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OPEN-CYCLE HEAT PUMPS FOR INDUSTRIAL WASTE-HEAT UTILIZATION

Project Technical Report: Phase I - Feasibility Study
May 12, 1980 through October 10, 1980

for

U.S. DEPARTMENT OF ENERGY
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
Subcontract No. 86X-24717C
Contract No. W-7405-eng-26

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by

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FOREWORD

This Phase I Technical Report, "Open-Cycle Heat Pumps for Industrial Waste Heat Utilization," was prepared by the Thermal and Fuel Sciences Branch, Mechanical Systems and Technology Laboratory, General Electric Research and Development Center in Schenectady, New York. The report describes work completed under Subcontract No. 86X-24717C to the Energy Division of Oak Ridge National Laboratory in Oak Ridge, TN and Contract NYSERDA/245-EUC-IU-80 to the New York State Energy Research and Development Authority. The work was completed during the period from May 12, 1980 to October 24, 1980.

Work on the program at General Electric was carried out under the direction of Heinz Jaster, Program Manager, Warren Bessler, who served as principal investigator through July 22, 1980, and Clarence R. Snyder, who is presently the principal investigator.

This report represents a team effort of General Electric Corporate Research and Development, Installation and Service Engineering Division, Energy Technology Operation, and Heat Transfer Products Operation.

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ABSTRACT

This report describes General Electric Corporate Research and Development efforts on the Open-Cycle Heat Pump for Industrial Waste Heat Utilization. Phase I of the contract provided for a feasibility study to evaluate sites for the demonstration of industrial process heat pump equipment. The five months of Phase I work, beginning May 12, 1980 and ending October 24, 1980 are presented in this report. Emphasis is placed on two sites providing applications that give an opportunity to exploit the features of an open-cycle industrial process heat pump. The components described herein are presently commercially available. These components, packaged in the novel approach described, can lead to widespread industrial application.

A study of four heat pump applications at three industrial sites was completed. Only one site provides for a cost-effective demonstration of the process. The Amstar facility was not chosen because of a cyclical plant operating schedule and a small waste water flow rate. The Schoeller Paper facility offered an opportunity for application, but more cost-effective means of energy utilization could be employed with more positive results. The NORYL[®] application provides for the best utilization of the concept.

[®] Registered trademark of the General Electric Company.

Section 1

INTRODUCTION

Open-Cycle Industrial Process Heat Pumps (IPHP) are potentially a cost-effective method of utilizing an industrial plant's waste heat. The objective of Phase I of the work was to determine the feasibility of an open-cycle industrial process heat pump. This was accomplished by the evaluation of four potential sites for the installation of open-cycle industrial process heat pump equipment.

Efforts during the five months of the contract concentrated on the four IPHP applications. While it was the original plan to evaluate only three sites, the need for a fourth site became apparent upon completion of studies of the Amstar applications. On the basis of initial screening, it was decided to concentrate on the large waste stream at General Electric's NORYL facility (Selkirk, NY) and a smaller waste stream at the Schoeller Paper Company (Pulaski, NY). These two sites provided opportunities to exploit the features of the open-cycle IPHP without major site constraints.

Site studies were conducted to obtain process information such as flow rates, process temperatures, dynamic behavior of the process streams, process control functions, and capacity/time schedules. Information relating to structure and utilities, floor loadings, physical space constraints, electric service, piping runs between equipment location, and waste water tapping points was gathered. These data were analyzed and resulted in the selection of two applications with acceptable thermodynamic performance.

All sites were evaluated on the same basis. The recommendations are based upon the criterion that a demonstration must provide a test of the technology and/or promise to prove the economic merit of the system.

Section 2

PROCESS DESCRIPTION

The industrial process heat pump is shown schematically in Figure 2.1. Numbers on the schematic diagram correspond to states shown on the temperature-enthalpy diagram of Figure 2.2. The waste water stream (1) at temperature T_1 enters a throttling control valve which decreases the pressure of the water. The water leaving the control valve (2) is below the saturation pressure for the temperature T_1 and therefore exits as a two-phase mixture. This two-phase mixture enters a flash chamber which is maintained at a low pressure by the suction of the compressor. The flash chamber separates the liquid portion (3) of the waste stream from the steam portion (4) by gravity. Typically, 1-3% by mass of the incoming flow will be flashed to steam while the remaining liquid is pumped back into the waste water system. The discharge liquid is of a lower temperature than the liquid before flashing, since the liquid's sensible heat is the source of the latent heat of the steam which is produced in the flashing process. Saturated steam (4) enters the compressor where it is compressed to a higher pressure; the steam may now be used for process heating. In this report, we discuss only those industrial process heat pumps which produce steam from liquid water. However, the process physics are generally true for all fluid systems. In fact, we expect industrial applications for which the heat pump fluid is a fluid other than water.

Figure 2.1 Open-Cycle Industrial Process Heat Pump

Figure 2.2 Temperature-Enthalpy Diagram of an Open-Cycle Vapor Compression Heat Pump

The coefficient of performance (COP) of a heat pump is defined as the ratio of heat delivered by the heat pump to the work supplied. Thus, in terms of Figure 2.2, the coefficient of performance is

$$\text{COP} = \frac{\text{heat delivered}}{\text{work supplied}} = \frac{m_s (h_5 - h_1)}{m_s (h_5 - h_4) + W_p}$$

where

m_s = mass flow rate of steam

W_p = pump work

h_1 = inlet water enthalpy

h_5 = steam enthalpy at compressor outlet

h_4 = steam enthalpy at compressor inlet

Values of COP for IPHP applications under consideration are between 4 to 6. A COP of 5 means that 5 units of heat may be obtained by supplying 1 unit of work.

The basic vapor compression cycle may be modified to increase cycle efficiency. One effective modification consists of desuperheating between compressor stages. The efficiency advantage is due to lower compressor power requirements for lower inlet vapor temperature. Desuperheating between stages lowers vapor intake temperatures for successive compression.

Section 3

SITE STUDIES

3.1 AMSTAR: SITE 1

The Amstar Sugar Refinery in Brooklyn, New York offers two potential IPHP applications. The first is a sugar liquor evaporator (Figure 3.1) and the second is a cooling water waste stream (Figure 3.2).

Figure 3.1 Amstar Sugar Plant Sugar Liquor Evaporator

Figure 3.2 Amstar Sugar Plant Waste Stream Alternative

The sugar liquor evaporator application as an integral part of the quadruple effect evaporator has the potential of saving 2.4 MBtu/hr with an annual energy cost savings of \$38,000. The industrial process heat pump (IPHP) would produce 3000 lb/hr of 233 °F steam for process requirements.

The temperatures of each effect are provided in Figure 3.1 and indicate typical temperatures occurring within this process. Discussions with representatives of Amstar indicated that weight loading and space restrictions would not permit installation of IPHP

equipment. Representatives of Amstar and General Electric concurred that further study of this application should be terminated.

3.2 AMSTAR: SITE 2

The second potential application at Amstar is the use of a cooling water waste stream. This location would permit installation of the IPHP equipment. As shown in Figure 3.2, the cooling water stream from barometric condensers usually yields 120 to 160 °F waste water, which is presently dumped into city sewers at a substantial cost to Amstar.

Normal operation of the barometric condensers would yield a waste stream of 160 °F water at a flow rate of 168 gpm.

However, temperature variations from 110 to 160 °F and process flow variations from 82 to 229 gpm have been noted. Figure 3.3 illustrates this variation in a 24-hour period. Operation of this waste stream is presently restricted to 3900 hr/yr on a three day per week schedule.

Figure 3.3 Waste Stream Temperature Variation During a 24-Hour Period at the Amstar Sugar Refinery

This application is not considered technically or economically feasible due to the large temperature variations and the few operating hours. The temperature variation of the waste stream would necessitate a complex controller and a further reduction in operating hours. The present operating schedule would complicate equipment startup and reduce the open-cycle IPHP's economic attractiveness.

3.3 NORYL®: SITE 3

The General Electric Company's NORYL Product Department located in Selkirk, NY is a large, modern, chemical plant manufacturing engineered plastic products. Within the plant, a very large water cooling system is used to maintain process temperatures. This tempered water circulates throughout a major portion of the facility.

The tempered water loop is shown in Figure 3.4. Within the system, 5000 gpm of water flow sustains process temperature requirements. Return water is maintained at a temperature of 170 °F. This stream is then cooled by banks of fin-fan heat exchanger units. The open-cycle IPHP can utilize a portion of the available energy (which is presently discharged to the atmosphere) to provide a substantial quantity of process steam. The modified system is shown in Figure 3.5.

Figure 3.4 NORYL Tempered Water Loop

Figure 3.5 NORYL Tempered Water Loop Heat Recovery

System parameters for a heat pump application utilizing the NORYL tempered water loop are outlined in Tables 3.1 and 3.2. IPHP design parameters are also detailed in Table 3.2. The proposed system flashes 1.0% of the 170 °F waste stream to provide a steam flow of 25,127 lb/hr. This flashed steam will exist at a temperature of 160 °F (saturated) as it enters the compressor. This system is anticipated to be equipped with a variable speed motor to permit load following capability.

Table 3.1
PARAMETERS USED TO MODEL NORYL APPLICATION

<u>General Data</u>	
Hours of Operation per Year	8,000
Electricity Cost (\$/kWh)	0.035
<u>Boiler</u>	
Fuel Oil Cost (\$/gal)	0.62
Heating Value (Btu/gal)	145,000
Boiler Efficiency	85%
Inlet Water Temperature (°F)	170

The compressor would provide 50 psia steam which would feed a header for various steam requirements, thus reducing conventional boiler requirements. The system coefficient of performance would be 4.4.

The open-cycle industrial process heat pump control system can be integrated with the plant control system. System design will allow for variations in process conditions. Balance of plant steam piping will be insulated to ensure minimum energy losses. With the equipment on its own foundation, accessibility for testing and maintenance would not be limited or restricted.

3.4 SCHOELLER: SITE 4

Schoeller Technical Papers, Inc., Pulaski, New York was visited on August 6, 1980 as another alternative application site.

The Schoeller plant is a paper processing plant located north of Syracuse, New York. Schoeller's representative and plant engineer Charles W. Osburn, provided all information necessary to complete our study. Mr. Osburn has also stated his willingness to work with us on the continuation of the contract.

The plant discharges 35,000 lb/hr of water condensate from three paper dryers along with other condensate returns. This waste stream is pumped to a tank referred to as a hot well; waste stream with temperatures of 190 to 195 °F is discharged. The-open cycle industrial process heat pump arrangement would flash approximately 3.5% of the waste stream and convert that to 7 psig steam. Within the plant and in close proximity to the proposed location of the IPHP, a 7 psig steam header is available.

Table 3.2
IPHP DESIGN FOR NORYL APPLICATION

<i>Compressor</i>		
2-body, 3-stage each, Centrifugal, Variable Speed		
Isentropic Stage Efficiency		80%
Pressure Ratio		10.5
Volumetric Flow, Inlet (Cfm)	32,343	
Water Injection Between Bodies (lbm/hr)	3,078	
Normal Compressor Power (kW)	1970	
Normal Compressor Speed (rpm)	8,300	
Weight (lbm)	70,000	
<i>System</i>		
Gear Efficiency		98%
Normal Motor Efficiency		98%
Water Discharge Pump (kW)	34	
Total Water Flow (gpm)	5,000	
Flash 1% (lbm/hr)	25,127	
Compressor Heat Losses (Btu/hr)	200,000	
<i>States</i>		
	<u>P(psia)</u>	<u>T(°F)</u>
Inlet to Throttle	54.0	170
Flash Tank	4.75	160
Discharge	50.0	410
<i>Performance</i>		
Normal Net Heat Generation (MBtu/hr)	30.88	
Normal Gross Power Requirement (kW)	2,086	
Normal Coefficient of Performance	4.4	
Normal Steam Delivery (lbm/hr)	28,205	

Figure 3.6 provides a schematic view of the proposed arrangement. Tables 3.3 and 3.4 provide system specifications. The system would deliver 1052 lbm/hr of steam at a COP of 5.9.

The cost of fuel and electricity at Schoeller follows the New York State figures which are shown in Section 7. Fifty-five cents per gallon fuel oil and three and one-half cents per kilowatt hour electricity provides a saving in energy cost each year the IPHP is in service. The plant is run at near-continuous duty.

The basement location provides space between the second and third dryers for adequate installation space. Floor loading for the 16,000 lb compressor skid and flash tank presents no problem. There would be a requirement for support pads to be poured for installation. This is normal practice for mounting of high-speed machinery. This area is close to condensate return lines and steam headers, and would provide ease of installation and ample space for future maintenance.

Figure 3.6 Schoeller Process with Industrial Process Heat Pump

Table 3.3
PARAMETERS USED TO MODEL SCHOELLER APPLICATION

<i>General Data</i>	
Hours of Operation per Year	8,000
Electricity Cost (\$/kWh)	0.035
<i>Boiler</i>	
Fuel Oil Cost (\$/gal)	0.55
Heating Value (Btu/gal)	145,000
Boiler Efficiency	80%
Inlet Water Temperature (°F)	70

The location of the IPHP equipment is easily reached. The Schoeller application, because it is small, has the advantage that the equipment can be tested in both laboratory and field environments.

The Materials and Process Laboratory at the Heat Transfer Products Operation in South Portland, Maine offers the opportunity to test the flash tank and compressor train at full load. The sophisticated test arrangement could provide important data on the complete system. Successful laboratory testing could then lead to accelerated field installation and ease of startup. The Schoeller site would provide sufficient space for testing during the startup phase.

Table 3.4
IPHP DESIGN FOR SCHOELLER APPLICATION

<i>Compressor</i>		
9-Stage, Centrifugal		
Isentropic Stage Efficiency		74%
Pressure Ratio		4.6
Volumetric Flow, Inlet (cfm)		1354
Compressor Power (kW)		52.7
Compressor Speed (rpm)		18,100
Weight (lbm)		14,500
<i>System</i>		
Gear Efficiency		95%
Motor Efficiency		96%
Water Discharge Pump (kW)		1.2
Total Water Flow (gpm)		70
Flash 3.5% (lbm/hr)		1,052
Compressor Heat Losses (Btu/hr)		20,000
<i>States</i>		
	<u>P (psia)</u>	<u>T (°F)</u>
Inlet to Throttle	10.4	195
Flash Tank	4.75	160
Discharge	21.7	490
<i>Performance</i>		
Net Heat Generation (MBtu/hr)		1.18
Gross Power Requirements (kW)		59.0
Coefficient of Performance		5.9
Steam Delivery (lbm/hr)		1052

Section 4

COST ESTIMATES

4.1 BALANCE OF PLANT

Preliminary estimates for completing balance of plant work at the two viable sites were collected. The balance of plant design was split into three categories:

- 1) Structural and Foundational
- 2) Mechanical
- 3) Electrical

Structural and foundational considerations include shelter and environmental protection for the equipment and instrumentation, and a concrete pad for installation of equipment. Mechanical design includes valves, water and steam piping, and insulation. Electrical considerations include wiring, cable, and transformers.

A detailed estimate for the balance of plant work at the NORYL Plastics facility in Selkirk, NY is given in Table 4.1. The IPHP will be located outdoors and away from major manufacturing facilities. A concrete pad with pilings and a shelter to protect the equipment will be constructed. As a result of its remote location, long piping and cable runs have been included in the balance of plant cost estimate. The total estimated cost of the IPHP balance of plant work at NORYL Plastics is \$1,033,000.

Table 4.2 contains a detailed cost estimate for balance of plant work at the Schoeller Paper Company plant in Pulaski, N.Y. The Schoeller Paper Company can provide a basement location for the IPHP. Structural and foundational work at this site is minimal and has been combined with mechanical design work. The longest piping run encountered at this site is 100 feet. Electrical requirements for this site are also detailed in Table 4.2. The total estimated balance of plant work at the Schoeller Paper Company is \$108,000.

Estimates for the balance of plant work were based on engineering sketches and day-long visits to each of the two viable sites. Therefore, these estimates are preliminary in nature with more detailed work required under Phase II of the contract.

4.2 SYSTEM COST

Most component cost estimates for the NORYL and Schoeller industrial process heat pumps were obtained from vendors. Costs of components which could not be rigorously specified before a detailed design is generated were estimated in house (e.g., control systems and expansion valves). Tables 4.3 and 4.4 give installed system and component cost estimates for the NORYL and Schoeller heat pumps, respectively.

Table 4.1
BALANCE OF PLANT COST ESTIMATE
IPHP Demonstration – NORYL Plastics, Selkirk, N.Y.

Cost Estimate – Fall, 1980 Pricing		Cost Including Subcontractor OH
<hr/>		
A. Structural, Foundation		
(Including Weather Protection and Pipe Rack Extension)		
1.	Piling	\$ 48,000
2.	Concrete (including excavation)	15,200
3.	Reinforcing Steel	2,300
4.	Structural Steel	16,600
5.	Metal Roofing	4,300
6.	Metal Siding	7,900
7.	Doors	800
8.	Louvers	1,700
9.	Ridge Vents	1,100
10.	Floor Drain	200
11.	6" ϕ Drain Pipe	400
12.	Lighting	1,300
	Subtotal	\$ 99,800
<hr/>		
B. Mechanical		
(Valves, Insulation, etc. included)		
1.	Water Lines - 12" ϕ Supply & Return	\$ 226,300
2.	Steam Output Line - 10" ϕ	143,800
3.	Steam Tracing (safety for dead end & pump protection)	18,000
4.	Condensate Return Line	4,600
5.	Cooling Supply & Return Lines	8,900
6.	Insulated Carrier	7,000
7.	Condensate Return Unit, Pumps, etc.	3,600
8.	Oil, Local Piping	600
9.	Dual Water Pumps - 5000 gpm each, 120 ft. HD., 50 HP Drives (including motors)	49,300
10.	Flash Tank Sight Gage, Level Controllers Expansion Joint, 24" Pipe, etc.	37,900
11.	Rigging, Setup	10,100
	Subtotal	\$ 510,900
<hr/>		

Table 4.1 (Continued)

Cost Estimate — Fall, 1980 Pricing	Cost Including Subcontractor OH
<hr/>	
C. Electrical	
(From Main Substation Breaker)	
1. Rigid Galvanized Steel	\$ 30,000
2. 15 kV Cable	27,600
3. 3500 HP Driver Wiring	20,300
4. Auxiliary Transformer — 750 kVA	26,800
5. 480 VAC Wiring	19,400
6. Uninterruptible Power Supply	7,600
Subtotal	\$ 131,700
<hr/>	
Summary	
A. Structural, Foundation	\$ 99,800
B. Mechanical	510,900
C. Electrical	131,700
Subtotal	\$ 742,400
<hr/>	
General Contractor's Fee (10%)	74,200
	\$ 816,600
Engineering, Design (Est. 15%)	122,500
	\$ 939,100
Contingency, 10%	93,900
GRAND TOTAL	\$1,033,000
<hr/>	

Table 4.2

BALANCE OF PLANT COST ESTIMATE

IPHP Demonstration - Schoeller Co., Pulaski, N.Y.

Cost Estimate — Fall, 1980 Pricing		Cost
A. Mechanical, Structural		
1.	Concrete Pad(s) with Anchoring	\$ 2,704
2.	Source Water Supply, Return - 4"	10,543
3.	Steam Output Header - 2"	4,112
4.	Cooling Lines - (2) 1"	1,296
5.	Miscellaneous Piping	250
6.	Dual Water Pumps - 100 gpm each, 125' Hd	4,035
7.	Flash Tank, Ftgs. Insulation, etc. - 1000 gallons includes sight gage, controllers 12" expansion joint, 12" piping	12,732
8.	Rigging, Setup	6,013
	Subtotal	\$41,685
B. Electrical		
1.	Breaker for Substation Panel	\$ 899
2.	Cable, Conduit	6,727
3.	New Motor Control Center	8,507
4.	Motor Connections	615
5.	Supply to Services, including XFMR	808
		\$17,556
Summary		
A.	Structural, Mechanical	\$41,685
B.	Electrical	17,556
		\$59,241
	General Contractor's Fee (15%)	8,886
	Estimated Engineering, Design	30,000
		\$98,127
	Contingency (10%)	9,813
	GRAND TOTAL	\$108,000

Table 4.3
COST ESTIMATE – NORYL SYSTEM

Item	\$ Thousands
Compressor System	1,000
Steam Seal Piping (Installed)	100
Gear/Motor Coupling	16
Variable Speed Motor System	418
Machine Base	45
Flash Tank	100
Intercooler/Desuperheater	10
Desuperheater Pump	1
Variable Orifice Expansion Valve	7
Control System	46
Subtotal	1,743
Contingency 10%	174
Balance of Plant	1,033
Total	2,950

Table 4.4
COST ESTIMATE – SCHOELLER SYSTEM

Item	\$ Thousands
Compressor System	320
Motor System	8
Flash Tank	8
Variable Orifice Expansion Valve	2
Control System	10
Subtotal	348
Contingency 10%	35
Balance of Plant	108
Total	491

Section 5

COMPONENTS

5.1 COMPRESSOR

Several compressor manufacturers were contacted for use of their equipment in the IPHP system. Those responding to specific design criteria included Nuovo Pignone, Inc., Sulzer Brothers Company, Allis-Chalmers Company, and DeLaval, Inc.

Details of the compressor design for the 1052 lb/hr Schoeller Paper Company application are given in Table 3.4. The pressure ratio across the compressor is 4.6 and the motor requires 59 kW at rated conditions. The compressor outlet temperature (490 °F) is superheated by 259 °F.

The compressor design and performance specifications for the NORYL facility are given in Table 3.2. The design consists of two separate compressor casings. The compressed steam from the first casing is desuperheated by water sprays (see Section 5.4) in the connecting pipe between the two casings. The pressure ratio for this compressor arrangement is 10.5 and requires 3078 lb/hr of water for desuperheating between the casings. The compressor discharges 28,205 lb/hr of steam at 410 °F (corresponding to a 129 °F superheat) and requires 2010 kW input at the motor coupling. A similar compressor designed without steam desuperheating would require 2204 kW at the motor coupling and would discharge 25,127 lb/hr at 760 °F. Interstage desuperheating, therefore, not only improves system efficiency, but also permits lower temperature compressor operation and therefore a relatively inexpensive compressor.

Plant operation is significantly dependent upon load-following capability of the steam supply system. For this reason, a motor system is specified which is capable of operating at speeds between 0 and 1900 rpm. Steady-state compressor rotor speeds are proposed to vary from 6500 to 9100 rpm, with a normal speed of 8300 rpm.

5.2 FLASH EVAPORATOR

All system performance estimates which were made in this report assume that waste water flashing results in completely separated phases within the flash tank, and that these phases are at thermodynamic equilibrium with each other. These assumptions cannot hold exactly. For one, the flashing process (here intended to be violent, across a variable opening, sharp-faced orifice) is a heat transfer process; that is, finite temperature differences are necessary to transfer heat from one phase (liquid) to the other (vapor). For another, the violence of flashing and the relatively brief residence period of the fluid within the flash tank should cause some liquid droplet carry-over into the compressor inlet.

Non-attainment of thermodynamic equilibrium after flashing will result in the discharge of superheated liquid. The consequence is that vapor generation, and therefore availability of vapor for compression, is reduced. For the NORYL case, for example, a 1 °F liquid superheat would result in a 10% vapor flow rate reduction.

Liquid droplet carry-over into the compressor can be a beneficial effect if droplets are sufficiently small so as not to cause erosion on the compressor impeller and if liquid mass fraction is less than 2%. Droplets will provide intercooling during compression, thus reducing compressor power requirements. For the compressor which is proposed to

operate the NORYL system, maximum droplet size to prevent erosion is approximately 30 μm .

Another flash tank process needs to be addressed before a rigorous system specification can be made. Since the flashing process produces lowered liquid temperatures, it may cause solids to precipitate from the waste liquid. Solids may also be present in industrial waste water streams in non-solute form. These solids must not be permitted to clog the flash tank, but rather, must be continuously purged via the exiting water stream. Proper shape design of the lower tank region (impose swirl) should provide for effective purging.

The most critical issue is the non-equilibrium state of the liquid. Little is known of the transport process for violent flashing. It may be necessary to follow the expansion valve with a tank which augments the vaporization process rather than one which just serves to separate the phases. Such augmentation may take the form of trickle trays, film vaporization, or multiple spray arrangement to provide surface area and residence time to more nearly approach thermodynamic equilibrium.

For the purpose of the work reported here, relatively large flash tanks with man-hole access were specified to assure low vapor velocities at the vapor outlet, and to make possible periodic manual removal of sludge.

Better understanding of flash tank issues (non-equilibrium, droplet entrainment, continuous solids purging) is necessary before the first commercial industrial process heat pump is commissioned.

Section 6

COMPARATIVE EVALUATIONS OF DEMONSTRATION SITES

Four potential IPHP applications were evaluated during the site studies phase of this report (Section 3). Two sites were recognized as showing merit. The technical, installation, operational, and test feasibilities for these sites were studied and established. Results from these studies will be compared on the basis of energy savings, cost savings, and the expected value of operating experience.

An evaluation of the NORYL facility site in Selkirk, NY is given below. The large waste stream (5000 gpm) of 170 °F water can provide 28,205 lb/hr of steam by flashing the steam at 160 °F. A pressure ratio across the two compressor bodies of 10.5 yields 50 psia steam which can be used in the facility. The work input into the compressor is 1970 kW. The cost of electricity (8000 hr/yr) for the IPHP is \$584,000 per year (\$0.035/kWh). An equivalent amount of steam produced by a conventional boiler would consume 2.06 million gallons of oil per year at a cost of 1.28 million dollars (\$.62/gallon — 1980 average). The energy cost savings is \$696,000 per year while a simple payback calculation yields a 4.2 year payback period.

The evaluation of the Schoeller Paper Company site in Pulaski, NY is given below. Flashing of the 30,000 lb/hr waste stream from 195 °F to 160 °F provides 1052 lb/hr of steam. The compressor pressure ratio is 4.6, which provides 21.7 psia steam to a steam header. The work input into the system is 59 kW (8000 hr/yr) which represents an electrical energy cost of \$16,520 per year (\$0.035/kWh). An equivalent amount of steam produced by a conventional boiler would consume 102,000 gallons of oil per year at a cost of \$56,000 per year (\$0.55/gallon). The energy cost savings is \$39,500 per year and the simple payback period is 12.4 years.

The NORYL alternative represents an economically attractive site where large energy and energy cost savings can be realized. However, the Schoeller Paper Company site provides a low-cost site where the concept of the open-cycle IPHP can be demonstrated with significant savings.

Management at both sites were interested in the IPHP and have been cooperative. Both sites would provide a useful IPHP operating experience.

It is the recommendation of this report to provide demonstration at the NORYL facility where the economics justify the application. The recognition of this site as an example for other major energy-users will lead to faster adoption of the open-cycle heat pump.

Section 7

PRELIMINARY ECONOMIC ANALYSIS

7.1 OBJECTIVE

The objective of the economic analysis has been to determine the economic attractiveness of the Industrial Process Heat Pump (IPHP) for prospective users. To accomplish this, current fuel oil and electricity costs throughout New York State were compiled, which recognized that regional variations had to be taken into account. IPHP performance was used to determine annual oil consumption versus electrical consumption and consequent operating cost savings. Capital costs were introduced to estimate payback period for the various regions.

7.2 SUMMARY OF RESULTS

The results are very encouraging for the IPHP. Present energy costs in all areas of New York State would allow an IPHP user to achieve payback of capital investment in less than five years with a COP of 5 or better. If a COP of 6 is achievable, then payback in 3 years or less can be realized in all areas.

Anticipated escalation of energy costs will enhance this already encouraging situation.

Open-cycle industrial process heat pumps are presently economically attractive for many applications in New York State. This preliminary economic analysis indicates that a timely completion of the development program will benefit both New York State and the country through significant oil savings, and will benefit industrial users through long-term energy and economic savings.

7.3 APPROACH

The approach to conducting the economic analysis has been divided into two parts. The first was to determine economic and performance input data needed for the economic analysis. This was accomplished by reviewing electricity and oil prices supplied by the New York State Energy Office (NYSEO) to determine representative energy costs as of Summer 1980 for various regions of the State, and by establishing capital cost and performance data for the IPHP. The second step was to derive the applicable economic equations introducing capital cost, operating energy costs, performance, and annual operating hours; and, to calculate the anticipated payback periods for several regions of the state as a function of heat pump coefficient of performance based on current energy costs.

7.3.1 Energy Costs

Oil and electricity costs exhibit strong regional characteristics in New York State. Oil cost variations are driven largely by environmental emission allowances which differ throughout New York (these require different sulfur content fuels). Electricity costs vary with fuel cost and a number of other factors, such as labor cost and the mix of electricity supply sources (e.g., hydro, nuclear, coal, oil). The areas in New York State which require use of high-priced fuel also tend to have highest electricity prices.

7.3.2 Oil Costs

Much of the industry in New York is using oil fuel for steam generation. Consistent with this, costs for #6 oil, the primary fuel for industry, have been selected as the base costs.

In New York City and environs, the maximum allowable sulfur content in oil fuel is 0.3% by weight. In much of Long Island and certain industrial regions of Buffalo, less than 1% sulfur oil is required. Elsewhere, at present, users are allowed, under most conditions, to burn oil fuel containing 2 to 3% sulfur.

Tables 7.1a and 7.1b give prices for #6 oil from January to July 1980. Reseller prices, Table 7.1a, are essentially wholesaler prices, and show that in New York City a significant premium is paid for lower sulfur oil.

Table 7.1a
1980 RESELLER TANK CAR PRICES FOR #6 OIL
IN NEW YORK STATE
(\$/gallon)

(Source: Monthly Energy Price Reports by Peter McKee, New York State Energy Office)

Location	Sulfur Content								Average	
		Jan.	Feb.	Mar.	Apr.	May	June	July	3 mos	7 mos
New York City	Regular	0.502	0.525	0.485	0.389	0.377	0.377	0.438	0.504	0.442
	1.0%	0.670	0.717	0.697	0.620	0.609	0.609	0.609	0.695	0.647
	0.3%	0.737	0.791	0.789	0.758	0.738	0.738	0.738	0.772	0.756
Albany	Regular	0.502	0.524	0.485	0.389	0.383	0.383	0.444	0.504	0.444
Buffalo	Regular	0.494	0.519	0.519	0.479	0.469	0.469	0.469	0.511	0.488
	1.0%	0.505	0.549	0.549	0.509	0.499	0.499	0.489	0.534	0.514

Table 7.1b
1980 CONSUMER TANK WAGON DELIVERY PRICES IN NEW YORK CITY
(\$/gallon)

Location	Sulfur Content								Average	
		Jan.	Feb.	Mar.	Apr.	May	June	July	3 mos	7 mos
New York City	0.3%	0.795	0.858	0.858	0.858	0.787	0.788	0.788	0.837	0.819

There is significant price variation with time. Figure 7.1 shows New York City prices for various sulfur grades of #6 oil versus time for January thru July 1980. This shows clearly the impact of the oil "glut" early in the year. Since these depressed prices are expected to move back to early 1980 levels as already reflected by the 2-3% sulfur oil, it was decided to use the average oil price for the first three months of 1980 rather than the July 1980 oil prices.

The only consumer prices for #6 received from the New York State Energy Office were for New York City, 0.3% sulfur oil (Table 7.1b). The differential price, i.e., consumer price less seller price, was calculated month by month and averaged over the first

Figure 7.1 1980 Oil Price Versus Time – New York City

three months at 6.5 cents per gallon (Table 7.1c). This average markup was used to convert all reseller average prices to consumer prices.

The resultant oil prices needed for further analysis are shown in Table 7.2.

A spot check with two GE facilities, Selkirk, NY and Glens Falls, NY, found they were both paying 57 cents per gallon in July 1980, which tends to confirm the methodology above. These are both upstate locations using 2 to 3%, #6 oil.

Table 7.1c

**DIFFERENTIAL PRICE, CONSUMER LESS RESELLER
(\$/gallon)**

Location	Sulfur Content								Average	
		Jan.	Feb.	Mar.	Apr.	May	June	July	3 mos	7 mos
New York City	0.3%	0.058	0.067	0.069	0.100	0.049	0.050	0.050	0.065	0.063

Note: Regular sulfur content indicates from 2 to 3, usually about 2.2%.

Table 7.2

NEW YORK STATE REVIEW OF 1980 OIL PRICES

Region	% Sulfur	Industrial Consumer Price (\$/gallon)
New York City	0.3	0.837
Long Island	1.0	0.760
Upstate	2-3	0.569
Buffalo	1.0	0.599

7.3.3 Electricity Prices

Electricity price data obtained from NYSEO varies more by utility than with time. The July 1980 data for larger industries (10,000 kW peak or 4,680,000 kWh/month) is extracted from the NYSEO July Energy Price Report by Peter McKee:

Table 7.3
NEW YORK STATE 1980 UTILITY RATES

Utility	Electricity Price for Large Industrial Use (¢/kWh)
Central Hudson	6.52
Con Edison*	7.52
LILCO	6.85
NYSE&G	3.21
Niagara Mohawk	3.70
Orange & Rockland*	6.16
Rochester G&E	3.25

*Summer and winter rates averaged

In order to make this data regionally consistent with the oil price data developed earlier while limiting the number of regions under study, certain regional cases were constructed. New York City oil prices would be used with Con Ed prices. The Long Island oil price would be used with Long Island Lighting Company (LILCO) electricity prices. The Buffalo 1% sulfur oil prices would be used with New York State Electric & Gas electricity prices, the utility serving that region. And, the "upstate" oil price would be used with an "upstate" electricity price obtained by averaging NYSE&G and Niagara Mohawk electricity prices. These two utilities serve the bulk of upstate New York. These four cases are believed to cover the spectrum of oil and electricity prices throughout New York.

The Power Authority of the State of New York (PASNY) which supplies electric power to certain industries, introduces two other cases both using upstate oil prices. PASNY contracts arranged in the 1950's provide that certain industries receive power at an estimated 4.4 to 5.4 mills/kWh (at 80 and 50% capacity factors, respectively). PASNY contracts from the 1970's provide power to contractees at an estimated 24.7 to 34.7 mills/kWh (80 and 50%). Note that wheeling charges are not included. Most PASNY supplied industries are assumed to be upstate, and upstate oil prices will be used.

7.3.4 Selected Energy Price Cases

The selected cases discussed above are:

Table 7.4
SELECTED ENERGY PRICE CASES FOR LARGER INDUSTRIAL USER

Location	Electricity Price (¢/kWh)	Oil Price (¢/gallon)
New York City Area	7.52	83.7
Long Island	6.85	76.0
Upstate	3.45	56.9
Buffalo (1% S oil area)	3.21	59.9
PASNY (1950's)	.44-.54	56.9
PASNY (1970's)	2.47-3.47	56.9

7.3.5 Economic Analysis and Results

We chose to express the economic merit of industrial process heat pumps in terms of the simple payback period (N). N is defined to be the ownership period over which the sum of the first installed cost of the IPHP and the operating cost of the system is equal to the sum of the first installed cost of a combustion fired steam generator and its operating cost. So:

$$\frac{\dot{Q} A_H}{\text{COP}} + \frac{\dot{Q} NT P_H}{\text{COP}} = \dot{Q} A_o + \frac{\dot{Q} NT P_o}{\eta} \quad (7-1)$$

or

$$N = \frac{A_H/\text{COP} - A_o}{T \left[\frac{P_o}{\eta} - \frac{P_H}{\text{COP}} \right]} \quad (7-2)$$

where

- A_H = Installed heat pump system cost per unit rated power input
- A_o = Installed combustion fired boiler cost per unit of rated heat rate output
- COP = Heat pump system coefficient of performance
- N = Simple payback period of heat pump system against combustion fired system
- P_H = Price per unit of electrical energy
- P_o = Price of combustion fuel per unit of fuel energy
- $\dot{Q}$ = Rated heating capacity
- T = Steam generator annual operating period
- η = Combustion fired steam generator efficiency

Equations 7-1 and 7-2 assume that operating costs consist of energy costs only. The equations are also valid for the case for which operating costs other than energy costs are equal for heat pump and combustion fired steam generators. Since no wide experience with steam generating heat pump systems now exists, maintenance costs are not established. We believe that open-cycle heat pumps are more likely to incur lower maintenance costs than oil or coal-fired systems since the fuel is clean (electricity), temperatures are low (corrosion, erosion) and turbocompressors are exceptionally reliable machines. We believe, therefore, that N , as given by Equation 7-2, represents an upper limit.

N , the simple payback period, does not contain any consideration of tax, interest, or fuel price escalation effects. N is therefore only a parameter for first-round evaluation of economic merit of heat pump systems for defined potential applications. Economic merit is measured differently by different owners of industrial plants; however, the simple payback period is the most common initial scoping measurement.

In order to carry out some numerical experiments to scope heat pump economic merit, we need to quantify the parameters contained in Equation 7-2.

For the purpose of these experiments we will fix A_H and A_o . As a result of costing analyses we have performed for the NORYL IPHP and other large systems, we arrived at a value for A_H of \$1440 per kW-rated system power requirement. This power require-

ment includes drive power for the compressor, purge pump, and injection pumps. It needs to be emphasized that this value for A_H is very approximate; it is most sensitively affected by: flash tank steam density (lower density increases compressor impeller diameter requirements), and the location of installation in relationship to waste water location and steam use location (long piping runs can substantially increase installation cost).

For the purpose of specifying the value for A_o , we used the results of analysis from the Cogeneration Technology Alternatives Study (DOE/NASA-0031-80/3 and NASA CR-159767) for packaged oil boilers of capacity of 50×10^6 Btu/hr. This value for A_o is \$27,400/(MBtu/hr). This value again is approximate; it is true that gas-fired installations are less costly and that coal-fired systems are more costly.

IPHP expected coefficients of performance are given by Figure 7.2 as a function of the sink temperature (steam saturation temperature at compressor discharge) and source temperature (temperature of liquid water leaving the flash tank). This family of curves was generated by use of

$$\text{COP} = \frac{T_H}{T_H - T_L} \times 0.65 \quad (7-3)$$

(T_H and T_L are sink and source temperatures as defined above - in absolute temperature), that is, by use of the assumption that actual system COP is 65% of Carnot COP. We believe 65% to be a lower limit for a reasonably well-designed system. We have found, on the basis of many detailed performance calculations for such heat pumps, that well-designed systems will operate between 70% and 75% of Carnot COP.

Figure 7.2 Coefficient of Performance – Open-Cycle Vapor Compression Heat Pump

The last parameter of Equation 7-2 which we will fix is η , the combustion-fired steam generator efficiency. We chose $\eta = 0.85$ on the basis of our experience in energy efficiency analysis of existing large industrial process plants.

When the dimensions of parameters in Equation 7-2 are as follows (assuming the combustion fired system to be oil fired):

A_H (\$/kW)

A_o (\$/(MBtu/hr))

N (years)

P_H (¢/kWh)

P_o (\$/gal)

T (hr/yr)

and if the energy content of a gallon of oil (#6) is 135,000 Btu, then Equation 7-2 must be converted by inclusion of some constants to make for dimensional consistency. The following equation results (it includes numerical values which were given in the preceding for A_H , A_o , and η):

$$N = \frac{1440/COP - 93.52}{T (0.0297 P_o - 0.01 P_H/COP)} \quad (7-4)$$

We believe that many of the early installations of IPHP will be to displace current oil-fired steam generation. If this is the case, then no credit can be taken for oil-fired steam generator cost to derive the payback period, since that steam generator already exists and is only to be decommissioned or its duty is to be reduced. Therefore, for such a case, the second term in the numerator (A_o) of Equations 7-2 and 7-4 must be set at zero. Equation 7-4 then becomes:

$$N = \frac{1440/COP}{T (0.0297 P_o - 0.01 P_H/COP)} \quad (7-5)$$

When the energy cost information of Table 7.4 is used in Equation 7-5, the simple payback period for these New York State cases can be computed as a function of COP. Figure 7.3 shows the results for the case of 8000 steam generator operating hours per year. Equation 7-5 shows N to be inversely proportional to T . Therefore, if the payback periods for annual operating periods other than 8000 hr/yr is desired, the result of Figure 7.3 can be multiplied by the specified annual operating period and then divided by 8000 hr/yr to provide the desired payback period.

Figure 7.3 Economic Analysis Results Using Summer 1980 Data – Years to Payback Versus COP

Figure 7.3 shows that even retrofitted IPHPs with COPs in excess of 5 achieve simple payback periods which are less than 5 years for all cases shown. COPs in excess of 6 will provide payback periods which are less than 3 years for all cases shown.

A nomograph was constructed for the graphical solution of Equation 7-5. The nomograph is given as Figure 7.4. To use it, one begins by computing the product of P_o (cost of oil (\$/gal)) and the heat pump's COP (obtained from Figure 7.2). A vertical line is then drawn from the determined P_o COP to intersect with the cost of electrical energy (P_H (¢/kWh)). From this point of intersection, a horizontal line is drawn to intersect the curve of fixed expected annual operating period (T (hr/yr)). From this point of intersection a vertical line is drawn to intersect the ordinate N (payback period). One example set of solution lines is superimposed on Figure 7.4. The case is the following: $P_o = \$0.75/\text{gal}$, $\text{COP} = 5$ ($P_o \text{ COP} = 3.75$), $P_H = 4¢/\text{kWh}$, $T = 6000 \text{ hr/yr}$. The result is $N = 3.4$ years.

Figure 7.4 Graphical Solution of Equation 7-5

Section 8

NEW YORK STATE MARKET STUDY

To evaluate the market potential for the open-cycle IPHP, a study was made of the existing New York State industrial process heat capacity and unit process sizes, together with the process temperature needs and waste streams available. A payback analysis was then made for comparison with oil-fired boilers in that particular market.

The results of this study are shown in Table 8.1, where several data bases were searched to develop the New York State process capacity for various combinations of process temperatures and waste water stream availability. The publically accessible data bases searched included the Drexel Industrial Applications Study, the GE-Cogeneration Technology Alternatives Study (1977-78), the Census of Manufacturers, the annual Survey of Manufacturers, and the New York State Industrial Energy Profile (ERDA 81-9). The industries included in this data base were: textiles, food, paper, chemical, petroleum, stone/clay/glass, and primary metals.

As shown in Table 8.1, the process temperatures investigated were split into several ranges and the waste water stream temperatures associated with these processes were also split into ranges. The resulting matrix has three entries at each matrix location. The first entry at any matrix location is the number of plants in New York State with potential IPHP applications which correspond to the temperature at the midpoints of the particular temperature ranges of that matrix location. The second entry is the pressure ratio that would be needed across the compressor to provide the desired process steam for the application. The pressure ratio is given because it can sensitively affect compressor cost. Efficient centrifugal compressors can not accommodate more than 5 or 6 stages at a single impeller speed. 5 to 6 stages may be capable of producing pressure ratios between 10 and 15 for water vapor compression. If larger pressure ratios are required, systems must contain multiple and series-placed compressors. The third entry gives the estimated COP.

The applications being addressed by this study lie within the 140-230 °F source temperature ranges. Applications for which available waste water temperatures are less than 140 °F were not considered, since for such cases water vapor density becomes so low as to require excessive compressor size. Table 8.1 identifies 165 possible open-cycle industrial process heat pump applications. Those which have waste heat available with temperatures at or above 212 °F do not require expansion devices, pumps, or flash tanks since there the source stream is already steam.

Table 8.1
NEW YORK STATE MARKET FOR IPHP

Waste Source Temp (°F)	Process Sink Temp (°F)											
	150	170	190	212	230	250	270	300	320	340	360	380
	to 170	to 190	to 212	to 230	to 250	to 270	to 300	to 320	to 340	to 360	to 380	to 400
-100												
100-120												
120-140												
140-160					34 12.4 4.0	19 14.4 3.7						
160-180												
180-212							2 3.7 6.7	32 7.8 4.3				
212-230					7 10.5 9.3	19 3.9 6.6	26 5.4 5.3		26 11.3 3.7			
230-250												

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