower (CT) backup capital as well as annual costs far in excess of those for air cooling. The air-cooled exchangers examined in this study used only 22 percent to 41 percent of the electric power required by water cooling. For the temperature ranges in which we would normally apply air cooling, the energy required for air cooling tops out at 32 percent of the energy used for water cooling. With all of the annual costs converted to equivalent annualized costs (present worth) and the cooling tower backup capital included, air-cooled heat exchangers are more cost effective in almost all of the cases which were studied.

2.0 Summary (Continued)

Present worth calculations based on 12 percent, 17 percent and 23 percent interest and a 25 year plant life were used to convert annual operating costs to an equivalent annualized cost. The sums of the installed capital costs, backup capital, and annualized costs for each exchanger were used to plot costs versus process exit temperatures. With a power cost of $0.055/Kwh, the only intersection (break-even point) occurs on the 23 percent interest curve at approximately 115°F. With the design ambient air temperature of 96°F, this intersection occurs at a much lower temperature than would be expected if we used the old accepted premise of a 40° to 50°F differential between the inlet air and exit process temperatures. This premise, however, was generated when ongoing costs, particularly energy, were considerably lower as shown in the energy cost sensitivity analysis. With the power cost at $0.035/Kwh, the 17 percent interest curve intersects at 115°F.

3.0 Design Basis

The intent of this study is to determine the cost breakpoint between air-cooled and water-cooled heat exchangers based on the process exit temperature. To accomplish this, a series of heat exchangers were set up as follows:

- A typical hot Lurgi gas stream was cooled from 345°F to 255°, 200°, 145°, and 115°F.
- Four pairs of specification sheets (total of 8) were prepared to describe the process duties.
- Each pair of specifications contained identical process-side duties and conditions for an air-cooled and a water-cooled exchanger.
- The dry bulb temperature was set at 96°F and the cooling tower water temperature fixed at 85°F based on a wet bulb of 78°F. Weather data is based on Owensboro, Kentucky, at the 2½ percent frequency level. This means that these temperatures will not be equaled or exceeded more than 2½ percent of the time, on the average, during the warmest consecutive six months as determined by the mean wet bulb temperature.

Power costs were calculated at $.055/Kwh with no escalation. To demonstrate the sensitivity of the analysis to energy costs, additional annual costs were developed for the 17 percent interest case with power costs at $0.035/Kwh and $0.075/Kwh with no

3.0 Design Basis (Continued)

escalation. Cooling tower incremental capital costs were calculated on the basis of several sizes of mechanical draft towers with a similar approach to the wet bulb temperature used in this study. Pumping costs were based on a 65 psig pump discharge. Cooling tower chemical costs were estimated on the basis of Fluor inhouse data. Operator labor was charged at a rate of $29,000/year.

Annual operating costs were converted to equivalent annualized costs at 12 percent, 17 percent and 23 percent interest rates and a 25 year plant life with present worth factors of 7.8431, 5.7662 and 4.3232 respectively. All equipment costs are installed capital costs, i.e., sell price.

4.0 Discussion

Until recently, air-cooled heat exchanger usage has been limited to areas with low water supply or very high temperature process applications. With ever tighter controls on waste water and escalating power costs, air cooling is becoming more economically acceptable everywhere.

In this study all of the costs associated with both air and water cooling were included to arrive at what is believed to be an accurate total cost for each system. The study demonstrates that the air-cooled systems use only 20 percent to 40 percent of the power used in the water-cooled systems (See Table I). With power costs at $.055/Kwh the air-cooled heat exchangers can be economically justified down to process exit temperatures within 20° to 25°F of the ambient air temperature. The base data for the study originates with four heat duty requirements generated by cooling a typical Lurgi gas stream as described in Section 3.0, Design Basis. These four heat duties were used to generate eight different specifications for air-cooled and water-cooled heat exchanger pairs. Fluor's Mechanical Engineering specialists sized and priced heat exchangers for each of the eight specifications. Independent price checks of the air cooled exchangers confirmed in-house pricing. The exchangers were primarily carbon steel construction. The air-cooled exchangers were equipped with corrosion resistant fins, sufficient winterization for Owensboro, Kentucky, and the usual platforms. Header box construction was standard two piece welded, with plug cleanouts. Brake horsepower for each air-cooled exchanger was included in the design. The estimated equipment prices were converted to sell prices (installed capital costs) and are listed in Table II. Table III lists the sum of total capital and equivalent annualized costs (present worth) for each heat exchanger at 12 percent, 17 percent and 23 percent interest.

4.0 Discussion (Continued)

Table IV lists the installed capital and equivalent annualized costs for the 17 percent interest case at power costs of $0.035/Kwh, $0.055/Kwh and $0.075/Kwh.

It should be noted that the ASME and TEMA codes have tended to ignore or sidestep air-cooled exchanger design and as a result, most of the design criteria have been originated by the manufacturers themselves. It is entirely conceivable that in some service applications the cost of air-cooled exchangers will not be as advantageous due to substantially more stringent design requirements for the header boxes. Incremental backup capital for a cooling tower and cooling water pumps was calculated based on its water usage. Annual power, chemicals, maintenance, and operator costs were calculated for each exchanger. These annual costs were converted to equivalent annualized costs (present worth) for 12 percent, 17 percent and 23 percent interest at a 25 year plant life. The total of equivalent annualized costs (present worth) for 12 percent, 17 percent and 23 percent interest plus all sell costs (installed capital costs) versus the process exit temperature are shown in Figures 1, 2 and 3, respectively. The total of equivalent annualized costs for the 17 percent interest case at power costs of $0.055/Kwh, $0.035/Kwh and $0.075/Kwh plus all installed capital costs versus the process exit temperature is shown in Figures 2, 4, and 5, respectively. Maintenance costs were allocated based on the following: Pumps at 3 percent of capital installed cost, heat exchangers at 2 percent of the capital installed cost and the cooling tower at 1 percent of the capital installed cost.

From a process standpoint, water cooling has several advantages over air cooling. The process stream can be cooled to a lower temperature during the summer months and process temperatures can be controlled to closer tolerances with relatively simple controls. On the other hand, shell and tube exchangers are subject to scale and corrosion on the water side. This problem can be reduced or eliminated if process stream temperatures are kept below 200°F (or less with chlorides requiring stainless materials) and water treatment and blowdown are at adequate levels.

Air-cooled exchanger cost can be highly variable depending on the alloy and the degree of winterization and control. Winter operation of an air-cooled exchanger does not necessarily bypass the cooling water freeze up problem of the shell and tube exchangers. Air-cooled exchangers can become a major problem without the proper accessories and controls such as automatic louvers, auto-variable pitch fans, steam coils, and warm air recirculation. A major

4.0 Discussion (Continued)

advantage of air-cooled exchangers in most installations is that they do not require makeup water and blowing down. Since Tri-State will be disposing of its process water via cooling tower evaporation, this is not a 100 percent advantage in our case.

Table II lists the individual exchanger installed capital costs, cooling tower backup capital, cooling tower and pump operating costs, maintenance costs and power costs which were used to generate the capital and equivalent annualized costs (present worth) plotted in Figures 1, 2, 3, 4 and 5.

Inspection of the five sets of cost curves indicates that the pairs of curves do not intersect except on the 23 percent interest, \$0.055/Kwh curves of Figure 3 and on the 17 percent interest, \$0.035/Kwh curves of Figure 4. As illustrated by Figures 4 and 5, the relative position of the pairs of curves is sensitive to the cost of electric power and as power cost escalates, the air-cooled exchangers will look even more economical.

5.0 Recommendations

5.1 Based on the air and water temperature conditions applicable to the Tri-State site and the costs used in this study, air-cooled heat exchangers can be cost effective at cold end temperature approaches of slightly over 20° or 25°F above ambient air temperature. A crossover point occured only on the 23 percent interest, \$0.055/Kwh curve at approximately 115°F and on the 17 percent interest, \$0.035/Kwh curve at approximately 115°F. The 12 percent and 17 percent curves do not intersect but may be presumed to cross at less than 115°F.

5.2 In Tri-State's facility, biotreated gas liquor will be disposed of by evaporation in cooling towers. This restriction will establish a limit on the precentage of air cooling which may be employed. The design of the plant is not sufficiently established at this time to determine this limit.

5.3 There can be no hard and fast rule as to where to use an air-cooled rather than water-cooled exchanger. Each system must be examined from the standpoint of process conditions, metallurgy, cooling water contamination and, most important of all, the available space.

5.0 Recommendations (Continued)

5.4 This study indicates that there is an economic incentive for air-cooled exchangers down to a 25°F approach range in carbon steel construction and, with moderate winterization for the exchangers used in this study, the economic transition temperature is approximately 115°F. Alloy construction and more elaborate winterization or control will tend to increase the crossover temperature to a modest extent. Where this is required, however, the guidelines and the annualized operating costs developed in this study can be applied to other cases to analyze the economic breakpoint between air and water cooling.

Table I

Energy Usage

Water Cooled Exchangers

Exchanger	Duty BTU/HR	Process Exit °F	Cooling Water GPM
Ea. 1	235,600,000	255	18,840
2	274,900,000	200	21,990
3	303,900,000	145	24,312
4	317,600,000	115	25,408

Pumping hp @ 65 PSIG: 45.61 hp/1000 GPM

Cooling Water Pump hp		3.6488 hp/MMBTU/Hr
Fan hp		1.2488 hp/MMBTU/Hr
	Total	4.8976 hp/MMBTU/Hr

Air Cooled Exchangers

MEA	Duty BTU/HR	Process Exit °F	HP/MMBTU/HR
1	235,600,000	255	1.0781
2	274,900,000	200	1.2368
3	303,900,000	145	1.5630
4	317,600,000	115	2.0088

Ratio of Air To Water Energy Usage

MEA/EA	Energy Ratio
1	.22
2	.25
3	.32
4	.41

Table II

Installed Capital Cost (ICC) and Annual Costs

Water Cooled Exchangers

EA	Exchanger ICC	GPM	CT Backup Capital @ $32.93/GPM	Total ICC
1	434,265	18,840	620,041	1,054,306
2	677,580	21,990	724,163	1,401,743
3	882,013	24,312	800,594	1,680,607
4	1,214,000	25,408	836,685	2,050,685

Cooling Tower and Pump Operating Costs

($ per year/1000 GPM)

	Power @ $0.035/Kwh	Power @ $0.055/Kwh	Power @ $0.075/Kwh
Chemicals	4,094.92	4,094.92	4,094.92
Operators	107.81	107.81	107.81
Maintenance	429.00	429.00	429.00
Power	14,022.44	22,035.53	30,048.00
	18,654.17	26,667.26	34,679.73
Round Off To	18.654 per yr/GPM	26.67 per yr/GPM	34.68 per yr/GPM

Total Annual Operating Costs

(Power at $0.055/Kwh)

EA	Exchanger Maintenance @ 2%	CT & Pumps	Total Annual Costs
1	8,685	502,462	511,147
2	13,552	586,473	600,025
3	17,640	648,401	666,041
4	24,280	677,631	701,911

Air Cooled Exchangers

MEA	Exchanger ICC	Annual Maintenance @ 2%	Annual Power Cost(1)	Total Annual Cost
1	1,681,714	33,634	91,424	125,058
2	2,135,258	42,705	122,380	165,085
3	2,810,811	56,216	170,792	227,006
4	3,592,000	71,840	229,641	30[illegible],481

(1) Based on $359.94/hp for a 340 day year.

TABLE III

PRESENT WORTH CALCULATION

(Power at $0.055/Kwh)

Water Cooled Exchangers

EA	Total Annual Cost	Present Worth 12% (1)	Present Worth 17% (2)	Present Worth 23% (3)
1	511,147	4,008,977	2,947.376	2,209,790
2	600,025	4,706,056	3,459,864	2,594,028
3	666,041	5,223,826	3,840,525	2,879,428
4	701,911	5,505,158	4,047,359	3,034,501

EA	Total ICC (4)	ICC+ 12% P. W.	ICC+ 17% P. W.	ICC + 23% P. W.
1	1,054,306	5,063.283	4,001,682	3.264,096
2	1,401,743	6,107,799	4,861,607	3,995,771
3	1,680,607	6,906,433	5,523,132	4,562,035
4	2,050,685	7,555,843	6,098,044	5,085,186

Air Cooled Exchangers

MEA	Total Annual Cost	Present Worth 12% (1)	Present Worth 17% (2)	Present Worth 23% (3)
1	125,058	980,842	721,109	540,751
2	165,855	1,294,778	951,913	713,695
3	227,006	1,780,431	1,308,962	981,392
4	301,481	2,364,546	1,738,400	1,303,363

MEA	Total ICC	ICC + 12% P. W.	ICC + 17% P. W.	ICC + 23% P. W.
1	1,681,714	2,662,556	2,402,823	2,222,465
2	2,135,258	3,430,036	3,087,171	2,848,953
3	2,810,811	4,591,242	4,119,773	3,792,203
4	3,592,000	5,956,540	5,330,400	4,895,363

(1) PWF for 12% and 25 years = 7.8431
(2) PWF for 17% and 25 years = 5.7662
(3) PWF for 23% and 25 years = 4.3232
(4) Includes Cooling Tower Backup Capital

TABLE IV

Sensitivity to Power Costs

(Cost of Capital at 17%)

Water Cooled Exchangers

	Power at $0.035/Kwh		Power at $0.075/Kwh	
EA	Total Annual Cost	Present Worth (17%)	Total Annual Cost	Present Worth (17%)
1	360,126	2,076,559	662,056	3,817,548
2	423,753	2,443,447	776,165	4,475,522
3	471,118	2,716,564	860,780	4,963,430
4	498,241	2,872,956	905,429	5,220,887

EA	Total ICC	ICC+Present Worth (Powr @ $0.035)	ICC+Present Worth (Power @ $0.075)
1	1,054,306	3,130,864	4,871,854
2	1,401,743	3,845,190	5,877,265
3	1,680,607	4,397,172	6,644,037
4	2,050,685	4,923,641	7,271,572

Air Cooled Exchangers

	Power at $0.035/Kwh		Power at $ 0.075/Kwh	
MEA	Total Annual Cost ($229.00/hp)	Present Worth (17%)	Total Annual Cost ($490.00/hp)	Present Worth (17%)
1	91,800	529,337	158,302	912,800
2	120,565	695,201	209,583	1,208,497
3	164,989	951,359	289,353	1,668,467
4	217,942	1,256,697	384,983	2,219,888

MEA	Total ICC	ICC+Present Worth (Power @ $0.035)	ICC+Present Worth (Power @ $0.075)
1	1,681,714	2,211,051	2,594,514
2	2,135,258	2,830,459	3,343,755
3	2,810,811	3,762,170	4,479,278
4	3,592,000	4,848,697	5,811,888

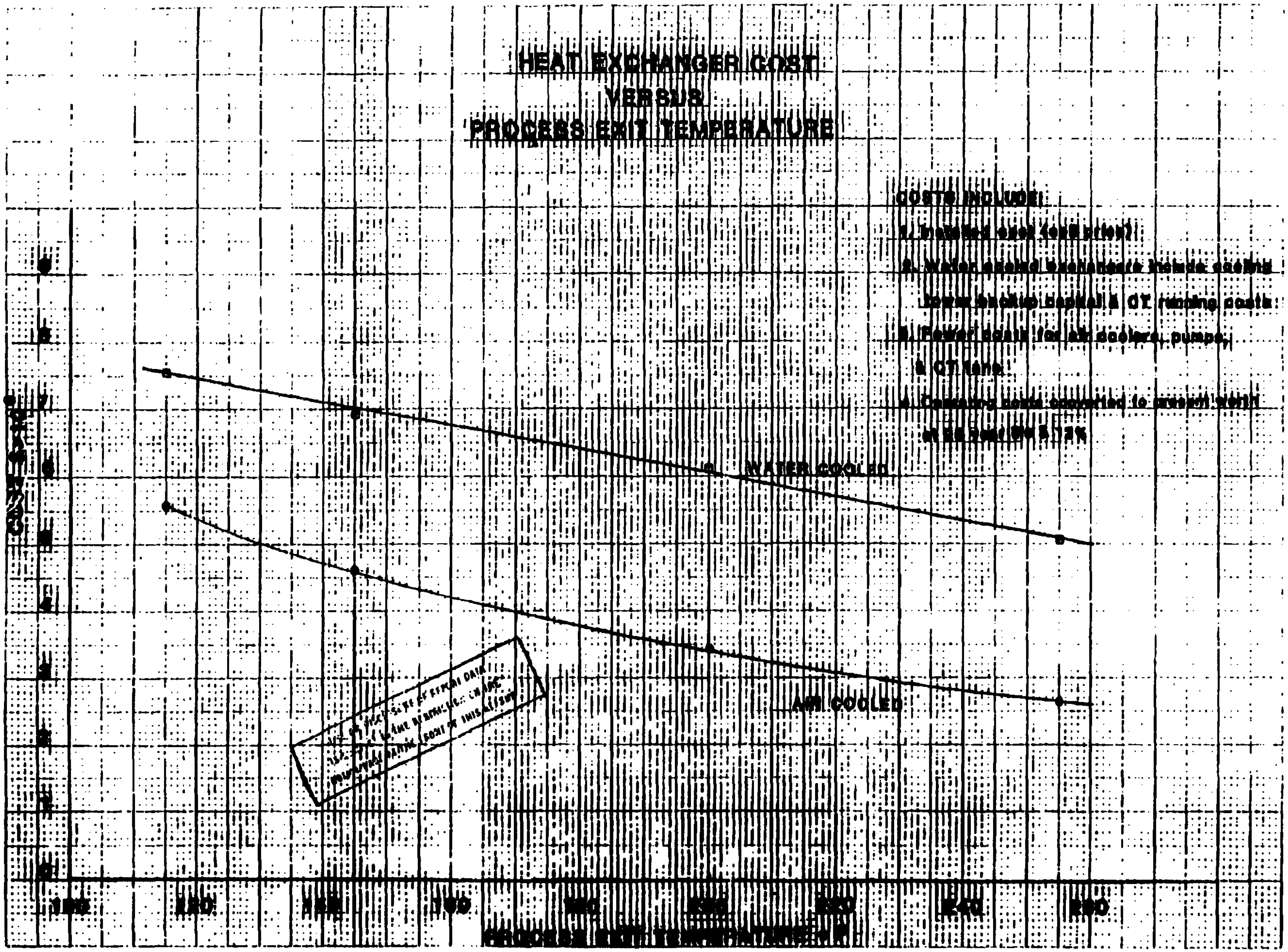

HEAT EXCHANGER COST
VERSUS
PROCESS EXIT TEMPERATURE
COSTS INCLUDE:
WATER COOLED
AIR COOLED

FIGURE 1

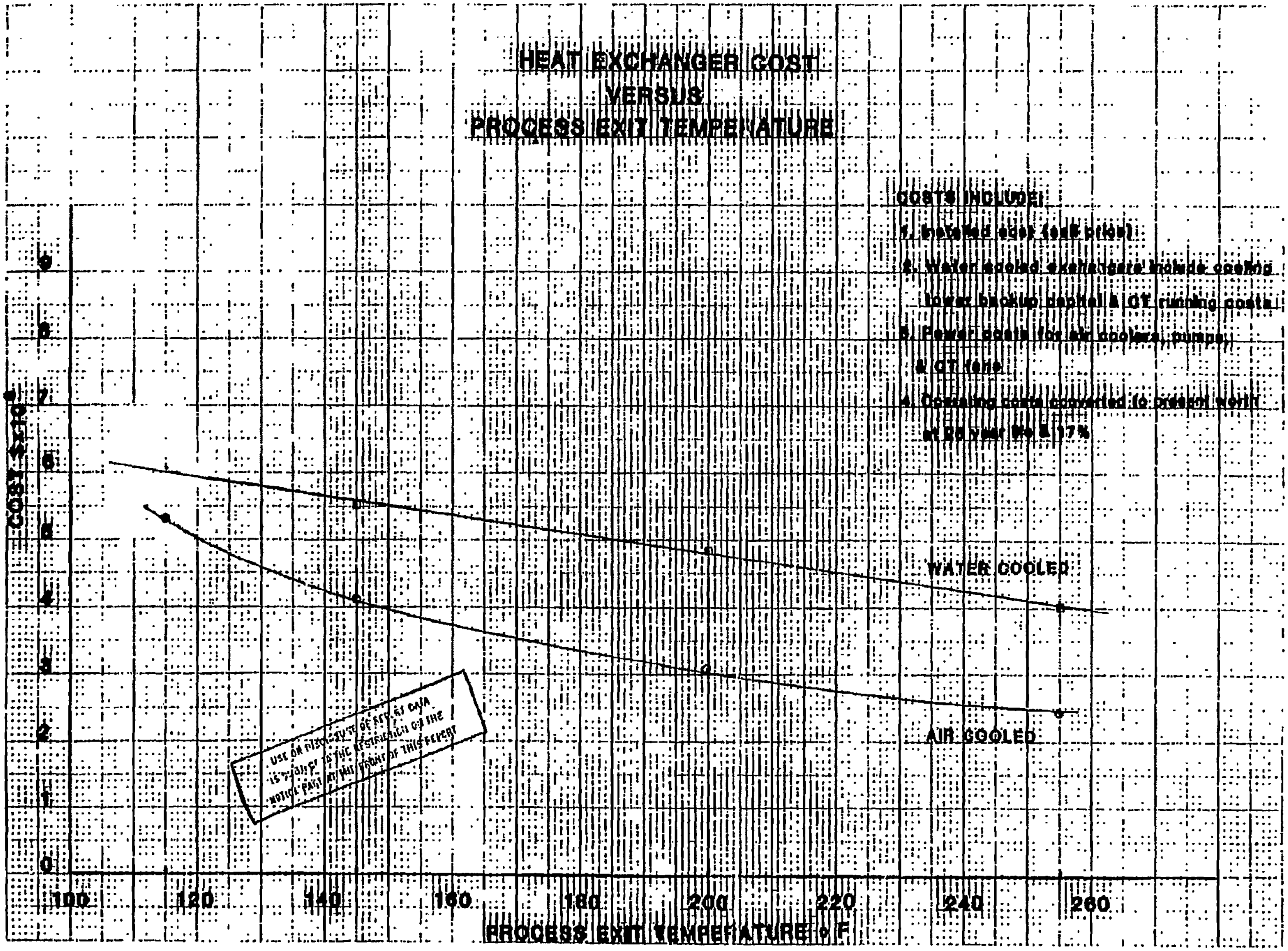
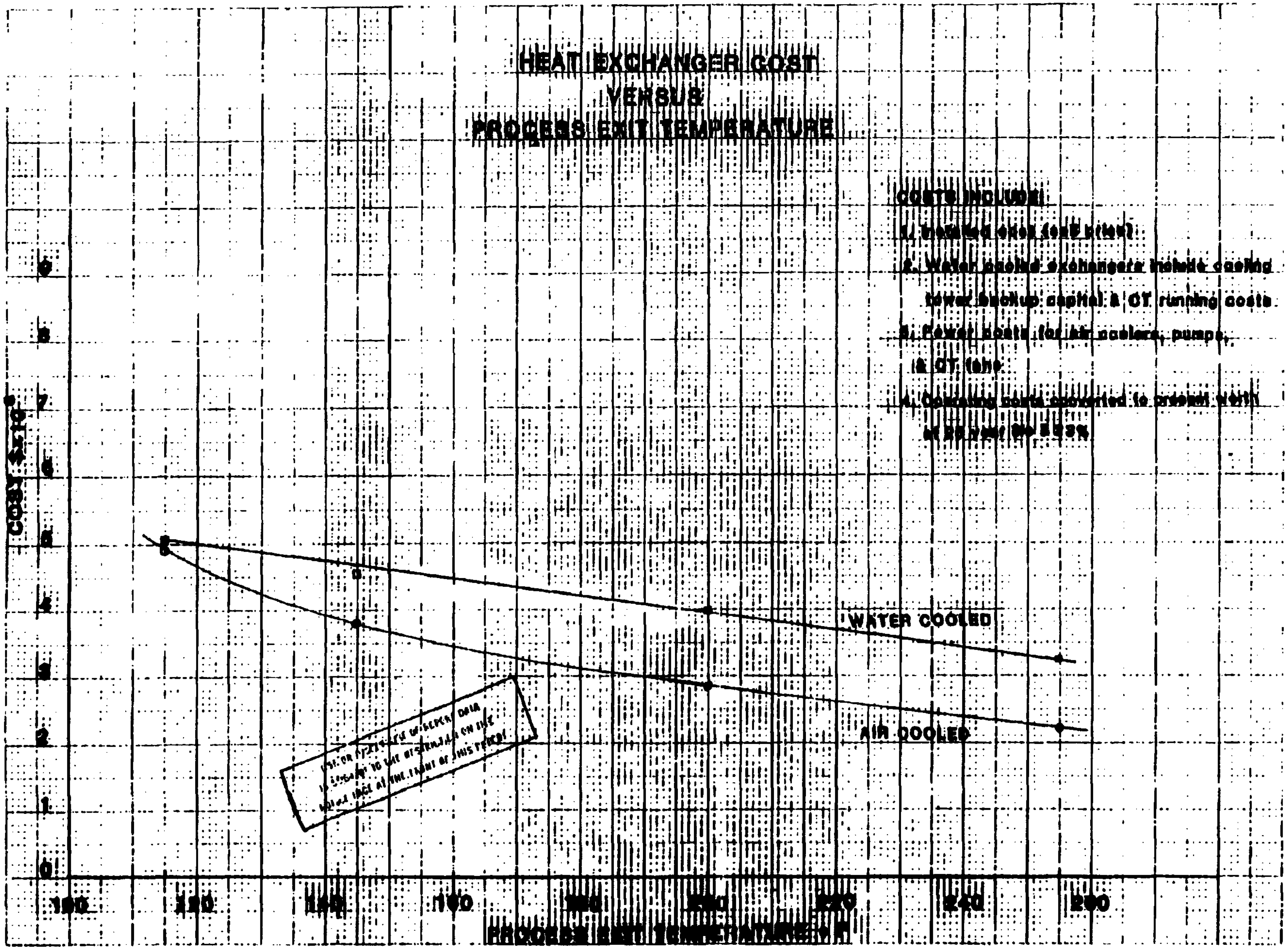

HEAT EXCHANGER COST
VERSUS
PROCESS EXIT TEMPERATURE
COSTS INCLUDE:
tower backup capital & CT running costs
& CT fans
WATER COOLED
AIR COOLED
COST
0
1
2
3
4
5
6
7
8
9
100
120
140
160
180
200
220
240
260
PROCESS EXIT TEMPERATURE °F

FIGURE 2


HEAT EXCHANGER COST
VERSUS
PROCESS EXIT TEMPERATURE
COSTS INCLUDE:
2. Water cooled exchangers include cooling
tower backup capital & CT running costs
3. Power costs for air coolers, pumps,
& CT fans
4. Operating costs converted to present worth
WATER COOLED
AIR COOLED
0
1
2
3
4
5
6
7
8
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100
120
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160
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240
260

FIGURE 8

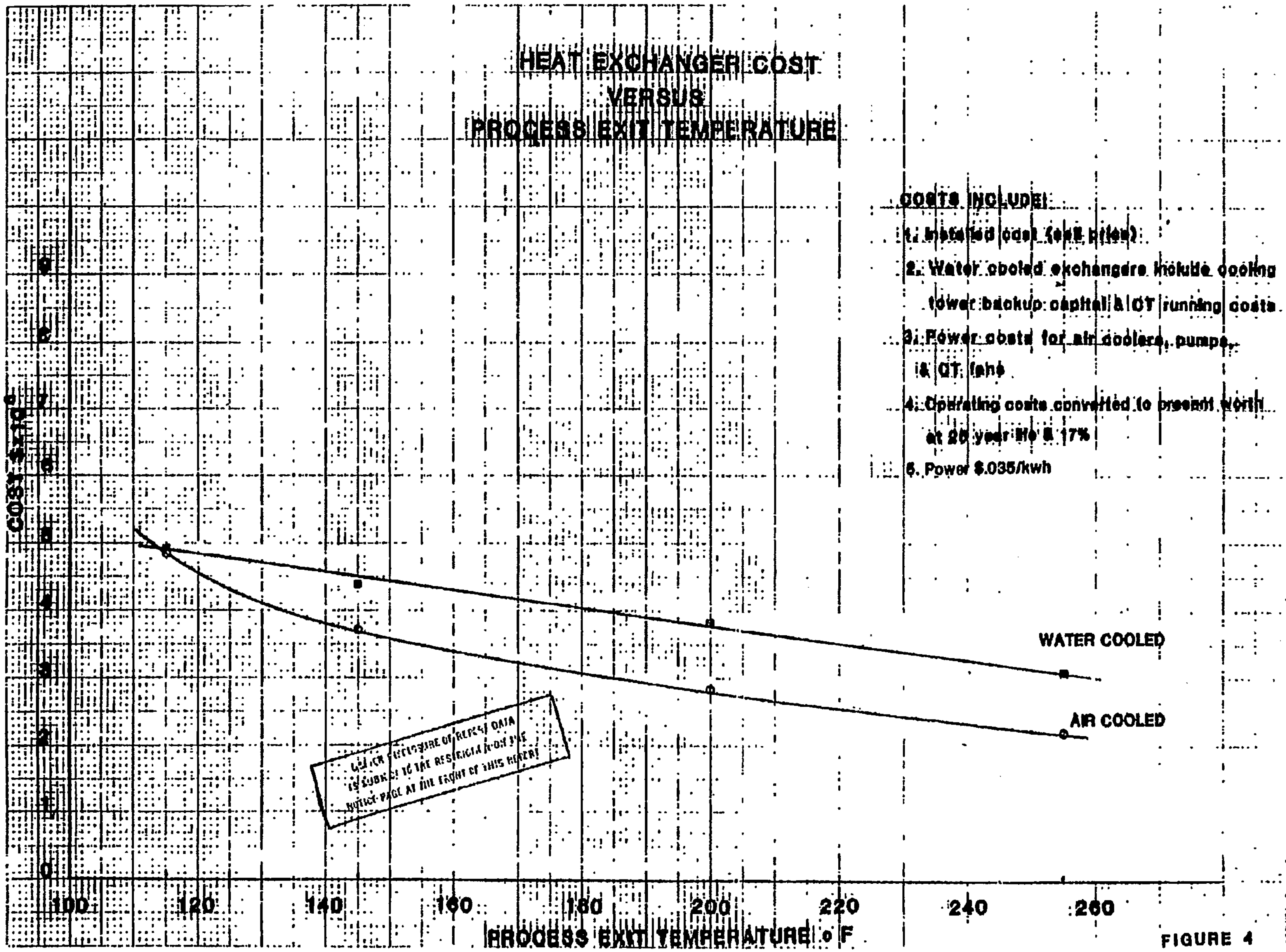
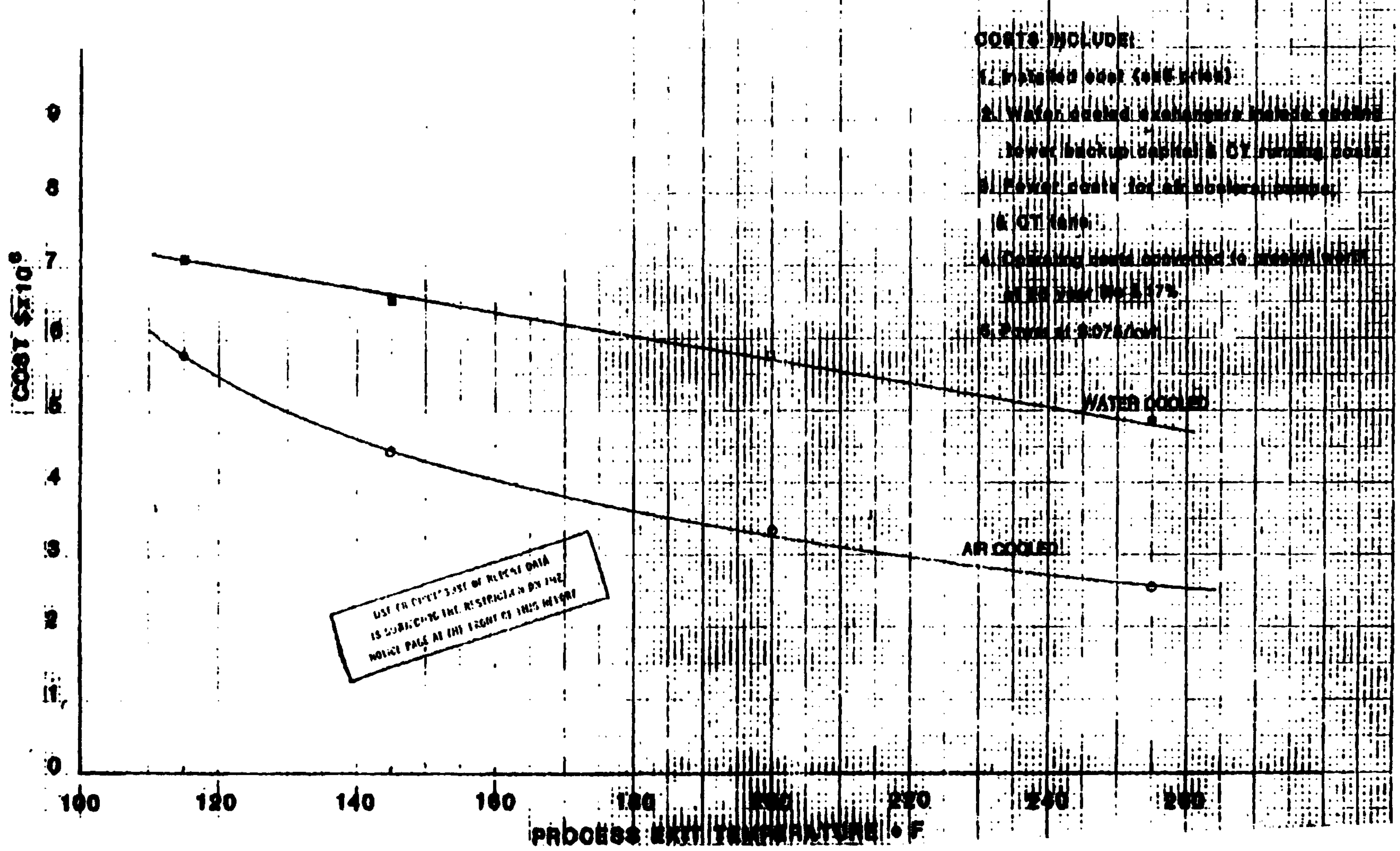

HEAT EXCHANGER COST
VERSUS
PROCESS EXIT TEMPERATURE
COSTS INCLUDE:
1. Installed cost (sell price)
2. Water cooled exchangers include cooling tower backup capital & CT running costs.
3. Power costs for air coolers, pumps, & CT fans
4. Operating costs converted to present worth at 20 year life & 17%
5. Power $.035/kwh
WATER COOLED
AIR COOLED
COST $x10
0
1
2
3
4
5
6
7
8
9
100
120
140
160
180
200
220
240
260
PROCESS EXIT TEMPERATURE o F

FIGURE 4

HEAT EXCHANGER COST VERSUS PROCESS EXIT TEMPERATURE



APPENDIX 1

PROCESS DEVELOPMENT STUDY NO. 5

AIR/WATER COOLING BREAKPOINT

SCOPE OF STUDY

PROCESS STUDY
BREAK POINT BETWEEN AIR AND WATER COOLING SYSTEM

1.0 GENERAL

This study will determine the economic transition temperature to change from air cooled exchangers to water cooled heat exchangers.

2.0 WORK DEFINITION

2.1 Develop typical data sheet, for several heat exchangers. Have mechanical engineering estimate the equipment cost as an air cooled exchanger and as a water cooled exchanger.

2.2 Have estimating determine the sell price for each of the installed exchangers.

2.3 Plot the curves of exchanger cost vs. temp. for both cooling media.

2.4 From the curve determine the break point.

3.0 DELIVERABLE TO TRI-STATE

A formal report that contains the following:

3.1 Curves of exchanger installed cost. vs. process fluid temperature and show the break point.

4.0 SCHEDULE

It is estimated that the above work will be completed 4 weeks after the work is started by Fluor.