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Survey of Industrial Coal Conversion Equipment Capabilities: Rotating Components

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OAK RIDGE NATIONAL LABORATORY
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Date Published: April 1978

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FOREWORD AND ACKNOWLEDGMENTS

This is one of four reports describing surveys of industrial coal conversion equipment capabilities which were conducted for and supported by the Equipment Branch (James Powell, Branch Chief, and T. K. Lau, Project Manager) of the Fossil Energy Major Facilities Project Management Division (MFPM)^{*} of the Energy Research and Development Administration (ERDA).^{*} This report describes the results of the survey relating to rotating components (pumps, compressors, gas expanders, and hydraulic turbines); other reports in this series are:

- W. A. Bush and E. C. Slade, *Survey of Industrial Coal Conversion Equipment Capabilities: Valves*, ORNL/TM-6071, Oak Ridge National Laboratory (1978).
- J. P. Meyer and M. S. Edwards, *Survey of Industrial Coal Conversion Equipment Capabilities: High Temperature, High Pressure Gas Purification*, ORNL/TM-6072, Oak Ridge National Laboratory (1978).
- W. R. Gambill and W. R. Reed, *Survey of Industrial Coal Conversion Equipment Capabilities: Heat Recovery and Utilization*, ORNL/TM-6073, Oak Ridge National Laboratory (1978).

The authors of this report appreciate the rotating-equipment-industry personnel who have given their time and effort to reply to our questionnaires and have met with us to discuss availability and problems of equipment required by the coal conversion industry. Without their cooperation, this report would not have been possible.

We also express our appreciation to the architect-engineers and users of rotating equipment who set aside time to meet with us. Our thanks also go to the many people in the Union Carbide Nuclear Division who have provided assistance during this study.

^{*} Effective October 1, 1977, ERDA became part of the Department of Energy (DOE); MFPM has since become part of the Division of Coal Conversion of DOE.

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ABSTRACT

A study was undertaken at the request of the Major Facilities Project Management Division of the Energy Research and Development Administration, Fossil Energy Division, to determine the capabilities of U.S. industry to supply the rotating equipment needed for future coal conversion facilities. Furthermore, problem areas were to be identified and research and development needs determined for producing the required equipment of advanced design. The equipment of interest includes pumps, compressors, hydraulic turbines, and gas expanders.

It has been concluded that equipment for essentially all clean-stream applications likely to be encountered in coal conversion facilities is generally available except high-pressure oxygen compressors. These oxygen compressors as well as slurry pumps need to be developed or significantly upgraded. Also, fans and blower for dirty-gas streams need developmental work, as do expanders for high-temperature service. Hydraulic turbines, which were not specified but which might be used for slurry applications in future coal conversion plants, are not available.

1. INTRODUCTION

With the increased realization of shortages of oil and natural gas and with increased U.S. dependence on foreign oil, serious attention is being given to the commercialization of advanced processes for the conversion of coal to clean liquids and gases. A number of these processes have been under development for many years; many additional processes are currently being studied. Of these processes, some are in the pilot-plant stage, others are ready for scale-up to demonstration-size units, and still others are ready for commercialization. There are many existing conceptual designs for coal conversion facilities based on such processes. The question now raised is whether or not the equipment specified in such

designs is indeed readily available from U.S. industry. If not, the question becomes one of determining how much lead time is required to develop such equipment.

The potential to have demonstration and commercial coal conversion facilities in timely production depends in part on the availability of the necessary equipment and in part on the time required for construction of the facilities. The Major Facilities Project Management Division (MFPM) of the Energy Research and Development Administration, Fossil Energy Division, has been charged with the task of overseeing the commercialization of coal conversion in the United States. This study, which supports the efforts of MFPM, was initiated with a twofold objective:

1. determination of present capabilities of U.S. industry to supply equipment needed for future demonstration and commercial coal conversion facilities and
2. identification of problem areas as well as determination of research and development needs for producing equipment of advanced design, including lead time requirements.

The total project includes all types of equipment found in a coal conversion plant; however, only four categories have been studied this year: rotating components, valves, hot-gas clean-up devices, and heat-recovery equipment. This report addresses only the first category, rotating components, which includes pumps, compressors, hydraulic turbines, and gas expanders. Three additional reports covering the other categories are being issued concurrently with this report; citations appear in the Foreword and Acknowledgments.

This study consists of three principal phases: (1) the determination of rotating equipment requirements based on existing conceptual designs, (2) a survey of industry to determine availability of equipment, and (3) an analysis of problem areas and possible solutions. Each of these phases will be discussed in detail in subsequent sections of this report. Section 3 considers the methods employed in pursuing these principal phases and gives the rationale for their use, Sect. 4 presents the data obtained during this study, and Sect. 5 presents the findings and conclusions drawn. Recommendations for research and development are

summarized in Sect. 6, with considerations of their relative importance. This last section also includes a summary of the availability of rotating equipment and presents unanswered questions raised by this study as well as additional topics needing further study. Section 2 presents briefly the findings of this study.

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2. SUMMARY

The first step toward meeting the objectives in Sect. 1 was selection of seven coal conversion conceptual design reports as a basis for equipment specifications. These reports cover both liquefaction and gasification processes. Information on these processes is included in Appendix A and is summarized in Table 1, Sect. 3.

Equipment specification lists in the design reports were screened for pumps, compressors, hydraulic turbines, and gas expanders operating under the more severe conditions. The operating parameters collected were compared and consolidated to yield the final equipment lists, which appear as a part of the questionnaires in Appendix B. Additional information on the models for the specified equipment may be obtained from Appendixes C and A. Table 2, Sect. 3, gives limits of operating parameters for each type of equipment.

The primary data source on equipment availability and problems was the rotating equipment industry. Information was obtained through a series of four questionnaires, each dealing with one of the major rotating equipment categories. A total of 222 questionnaires was sent to industry, and 57 responses were returned; responses were received from almost all of the first-line equipment vendors. Additional data were obtained during visits to architect-engineers and users of rotating equipment as well as in follow-up meetings with vendors, either at their facilities or in Oak Ridge. Industrial coverage is summarized in Tables 5 and 6, Sect. 3, and in Appendix D. The data received are presented in Sect. 4 and Appendix E without comment.

In Sect. 5, the data are analyzed and discussed with respect to availability, problem areas and proposed solutions, and research and development needs. In Subsect. 6.1, conclusions about equipment availability are reviewed, with present limitations on equipment being summarized in Table 17. Recommendations concerning research and development needs to develop unavailable equipment or to upgrade existing equipment to meet the demands of coal conversion appear in Subsect. 6.2. Finally, additional areas needing study but for which time was not available are reviewed in Subsect. 6.3.

It is concluded that equipment is generally available for essentially all clean-stream applications likely to be encountered in coal conversion facilities with the exception of oxygen compressors for pressures greater than 600 psia. Equipment critical to the success of the coal conversion industry which needs to be developed or significantly upgraded includes not only high-pressure oxygen compressors but also slurry pumps and low-pressure fans and blowers capable of handling dirty streams. The development of expanders is critical to the practicability of several processes. Hydraulic turbines may be desirable for power recovery from slurry streams; however, their unavailability will not seriously affect any processes.

3. DATA COLLECTION

The collection of accurate and pertinent data is a prerequisite to meeting the objectives of this study reliably. Because this survey is on equipment availability, a basis was first established for the specification of equipment-operating characteristics; these characteristics were then determined. Next, questionnaires were composed to establish the present and anticipated capabilities of industry and the problems that must be overcome. Last, the equipment specifications and questionnaires were sent to manufacturers of the equipment considered in this survey. Each of these phases is discussed in the following subsections.

3.1 Basis for Equipment Specifications

Many conceptual designs of demonstration and commercial facilities for coal liquefaction and gasification have been produced by several organizations such as architect engineers, national and other government laboratories, and consortiums. Several designs frequently exist for each process. To select the designs that would serve as a specification basis for equipment requirements, discussions were held with several staff members involved with the coal programs of the Oak Ridge National Laboratory. As a result of these discussions, seven designs were chosen, based on the following processes, as a basis for this study: BI-GAS, Coalcon, Fischer-Tropsch, Hydrocarbonization, HYGAS, Lurgi, and Synthoil. The range of operating characteristics for equipment in these processes is believed to include the most severe conditions likely to be encountered in coal conversion; however, there may possibly be more severe applications in processes not considered.* A summary of the conceptual designs selected is given in Table 1.

A more complete description of each process as to the source of information, coal feed requirements, and major products appears as

* During discussions with architect engineers and manufacturers, only a few slightly more severe requirements were encountered.

Table 1. Conceptual designs forming a basis for equipment requirements

Process	Report	Coal feed		Products	
		Rate (TPD) ^a	Type ^b	Gas (MM scfd) ^c	Liquid (M BPD) ^d
BI-GAS	ERDA 76-48 (March 1976)	21,000	Mont.	250	
		13,000	W. Ky.		
Coalcon	Coalcon (Aug. 15, 1975)	15,000	Ill.-Ind.-Ky.	105	24
Fischer-Tropsch	R. M. Parsons, R&D Report No. 114, Interim Report No. 3 (draft)	40,000	Ill.-Ind.-Ky.	260	50
Hydrocarbonization	ORNL-5212 (draft) (September 1976)	41,000	Ill.	63	23
HYGAS	ERDA 76-47 (March 1976)	22,000	Mont.	250	
		13,000	Pitt.		
Lurgi	ERDA 76-7 (August 1975)	24,000	N. Mex.	250	
Synthoil	ORNL-5209 (draft) (September 1976)	50,000	W. Ky.		100

^aTPD = tons per day.

^bCoal Type is identified by standard state abbreviations except W. Ky. = western Kentucky, Pitt. = Pittsburgh.

^cMM scfd = millions of standard cubic feet per day (standard conditions are 60°F and 14.7 psia).

^dM BPD = thousands of barrels per day.

Appendix A. A simplified block flow diagram for each process and a list of equipment items that serve as models for the specification of equipment requirements are also included in Appendix A.

Three additional conceptual designs, based on the CO₂ Acceptor, HYGAS, and HYGAS (Steam-Iron) processes, were reviewed to supplement information on hydraulic turbines and gas expanders. Information sources for these processes are also included in Appendix A.

The conceptual designs considered include pressures to more than 1000 pounds per square inch absolute (psia) for gasification processes and more than 4000 psia for liquefaction. Except for hot-gas expanders, the maximum temperature encountered by the rotating equipment is approximately 750°F; expander inlet temperatures range up to about 1750°F. Slurry concentrations are as great as 60 wt %.

3.2 Equipment Characteristics

Each conceptual design examined in this study included equipment specifications lists, which were screened for equipment operating under the more severe conditions. Additional information on these equipment items was obtained from the flow sheets for each process. Operating conditions thus collected were compared and consolidated to yield lists of equipment appearing as part of the questionnaires sent to industry. These equipment lists may be found in Appendix B.

Each of the operating parameters considered is discussed below to identify limitations of the data and assumptions that were made. The discussion follows the order in which these parameters appear in the equipment lists.

Flow Rate is the most basic parameter required for sizing a piece of rotating equipment. For pumps and hydraulic turbines, flow rates were specified as gallons per minute (gpm); flow rates for compressors and gas expanders were specified as actual cubic feet per minute (acfm) at inlet conditions (i.e., inlet temperature and pressure).

Some equipment has been specified with flow rates in excess of those required by the conceptual designs that form a basis for this study. In some instances, several items of equipment appear in the equipment lists

differing only in flow rate; in these cases, the larger capacities represent the replacement of several smaller units by a larger unit. When there is demonstrated equipment reliability, these larger units may be desired. At other times, however, the data as a whole warranted dropping some required flow rates in favor of larger rates because of similar operating conditions for different flows in several conceptual designs.

Solids handling in rotating equipment requires specific attention. Solids Content was therefore identified apart from the stream composition.

For slurries, the solids content was presented as a weight percent of the total stream flow and was included under both this parameter and under "Stream Composition" because the solids could represent a significant portion of the volume flow through the pump or hydraulic turbine. Solids found in slurries were ash, char, and coal, either individually or in combination; there were no levels of solids loading in which any one solid predominated in the slurry stream. Therefore, the particular solid was not specified in the final equipment lists. The solids content of gas streams was specified as grains per actual cubic foot of gas at inlet conditions.

For compressors, coal dust was found to be present in several high-flow, low-pressure ratio blowers. Expanders were required to handle several different types of particulates; some information on these particulates was also supplied in the expander equipment list.

Solids content with respect to both the level of loading and the nature of the particles has a significant effect on materials selection and the life of equipment because of resulting erosion.

The density of the fluid being pressurized, whether it is a liquid or a gas, is another parameter that will significantly affect the design of rotating equipment. Specific Gravity with respect to water can be used as a relative measure of density for liquids because almost all pumps that are performance tested in manufacturers' facilities are tested on water. Molecular Weight serves a similar purpose and is also better suited for gases because they are compressible.

Inlet Temperature can have a significant effect on construction materials and the overall design of both liquid- and gas-handling equipment. With respect to gases that are compressible fluids, inlet temperature will affect the density of the gas and hence the size of the equipment as well as the amount of intercooling required during compression. For high temperatures, case cooling may be required; blade cooling may also be required in compressors and, particularly, in expanders. Temperatures are in degrees Fahrenheit ($^{\circ}\text{F}$).

Inlet Pressure can influence significantly the design and performance of equipment. This fact is particularly true of pumps in which the net positive suction head (NPSH) required must be no greater than the NPSH available* from the process; otherwise, cavitation can occur, leading to severe pump damage. Required NPSH can be reduced by increasing the diameter of the impeller eye; alternatively, NPSH required can be met by using booster pumps specifically designed for low available NPSH. Information available in the conceptual design reports was insufficient to evaluate NPSH available for all of the various applications and was therefore not included.

Based on volume, inlet flow rate in compressors is approximately inversely proportional to inlet pressure for a given mass flow rate; thus, when all other parameters are equal, a lower inlet pressure requires a larger compressor. In the case of hydraulic turbines and gas expanders, the inlet pressure will affect their design with respect to pressure containment and materials of construction. Both inlet and outlet pressures are specified as pounds per square inch absolute (psia).

Outlet Pressure affects the design of pumps and compressors with respect to pressure containment and materials of construction. Back pressure on turbines and expanders is also important to design; in particular, back pressure on turbines must be sufficient to prevent cavitation; expander-outlet pressure will do much to determine the size of the unit.

* NPSH available is equal to the difference between the inlet pressure and the vapor pressure of the liquid at inlet temperature.

Pressure Head and Pressure Ratio, which are derived quantities, are important parameters in the design of rotating equipment. The magnitude of these quantities is related to the total number of stages required in an equipment unit, though other factors are also involved.

Pressure head is the change in pressure from the inlet to the outlet of a pump and may be expressed as

$$\Delta P = P_o - P_i , \quad (3.1)$$

where

ΔP = pressure head, psi,

P_o = outlet pressure, psia,

P_i = inlet pressure psia.

In the case of hydraulic turbines, this equation also holds except that ΔP is negative.

For compressible gases, pressure ratio serves a purpose analogous to pressure head for incompressible liquids and is defined as

$$r = P_o / P_i , \quad (3.2)$$

where r is the pressure ratio. This ratio can be used to characterize both compressors and expanders; however, the reciprocals of the pressure ratio ($r^{-1} = P_i / P_o$) were used for the expanders.

Positive heads or ratios greater than 1 imply that power is required. Power is available for recovery when the head is negative or the pressure ratio is less than 1.

Ideal Horsepower was determined for each item of equipment as a function of inlet and outlet conditions, using the general relationship

$$W = \int_{P_i}^{P_o} V \, dP , \quad (3.3)$$

where

W = work input (positive) or output (negative), hp,

V = volume flow rate,

P = pressure.

Inefficiencies resulting from mechanical or fluid considerations are not considered.

For incompressible (constant volume) liquids, Eq. (3.3) integrates to

$$W = V\Delta P, \quad (3.4)$$

or

$$W = \frac{Q\Delta P}{1714}, \quad (3.5)$$

where

Q = flow rate, gpm.

For compressible gases, the following additional assumptions were made: (1) the ideal gas law applies in all cases, and (2) all compressions or expansions are isothermal. The ideal gas law states that

$$PV = nRT, \quad (3.6)$$

where

n = molar flow rate,

R = ideal gas constant,

T = absolute temperature.

Inserting this equation into Eq. (3.3) and integrating yields, for isothermal compression or expansion,

$$W = nRT \ln(P_o/P_i), \quad (3.7)$$

or

$$W = 0.00436 Q_i P_i \ln(P_o/P_i) , \quad (3.8)$$

where

Q_i = inlet flow rate, acfm.

For compressors, the horsepower calculated by Eq. (3.8) is the minimum required for the desired compression, assuming (as previously stated) that there are no inefficiencies, that the ideal gas law holds, and that the compression is isothermal. Under the same assumptions, Eq. (3.8) yields the maximum horsepower recoverable by an expander.

In practical compressors, the temperature of the gas increases in either an adiabatic or polytropic manner; in expanders, temperature decreases in a similar manner. Single-stage uncooled compressors require the maximum power input for compression. If the compression process is divided into a number of stages, each consisting of a partial compression followed by intercooling to the initial temperature, then the horsepower requirement decreases as the number of stages increases and, for a very large number of stages, approaches the isothermal horsepower given by Eq. (3.8). Conversely, nonisothermal expansion leads to a decrease in recoverable power; multistaging of an expander with reheating to the initial temperature between stages causes recovered horsepower to approach the maximum calculated from Eq. (3.8).

Because all horsepower values are ideal and exclude all inefficiencies, the values tabulated in the equipment lists in Appendix B are less than those required to drive pumps and compressors and are greater than those recovered by turbines and expanders.

The Stream Composition of liquid streams is reported in weight percentages. The composition includes not only the liquid portion of those streams but also solids and/or dissolved gases when they are present. Because the density of solids does not differ greatly from that of the liquid medium, the solids can represent a significant portion of the total volume passing through the pump or hydraulic turbine. In gas streams, however, solids form an infinitesimal part of the total volume flow and

are therefore not represented as part of the total stream. Gas composition is expressed in mole percentages. The stream composition plays an important part in equipment design materials selection. The effect of solids was discussed earlier. Corrosive streams may require special materials, and toxic or flammable streams will require special equipment designs.

In addition to the preceding characteristics, information was also supplied on hydraulic turbines and gas expanders. For the hydraulic turbines used to drive pumps, both the flow rates through the pumps and the ideal horsepower required by those pumps were provided. Some information on particulate characteristics was supplied in the expander equipment lists.

The most severe operating condition encountered in each characteristic by each type of equipment is tabulated in Table 2. No one single piece of equipment is expected to operate under the combination of all of these severe conditions; individual items of equipment, however, may involve one or more of these limits in a given application.

3.3 Equipment Grouping and Identification

Once the initial lists of equipment characteristics were compiled, it was advantageous to eliminate excess equipment having similar operating conditions. It was found that the pump and compressor lists could be most easily reduced by first dividing them according to outlet pressure and either pressure head (for pumps) or pressure ratio (for compressors) and then comparing them with other operating parameters in these groupings. This categorization was retained for identifying equipment throughout the project and in this report. These categories are illustrated in Figs. 1 and 2 and are more fully explained in Table 3. Because of the smaller numbers of hydraulic turbines and gas expanders, these lists were not subdivided.

Individuals who wish to study the various equipment applications in more detail should find Appendix C useful. This appendix is a cross reference between the applications appearing in Appendix B and the models on which they are based. Appendix C includes both the flow rate of the model and the process in which it is found. One may find the reference report and the unit operation in which the model occurs in Appendix A.

Table 2. Limits of operating parameters encountered by rotating equipment

Operating parameter	Limit of specified operating parameter ^a			
	Pumps	Compressors	Turbines	Expanders
Flow rate (maximum)	50,000 ^{b, c}	1,230,000 ^d	31,000 ^e	310,000 ^d
Solids content (maximum)	60 ^e	1.5 ^f	25 ^e	3.15 ^f
Specific gravity	0.72 to 1.3		0.84 to 1.13	
Molecular weight		2.3 to 44.1		5.3 to 33.3
Temperature (inlet, maximum), °F	750	700	573	1744
Pressure (inlet, maximum), psia	2,490	3,970	4,000	2,400
Pressure (outlet, maximum), psia	4,300	4,268	200	500
Pressure head (maximum), psi	4,285		3,974	
Pressure ratio (maximum)		47.3		16.6
Horsepower (maximum ideal isothermal), hp	35,000	116,000	39,186	203,000

^aIn no case do all limits apply concurrently for a given type of equipment.

^b100,000- and 200,000-gpm units operating under identical conditions to a 50,000-gpm unit were included but are exceptional cases.

^cGallons per minute.

^dActual cubic feet per minute.

^eWeight percent.

^fGrains per actual cubic foot.

Fig. 1. Categories of pumps showing locations of pumps specified in the final pump list.

Fig. 2. Categories of compressors showing locations of compressors specified in the final compressor list.

Table 3. Equipment identification key

(Equipment in this report is identified by one or two letters followed by a hyphen and a number. Letter meanings are given below. See Appendix B for complete identifier and corresponding equipment operating conditions.)

Category	Letter(s)	Meaning
Pumps	LL	Low outlet pressure (0 to 200 psia) with low-pressure head (0 to 200 psi)
	ML	Medium outlet pressure (200 to 800 psia) with low-pressure head
	HL	High outlet pressure (800+ psia) with low-pressure head
	MM	Medium outlet pressure with medium-pressure head (200 to 800 psi)
	HM	High outlet pressure with medium-pressure head
	HH	High outlet pressure with high-pressure head (800+ psi)
Compressors	FB	Fans and blowers (approximately atmospheric operating pressure with pressure ratio less than 1.1)
	L	Low outlet pressure (20 to 250 psia)
	ML	Medium outlet pressure (250 to 700 psia) with low-pressure ratio (1.0 to 5.0)
	HL	High outlet pressure (700 to 1500 psia) with low-pressure ratio
	MH	Medium outlet pressure with high-pressure ratio (5.0+)
	HH	High outlet pressure with high-pressure ratio
	VH	Very high outlet pressure (1500+ psia)
Hydraulic turbines	T	
Gas expanders	E	

3.4 Questionnaires

The method of collecting data is extremely important in the assessment of equipment availability and the identification of problem areas. Four questionnaires of the same basic format, one for each of the four equipment categories, were prepared for this survey. These questionnaires appear in Appendix B and include the equipment lists described in Sect. 3.2.

The questionnaires were designed to provide answers to the following questions:

1. Is equipment available to meet the specified process conditions?
if not, what are the limiting factors?
2. What maintenance requirements and problems are expected during the operation of each item of equipment?

In the following discussion it may be useful to refer to the actual questions in the questionnaires.

The following paragraphs were designed to answer the first of these primary questions. Availability of the equipment, its type, and the associated components of its drive train are considered.

The question on Availability addresses the key objective of this survey, determining the potential of U.S. industry to supply rotating equipment for demonstration and commercial coal conversion facilities. To facilitate the response procedure and to categorize the various possibilities that might have been encountered, an availability code was prepared, which includes predefined coded responses. This code is presented in Table 4.

The question on Largest Capacity seeks to supplement the response on availability. The manufacturer's response indicates whether or not he has experience in building equipment to meet the process requirements of a given application and, perhaps, that this equipment might actually have been larger than the equipment specified in this study. If it were smaller, the amount of scale-up required could be determined.

Responses to the question on Limiting Factors were intended to focus attention on the key factors limiting the availability of equipment. For those applications for which equipment is not presently available, it

Table 4. Availability codes

Code	Description
<u>Available equipment</u>	
A1	Available off-the-shelf equipment produced by <u>our company</u> .
A2	Equipment available by special order through <u>our company</u> .
A3	Equipment not presently available through our company but believed to be available within the <u>industry</u> .
<u>Technology available for scale-up</u>	
B1	Equipment is not presently available through our company but technology is available <u>in-house</u> which will likely be used if market forces are attractive.
B2	Equipment is not presently available through our company but technology is available within the <u>industry</u> which will likely be used by one or more companies if market forces are attractive.
<u>Anticipated technology by 1982</u>	
C1	Anticipated technology requiring R&D which will likely be funded by <u>our company</u> if market forces are attractive.
C2	Anticipated technology requiring R&D which can be funded by <u>industry</u> if market forces are attractive.
C3	Anticipated technology requiring R&D which can be handled through <u>our company</u> provided <u>governmental assistance</u> is available.
C4	Anticipated technology requiring R&D which can be handled <u>within the industry</u> provided <u>governmental assistance</u> is available.
<u>Anticipated technology: 1982 to 1987</u>	
D1	Very advanced future technology requiring extensive R&D which is likely to be handled by industry by 1987 <u>without governmental assistance</u> .
D2	Very advanced future technology requiring extensive R&D which <u>requires governmental assistance</u> for development by 1987.
<u>Questionable technology</u>	
E1	Technology not believed possible before 1987.
E2	Technology not believed possible for these conditions.
<u>Inapplicable</u>	
F1	None of the above codes are applicable or appropriate for our firm to use. Insert a footnote in column 14 for additional comments, if so desired.

was of interest to know what factors limited availability. Such factors would primarily involve physical limitations such as temperatures, pressures, flow rates and stream composition, or combinations of such factors.

At this point in the pump and compressor questionnaires, a qualifying statement was included. Responses to the remaining questions in these questionnaires were to be made with respect to the equipment size indicated by the manufacturer if his largest capacity exceeded that which had been specified in the equipment list under Flow Rate; otherwise, responses were to be based on the capacity under Flow Rate. It was assumed that smaller equipment was available if the manufacturer could make the larger unit; information was desired on the larger unit to establish more firmly the capability of the manufacturer. This qualifier was not included in the hydraulic turbine and gas expander questionnaires; all answers were to be based on the specified flow rate.

Responses to the question on Equipment Type indicated the type of equipment which the manufacturer could build for the specified application; that is, for a compressor application, a centrifugal or axial type might be used. In addition to rotating-machine types, reciprocating machines were also included in this survey.

The question on Stages allowed for refinement and comparison of the responses to the preceding question by allowing the manufacturers to indicate the number of stages required to provide the specified pressure rise. Responses to this question may also indicate that the placing of several multistage units in series may be required.

The Recommended Driver for an item of equipment may depend on conditions imposed by the customer; however, the choice of the driver might be left to the manufacturer. The recommendation of the latter was sought. This question applied only to pumps and compressors.

Information on the type of Load and Speed Control suitable for preventing runaway of hydraulic turbines and gas expanders was requested.

A question on Estimated Efficiency was added to the questionnaires on turbines and expanders to secure an indication of the efficiency of power recovery. Pump and compressor questionnaires, which had been

prepared earlier, did not include this question, although it would have been desirable to know the efficiency of power usage.

The Recommended Intermediate Transmission (coupling) prepared for a driver-rotating equipment system was requested to more fully characterize the proposed equipment train.

Catalogs were requested to supplement responses previously made.

The next several questions in the questionnaires highlight maintenance requirements and focus attention on problem areas that might be encountered during operation of each equipment item. These data indicate (1) where possible improvements to existing designs can be made and (2) potential problems to be dealt with in the development of new equipment.

Absolute maintenance costs are not very beneficial unless the purchase price of the equipment is also available. Because it is not possible to assess accurately the price of equipment items yet to be developed, it was assumed that Anticipated Maintenance Costs should, in some manner, be related to initial costs. It was also assumed that maintenance requirements, such as the need and frequency of replacing parts, might be postulated for those items. If these assumptions are acceptable, the price of parts relative to a new unit can be approximated and, eventually, maintenance costs estimated for the first 10 years. Once these costs are established, an average 1-year maintenance cost can be expressed as a percentage of the initial purchase price. For those items of equipment similar to existing machines, the determination of maintenance costs is readily accomplished.

In-Service Availability, a measure of the fraction of time a machine will be available for its intended use, indicates both the need for spares and time required for maintenance. In-service availability and maintenance costs are inversely related.

The question on Problem Areas highlights the problems affecting in-service availability and maintenance costs. It indicates areas in which (1) possible improvements to existing equipment designs can be made and (2) research and development work should be concentrated during the design of new equipment.

The overall time frame in which equipment becomes available for installation in coal conversion facilities was addressed previously by the initial question on availability. The next two questions refine this first question on equipment availability by indicating lead time required to develop (if necessary) and build the equipment.

Delivery Time is the time from the order of equipment (which needs no developmental work) through the time of its installation and check-out in the coal conversion facility.

Development Lead Time is the time required to do research and development work necessary to make equipment available on a special-order basis.

A provision was made to allow manufacturers to include any Additional Comments they considered appropriate.

The question on Capabilities and Quantities was asked independently of any particular application; it sought an industry assessment of its capabilities to meet increased demand for rotating equipment which could occur if a number of coal conversion facilities were under construction. This question is of limited usefulness because the demand picture is not clear.

Other questions might also have been asked; however, those presented above give significant information with which to meet the objectives of this study.

3.5 Manufacturers

The reliability of this study is dependent to a great degree on responses of manufacturers to the questionnaires. It was important, therefore, to contact a large cross section of U.S. industry and to enlist its expertise to determine industry's actual capabilities. Four primary sources were used to compile the list of manufacturers to receive questionnaires: Chemical Engineering Catalog,¹ Hydraulics Institute list of members,² ThomCat,³ and VSMF.⁴ Lists of manufacturers from these sources were compared and a final list compiled of those to

whom questionnaires would be sent.* Table 5 summarizes the number of questionnaires sent to industry and the number of responses received. A list of manufacturers responding to the questionnaires appears as Appendix D.

In addition to the information received in response to the questionnaires, a number of visits, which yielded much beneficial information, were made to architect-engineering firms, users of rotating equipment, and manufacturers. A list of those visited is provided in Table 6. During visits with manufacturers, information was obtained that supplemented and expanded the data provided in their responses to the questionnaires; their manufacturing facilities were also toured. Discussions held with architect-engineers and users of rotating equipment indicate that responses have been received from nearly all of the first-line equipment vendors. It is therefore concluded that reliable information has been obtained.

Table 5. Summary of industry coverage and response to equipment questionnaires

(A questionnaire was occasionally sent to several different divisions of the same company; likewise, several responses to a questionnaire were sometimes received from different divisions of the same company.)

	Equipment category			
	Pumps	Compressors	Hydraulic turbines	Gas expanders
Questionnaires sent	80	49	67	26
Responses received	26	18	5	8

* In addition to U.S. manufacturers, several European firms having offices in the United States also received and responded to the questionnaires.

Table 6. Site visits or meetings in Oak Ridge

	Discussion topics			
	Pumps	Compressors	Turbines	Expanders
<u>Architect engineers</u>				
Stearns-Roger (Denver, Colo.)	x	x	x	x
Ralph M. Parsons (Pasadena, Calif.)	x	x	x	x
<u>Users</u>				
Union Carbide, Chemicals and Plastics Division (Taft, La.)	x	x	x	x
Charter Oil (Houston, Tex.)				x
Exxon (Baytown, Tex.)	x	x	x	x
<u>Manufacturers</u>				
Airco Cryogenics (Irvine, Calif.)		x		x
Worthington (Bramford, Ontario, Canada)	x			
Ingersoll-Rand (Phillipsburg, N.J., and Allentown, Pa.)	x	x		x
Elliott (Jeanette, Pa.)		x		x
Dresser-Clark (Orlean, N.Y.)		x		x
Sulzer (Oak Ridge, Tenn.)		x		
Bingham-Willamette (Portland, Oreg.)	x		x	
United (San Jose, Calif.)	x			
Pacific (Los Angeles, Calif.)	x		x	
Byron Jackson (Los Angeles, Calif.)	x		x	
Wilson-Snyder (Dallas, Tex.)	x			
American Demag (New York, N.Y.)		x		
Allis Chalmers (York, Pa.)			x	
Mechanical Technology (Oak Ridge, Tenn.)		x		x

4. SURVEY RESULTS

A total of 57 responses to the various questionnaires was received from industry. The data contained in these responses and information received during visits, meetings, and phone conversations with manufacturers are presented in the following subsections, each dealing with one of the four equipment categories. The order of presentation in each of these subsections begins with availability, proceeds to problem areas and solutions, and concludes with research and development needs as perceived by the manufacturers. Analysis of the data is not undertaken in this section; therefore, conflicting opinions appear in the text. Responses from manufacturers to the questions on availability and largest capacities (questions 1 and 2 in the questionnaires) are tabulated in Appendix E.

4.1 Pumps

Twenty-six responses to the questionnaire on pumps were received from a number of companies, representing a broad cross section of the industry. Many of these companies have experience in supplying pumps for both the petrochemical and nuclear industries, which have stringent requirements concerning design and manufacture to ensure high reliability and safe operation. Manufacturers of both centrifugal and reciprocating pumps provided information. Several of the responding companies specialize in slurry pumps; however, these companies generally supply single-stage pumps for low-head applications.

Availability

Responses of manufacturers to the pump questionnaire indicate that pumps are available for all specified applications. In many cases pumps are available from a number of manufacturers, which is particularly true for clean-liquid applications. However, discussions subsequent to receipt of responses have raised questions as to the actual availability of pumps for slurry applications. Table 7 summarizes the number of manufacturers indicating their capability to supply equipment for the various

classes of pump applications either on an off-the-shelf basis or by special order.

Table 7. Completeness of coverage as reported by vendors

Equipment identifiers ^a	Number of companies reporting available equipment for				
	All items (100%)	75%+	50%+	25%+	One or more
<u>Liquid pumps</u>					
LL-1 through LL-14	2	8	12	17	20
ML-1 through ML-7	3	6	8	14	15
MM-1 through MM-7	2	5	6	9	13
HL-1 through HL-2	6	6	7	7	7
HH-1 through HH-8	1	5	6	8	9
All liquid pumps	0	3	8	11	24
<u>Slurry pumps</u>					
LL-15 through LL-22	3	5	10	12	15
ML-8 through ML-10	2	2	3	4	4
MM-8	6	6	6	6	6
HL-3	3	3	3	3	3
HH-9 through HH-14	1	1	2	3	3
All slurry pumps	0	0	4	8	18
All liquid and slurry pumps	0	2	6	10	25

^aSee Pump Questionnaire in Appendix B for equipment operating conditions.

Although only a few manufacturers provide pumps for all of the applications in a given category, generally a much larger number of manufacturers make 75% or more of the pumps. For instance, only one company builds equipment for all of the high-outlet-pressure, high-head, clean-liquid pump applications represented by HH-1 through HH-8;* however,

*See Pump Questionnaire in Appendix B for equipment operating conditions.

five companies produce pumps for at least 75% of the applications, six companies provide 50%, and nine companies supply one or more.

Four or more vendors indicated the capability of providing a pump for each clean-liquid application except HH-4. Only one manufacturer indicated having equipment available for this application; however, four other manufacturers have information available in-house for scale-up and stated that this would be an easy application to fill. Furthermore, this application is identical to HH-3 except that the flow rate is twice that required by HH-3. Four companies indicated they could supply equipment for HH-3. Comments from vendors during follow-up discussions supported their initial response that equipment is readily available for all the clean-liquid applications.

Slurry pumps, although less available than clean-liquid pumps, are also available from a number of manufacturers in certain instances, such as the low-outlet-pressure, low-head applications represented by LL-15 through LL-22. These applications are expected to require only single-stage centrifugal pumps. Comments from throughout the industry indicate that single-stage slurry pumps are available for heads of as much as about 100 psi; however, reservations have been expressed by one manufacturer on the availability of such pumps for high-temperature oil slurries. The reason for concern is the potential problem of thermal shock resulting in the breakage of the very hard material used in those areas of the pumps where ductile materials would normally be used.

The high-outlet-pressure, high-head slurry pumps, represented by applications HH-9 through HH-14, require multistage centrifugal or positive displacement pumps, which are either nonexistent or uncommon respectively. Only three companies, two reciprocating pump manufacturers and one centrifugal pump manufacturer, indicated that equipment was currently available for these applications. The centrifugal pump manufacturer decided during subsequent discussions that his indication of capability to provide equipment for these applications was premature. The two reciprocating pump manufacturers specified use of multiple units in making their claim of having equipment for these high-pressure, high-head slurry applications. Since reciprocating pumps are available only in sizes of up to 3000 to 4000 hp, the use of multiple units must be accepted to have pumps for all individual slurry pump applications at this time.

Several general statements were received in follow-up visits with manufacturers relative to the availability of slurry pumps. Although several of these statements are conflicting, they are presented as input to this study.

- Slurry concentrations of more than about 40 wt % solids will require reciprocating pumps.
- High-pressure slurry applications should use reciprocating pumps.
- Reciprocating pumps are available for 3000-psi outlet pressure.
- Centrifugal pumps, even with staging, are limited to an outlet pressure of about 600 to 800 psia.
- The maximum pressure rise per stage for centrifugal pumps is limited to about 100 psi per stage.
- A technology breakthrough allowing increased pressure rise per stage is needed for centrifugal pumps.
- Impeller-tip velocities in centrifugal slurry pumps are limited to a maximum of 100 fps. (This yields, approximately, the 100-psi per stage pressure rise.) One centrifugal pump manufacturer designs for maximum velocities of about 70 fps.
- Multistaging of centrifugals to handle slurries will be difficult.
- There is a trend toward using centrifugal pumps for slurry applications.
- Centrifugals are desired.
- Eventually, but not immediately, centrifugal pumps may be developed for 1 year of continuous operation.

Problem Areas and Proposed Solutions

The response of manufacturers to the question on problem areas was considered to be good. Problem areas were generally stated only by manufacturers who either have equipment available for a given application or appear likely to be among the first to have equipment available. Problem areas were stated for approximately one-half of the applications, for which responses were also provided for most of the other questions in the questionnaire. Since the most severe problem area for a given pump was requested, the stated problem might actually be minor. A summary of the problem areas reported by manufacturers is provided in Table 8.

Table 8. Problem areas reported by pump manufacturers

Equipment identifier ^b	Problem areas ^a												Intermediate transmission	Other ^c
	Corrosion	Erosion	Pitting	Deposits	Plugging	Bearings	Cavitation	Seals	Couplings	Vibration	Drivers			
<u>Liquid pumps</u>														
LL-1 through LL-14	14	18				26	36	33		9				2
ML-1 through ML-7	9	10				11	21	16		6	2			2
MM-1 through MM-7	7	5		2		10	20	14	3	4				7
HL-1 through HL-2						4	4	5		2				
HH-1 through HH-8	<u>6</u>	<u>3</u>		—		<u>8</u>	<u>25</u>	<u>17</u>	—	—	<u>1</u>			<u>9</u>
All liquid pumps	36	36		2		59	107	85	3	21	3			
<u>Slurry pumps</u>														
LL-15 through LL-22	15	53	7		5	9	9	10						1
ML-8 through ML-10	3	16	6	2		4	3	6						
MM-8		4			1	1		1		1				4
HL-3	1	4				3	4	4		1				
HH-9 through HH-14	—	<u>22</u>	<u>5</u>	—	—	—	—	<u>11</u>		—				<u>18</u>
All slurry pumps	19	99	18	2	6	17	16	32		2				

^aNumbers appearing in the table represent the total number of times that a particular problem area was cited for a given category of pumps. For example, one manufacturer cited cavitation as a problem for all 14 pumps in the liquid pump LL category, another cited cavitation 11 times, one for five pumps, and two each for one or two pumps. Cavitation was cited as a problem for the LL group 36 times and was cited as a problem at least twice for each of these LL pumps, five times in one instance.

^bSee Pump Questionnaire in Appendix B for equipment operating conditions.

^cThe Other problem area includes vane replacement (2 times), valves (17), plungers (12), and packing (12). All of these areas except vane replacement refer to reciprocating pumps.

For clean-liquid centrifugal pumps, cavitation was the most frequently mentioned problem, but this problem can be avoided by matching the pump design to the available net positive suction head (NPSH) at the pump inlet. When necessary, a charge pump (a pump designed for low available NPSH) should be used to provide sufficient NPSH for the primary pump. Bearings and seals were also frequently mentioned as problem areas. Follow-up comments indicated that these problems can be handled satisfactorily by use of the latest available technology in these areas. Use of separate seal-oil and lube-oil systems could be important in alleviating these last problems, although this would be more expensive initially. Seal isolation has also been suggested for hot-oil pumps.

Erosion was the problem mentioned most with respect to slurry pumps. Lower velocities in centrifugal slurry pumps were frequently mentioned as a means of handling slurries with currently available construction materials. Impeller-tip velocities of no more than 100 fps is a rule-of-thumb maximum generally accepted within the industry for very abrasive slurries; maximum velocities of no more than 70 fps were recommended by one manufacturer who is currently selling slurry pumps to the petroleum and coal conversion industries. Typically, centrifugal slurry pumps are relatively slow-running machines when compared to clean-liquid pumps. Larger pump diameters were suggested to compensate for head loss caused by lower operating speeds. Operation of centrifugal slurry pumps in a narrow band around the maximum efficiency point will prolong the life of such pumps by minimizing turbulence and backflow, which result in excessive wear rates. Improved hydraulic design may also be possible; this, too, can reduce wear rates.

Variable-speed drivers to permit speed adjustment as pumps wear have been suggested to maintain pumping characteristics and to prolong pump life. Axial adjustment of pump shafts might also be a means of maintaining interstage seal clearances as seals wear. Easily removable internal-wear components were recommended by most manufacturers. Such recommendations vary from use of easily replaceable "subparts" in high-wear areas such as volute tips to frequent replacement of all internal parts. These subparts would normally be an integral part of some larger component in a clean-liquid pump. Use of the most advanced materials and coatings was suggested.

The most severe problem of reciprocating slurry pumps is wear of sliding parts and valves. Wear is presently tolerated by use of designs that permit rapid replacement of worn parts. To permit repairs while maintaining continuous operation, multiple units are required. One spare is generally installed for one to eight required units. As they are developed, the application of better materials in valves, plungers, and packings has been recommended to improve the wear characteristics of reciprocating pumps.

Research and Development Needs

No research and development needs were reported for clean-liquid pumps. Some manufacturers may do some testing as they use scale-up information to develop their own line of equipment for applications for which equipment is already available from other vendors.

For slurry applications, the development of better materials has been suggested for both reciprocating and centrifugal-type slurry pumps. Test facilities have been suggested for evaluating the performance and wear characteristics of currently available clean-liquid multistage pumps on abrasive slurries. Identification of hydraulic and wear problems through such testing is needed to determine the starting point for modifying present-generation multistage pumps to handle slurries; reportedly, points of expected wear sometimes fail to materialize, while other points may wear severely.

A widespread belief exists throughout the industry that multistage centrifugal pumps need to be developed for coal conversion applications. This seems to be prevalent among equipment manufacturers and users with experience in the operation of smooth-running centrifugal pumps on clean liquids. On the other hand, those experienced with the reliability of reciprocating pumps with spares installed to minimize the effects of maintenance may prefer reciprocating machines. This latter group believes that improvements in materials will benefit both reciprocating and centrifugal machines and perhaps maintain a competitive edge for reciprocating machines.

Scale-up of existing reciprocating pumps to about 6000 to 7000 hp has been suggested as a means of reducing the large number of units in parallel, which is often required to meet capacity requirements. This might also reduce the initial and maintenance costs associated with reciprocating machines to more reasonable levels. One manufacturer has suggested that additional work needs to be done to develop reliable, single-stage slurry pumps for hot-oil applications.

4.2 Compressors

Compressors are used in many different industries for a variety of purposes; the manufacturers of this type of equipment generally tend to specialize their product line within a reasonably consistent range of specific applications, for example, air conditioning and refrigeration compressors, air compressors over a wide range of sizes, etc. Responses to the compressor questionnaire were obtained from 18 manufacturers, most of whom specialize in equipment for the petrochemical industry. Because of the wide range of compressor applications encountered in this industry, no manufacturer stocks machines for immediate delivery; instead, each item of equipment is designed and built to order for a specific application. The manufacturers' assessments of their capabilities to supply compressors for the coal conversion industry is considered in this subsection.

Availability

Of the 40 individual compressor applications, all but 7 can be supplied by one or more of the 18 manufacturers on a special-order basis, with deliveries ranging from 15 to 24 months. Volumetric flow and discharge pressure are two of the most significant parameters in determining the size, type, and availability of compressors for these applications. Figure 3 shows the location of each of the 40 applications on a plot of discharge pressure vs volumetric flow. The numeral adjacent to each point shows the number of manufacturers who indicated the capability to provide a full-capacity compressor for that application. These numbers tend to be highest near the middle of the figure; they decrease rapidly

Fig. 3. Compressor type as a function of inlet flow rate and outlet pressure.

at the highest levels of flow and pressure. Table 9 presents these same data by identifier.

As indicated by Fig. 3, several distinct types of compressors are required to cover the wide range of pressures and flows. Positive displacement compressors can be used over the entire range of pressures for volumetric flows of up to about 10,000 acfm. Centrifugal compressors are applicable from approximately 500 acfm to more than 100,000 acfm. Axial flow compressors are used for the highest levels of volumetric flow, including flows in excess of 1,000,000 acfm in some favorable cases.

As volume flow and discharge pressure are increased, compressors become larger and heavier. There are limits, both economic and practical, to the size and weight of compressor components that can be manufactured, shipped, and installed. The maximum pressure for which compressors are normally available therefore decreases with increasing volumetric flow, approximately as indicated in Fig. 3. Because of the large number of variables that can enter into compressor design and manufacture, appreciable deviations from the maximum pressure levels indicated in the figure may occur for specific individual applications.

Table 9 shows that none of the low-pressure, low-pressure-ratio fans and blowers listed under identifiers FB-1 through FB-9* are offered on a full-capacity, special-order basis by more than two manufacturers. One of these manufacturers is a German firm. The maximum discharge pressures for these machines range between 14.7 and 15.8 psia, and pressure ratios vary from 1.03 to 1.09. These blowers or fans are large in size but relatively light in weight. Few companies are set up to build such equipment. Axial-flow machines were specified by both manufacturers for identifiers FB-1 through FB-5, which handle relatively clean gas streams.

Particulate contents of 0.5 to 1.5 grains per actual cubic foot were specified for identifiers FB-6 through FB-9, and the manufacturers recommend that centrifugal compressors be used for these four applications because the relatively thin blades used in axial flow compressors would suffer excessive erosion from impingement of the particulates. Maximum volumetric flows for centrifugal machines of the double-flow type would probably be limited to about 350,000 acfm vs the specified

* See Compressor Questionnaire in Appendix B for equipment operating conditions.

Table 9. Summary of availability of compressors

Identifier ^a	Inlet flow rate (acfm)	Solid contents (grains per acfm)	Molecular weight	Inlet temperature (°F)	Pressure (psia)		Availability		Remarks
					Inlet	Outlet	Best	Number of vendors	
FB-1	220,000		26.0	225	14.5	15.8	A2 ^b	2	
FB-2	260,000		28.8	126	14.7	15.1	A2	2	
FB-3	400,000		28.9	200	14.5	15.8	A2	1	
FB-4	800,000		28.9	200	14.5	15.8	(A2) ^c	1	720,000 acfm maximum
FB-5	600,000	0.03	29.4	295	13.9	14.7	A2	1	
FB-6	410,000	0.5	30.2	700	14.7	15.6	(B1)	1	350,000 acfm maximum
FB-7	1,230,000	0.5	30.2	700	14.7	15.6			
FB-8	360,000	1.5	28.6	160	14.7	15.3	(B1)	1	350,000 acfm maximum
FB-9	720,000	1.5	29.6	160	14.7	15.3			
L-1	270,000		12.5	120	110	180	A2	4	
L-2	220,000		28.9	80	14.7	21.7	A2	3	
L-3	350,000		28.9	80	14.2	104	A2	5	
L-4	910,000		28.9	80	14.7	105	A2	1	
L-5	75,000		25.4	100	15	30	A2	6	
L-6	10,000		44.1	250	72	200	A2	9	
ML-1	32,000		13.1	150	455	475	A2	5	
ML-2	11,000		16.0	232	393	408	A2	7	
ML-3	20,000		16.8	125	415	440	A2	5	
ML-4	150,000		32.0	80	100	270	A2	2	Oxygen
ML-5	330,000		32.0	80	100	270	B1	3	Oxygen
ML-6	900,000		32.0	80	100	270	B1	1	Oxygen
MH-1	400		22.7	180	18	470	A2	3	Reciprocating
MH-2	35,000		27.4	625	22	460	A2	2	
MH-3	16,000		41.9	100	14	280	A2	9	
HL-1	10,000		15.8	125	1,040	1,090	A2	5	
HL-2	14,000		15.9	300	970	1,090	A2	6	
HL-3	40,000		15.9	300	970	1,090	A2	4	
HL-4	6,000		16.0	120	722	803	A2	6	
HL-5	10,000		16.7	100	388	1,020	A2	6	
HL-6	10,000		19.4	125	415	1,065	A2	6	
HH-1	25,000		11.0	89	64	830	A2	7	
HH-2	30,000		15.5	120	30	1,000	A2	6	
HH-3	30,000		18.9	100	225	1,160	A2	6	
HH-4	35,000		31.9	80	15	710	A2	5	Oxygen
HH-5	70,000		31.9	80	15	710	A2	3	Oxygen
VH-1	7,000		2.3	100	1,055	4,268	A2	2	
VH-2	2,000		2.6	120	550	2,600	A2	1	
VH-3	80,000		5.2	120	2,400	2,600	A2	1	
VH-4	7,000		5.9	100	3,970	4,268	A2	3	
VH-5	28,000		5.9	100	3,970	4,268	A2	2	

^aSee Compressor Questionnaire in Appendix B for other equipment operating conditions.^bA2 indicates equipment is available from the responding company; B1 indicates equipment will be available from the responding company.^cFor availability codes in parentheses, see Remarks column for maximum flow rate of proposed equipment.

capacities of 360,000 to 1,230,000 acfm. An additional problem is involved for applications FB-6 and FB-7; the inlet temperatures are specified as 700°F. Although it is feasible to build compressors for gas temperatures of this level, it is anticipated that high temperatures might aggravate the erosive effects of the particulates. In summary, applications FB-6 through FB-9 may be difficult to obtain at the specified capacity levels.

While two manufacturers offer to supply oxygen compressors ML-4 on a special-order basis, ML-5 and ML-6 will be more difficult to obtain. All three applications are identical except for volumetric flow. A review of the proposed applications for these compressors indicates that an initial misinterpretation of the process requirements resulted in the flow levels for ML-5 and ML-6 being overstated by a factor of 32. ML-4 as presented in the questionnaire should therefore provide adequate capacity for any of the corrected applications.

Problem Areas

Responses of the various manufacturers to the Problem Areas column of the questionnaire were not uniform. Many of them left the column blank in virtually all instances, but a few included an entry for almost every application. Subsequent discussions, primarily with the manufacturers of large compressors for the process industries, indicated that their evaluations of potential problems were far more uniform than was at first interpreted from their written responses. This subject will be discussed further in Sect. 5.2 under problem areas.

4.3 Hydraulic Turbines

Hydraulic turbines are supplied by manufacturers who specialize in hydroturbines for power generation at hydroelectric dams and by centrifugal pump vendors who generally offer their pumps as hydraulic turbines by operating them in reverse rotation. A number of companies formerly specialized in the hydroturbine field; however, as the size of these power production units became larger, many of these companies discontinued manufacturing hydraulic turbines because of decreased demand and

intense foreign competition. Currently, there are only two domestic hydroturbine manufacturers, one of which, Allis-Chalmers, responded to the hydraulic turbine questionnaire. Three pump manufacturers also responded as well as one hydraulic motor manufacturer, whose offerings were limited. Thus five responses were received to the hydraulic turbine questionnaire.

Availability

Most of the hydroturbines now produced by Allis-Chalmers are used for hydropower generation. These turbines are considerably larger than would be required for coal conversion plants; however, in the past, they have made smaller turbines that are more nearly compatible with coal conversion plant requirements. Many of the old drawings for these smaller units are still extant and may be revised for present applications with minimal effort. Furthermore, the significant advances made in increasing turbine efficiency can be applied to these small turbines once they are again manufactured. The reversible pump/turbine units manufactured by Allis-Chalmers have an efficiency of 91 to 92% when operated in either mode. This is approximately ten percentage points better than the pumps operated in reverse which are supplied by centrifugal pump manufacturers.

The need for hydraulic power recovery equipment in the chemical process and petroleum industries has been satisfied recently by pumps running in reverse rotation. The only modification made to pumps so used is the installation of an impeller* different from that used for the pumping mode.

Two of the three responding centrifugal pump manufacturers offered single or multistage units for each of the specified clean-liquid applications. The third company and the other domestic hydroturbine manufacturer (who was contacted by phone) indicated that they could supply machines for approximately one-half of these applications. These latter

* Runner is the proper terminology for hydraulic turbines.

companies indicated that technology should also be available for the other applications.

Hydraulic turbines for slurry applications are less available than are turbines for clean-liquid applications. Alternate suppliers exist only for applications T-18 and T-19.* One vendor initially indicated that he had available equipment for applications T-20 through T-24 but later expressed reservations. One or two other companies have in-house scale-up technology for these applications.

Equipment for applications T-25 and T-26 was not listed as available in any response. One company believes that it has the necessary information to develop and produce this equipment if market demand is sufficient; this claim was supported by another vendor who indicated that such technology should be available within the industry. Two other companies indicated that 5 to 10 years would be required to make such equipment available; this development may or may not require government funding, depending on market demand.

Francis-type turbines (including centrifugal pumps run in reverse rotation) have generally been suggested for the 26 hydraulic turbine applications. Allis-Chalmers suggested, however, that impulse (Pelton) turbines may be best suited for slurry applications, provided the back pressure on the unit is low. The buckets of the Pelton wheel will be subjected to severe erosion but can be replaced readily.

Problem Areas and Proposed Solutions

Technical problems reported for hydraulic turbines were generally the same as those reported for pumps. No significant problems appeared for clean-liquid applications; however, care must be taken to maintain the outlet pressure high enough to prevent cavitation. For slurry applications, erosion is a significant problem; however, slurry pump technology, as it is developed, can be applied to hydraulic turbines.

* See Hydraulic Turbine Questionnaire in Appendix B for equipment operating conditions.

Research and Development Needs

Although hydraulic turbines are available for clean-liquid applications, improved designs would increase efficiency.

Materials research is required to develop better materials for slurry applications.

4.4 Gas Expanders

Gas expanders are used by industry to recover energy from pressurized gas streams. Primary use of these devices has been in the fluidized catalytic cracking units of petroleum refineries and in nitric acid plants. The former application must handle particulates that remain entrained in the gas stream even after three stages of cyclones; the latter application involves a clean gas stream. Eight manufacturers, all of whom supplied information on compressors, responded to the questionnaire on gas expanders. Conventional steam and gas turbines were not considered in this study.

Availability

Six different expander applications were specified. Equipment for four of these applications could be supplied on a special-order basis by from two to four manufacturers, with delivery in 12 to 18 months. Although these applications cover wide ranges of temperature and pressure (see identifiers E-1 through E-4* in Table 10), they share one common characteristic — inlet temperatures are no more than 1200°F.

Two of the manufacturers propose radial inflow expanders for applications E-1 through E-3; only one of them proposes the same type of machine for application E-4. A third vendor specified axial flow expanders for each of these four cases; a fourth would supply lobe-type machines, which he proposes for E-2 and E-3.

Equipment for the remaining applications (E-5 and E-6) is not currently available because of the high inlet temperatures (1657°F; E-5;

* See Gas Expander Questionnaire in Appendix B for equipment operating conditions.

Table 10. Estimated delivery periods for hot-gas expanders

Identifier ^a	Inlet flow rate (acfm)	Solids content (grains per acf)	Molecular weight	Inlet temperature (°F)	Pressure (psia)		Maximum output (hp)	Development lead time (years)
					Inlet	Outlet		
E-1	60		5.3	120	2,400	500	1,000	0
E-2	16,000		28.2	135	106	20	12,400	0
E-3	85,000	0.23	26.7	348	120	20	80,400	0
E-4	85,000	0.15	31.3	1,200	113	25	63,800	0
E-5-A	15,000	3.15	23.0	1,657	1,095	66	203,000	2.5 - 7
E-5-B	15,000	0.16	23.0	1,657	1,095	66	203,000	2.5 - 6
E-5-C	15,000	0.016	23.0	1,657	1,095	66	203,000	2.5 - 5.5
E-6-A	310,000	0.15	29.0	1,744	66	25	87,400	2.5 - 7
E-6-B	310,000	0.0075	29.0	1,744	66	25	76,400	2.5 - 5
E-6-C	310,000	0.00075	29.0	1,744	66	25	87,400	2.5 - 5

^aSee Gas Expander Questionnaire in Appendix B for other equipment operating conditions.

1744°F, E-6) and the presence of particulates in the gas streams. Estimates of development lead time for these two applications vary from 2.5 to 7 years. Twelve to eighteen months will be required between the order and installation of equipment after it has been developed. Discussions with several vendors indicated that it might be difficult to obtain reliable expanders for these applications in less than 6 to 8 years.

Problem Areas and Proposed Solutions

When compared with the other listed applications, E-1 and E-2 are relatively small units working as modest (120 to 135°F) inlet temperatures. The manufacturers did not anticipate any particular service or reliability problems for either of them. Most vendors anticipate some corrosion, erosion, and possibly pitting problems for application E-3, which has an inlet temperature of 348°F and a volumetric flow of 85,000 acfm. Problems similar to those for E-3 are also anticipated for application E-4 (1200°F inlet temperature), and the number of vendors offering available equipment drops to two for this higher temperature application.

The still higher temperatures encountered by applications E-5 (1657°F) and E-6 (1744°F) pose more severe challenges. Four major U.S. manufacturers of hot-gas expanders appear to agree that the present state of the art limits maximum gas inlet temperatures to about 1350 to 1400°F if the life expectancy of the expander blading is to be maintained in the range of from 10,000 to 40,000 hr (i.e., about 1 to 5 years). This temperature limit is valid only for particulate loadings of no more than 0.06 grains per acf.*

Some type of blade cooling is required for operating temperatures above about 1300°F. Impingement cooling of the blade roots has been used for some expanders operating at temperatures as high as about 1450°F; however, as temperatures are further increased, more extensive and thorough forms of cooling are required. It will become necessary to keep gas temperature excursions under much closer control, and improved alloys

* Gas turbines are reported to have much lower tolerances for particulates.

will be required for the expander blades (buckets) or impellers, particularly when particulates are present.

There is a wide variation in the approach of the various manufacturers to the problem of entrained particulates. Although some prefer to restrict their activities to particulate-free gas streams, at least four companies have expressed an interest in developing expanders that can handle some level of particulate loading.

Airco Cryogenics is developing a concept for an expander of the radial inflow type, which should be suitable for handling particulate-laden gas streams. The concept includes repositioning the gas inlet nozzles and addition of passages for removal of particulates.

The Elliott Company has obtained a patent⁵ for a radial outflow expander that is intended to separate particulates from a hot-gas stream by centrifugal action while simultaneously obtaining some useful work output. A radial outflow stage could be followed by conventional axial flow stages in a multistage unit if required. A working model of the radial outflow stage has been built and is to be tested to determine its flow characteristics with clean gas at low temperatures.

Dresser-Clark, through their licensing arrangements with a German firm, Gutehoffnungshütte AG (GHH), should be able to obtain license rights to an invention by an Austrian company, Elin-Union. This latter organization has developed a method for minimizing the effects of erosion on the most critical portions of a hot-gas expander blade — by incorporating a "stumble-step" just upstream of the blade. It is understood that Elin-Union has received some patent protection for this concept; however, it is not currently known whether or not a U.S. patent has been granted.

Although formal drawings of the stumble-step concept were not available for review, a brief description of the principle was given by representatives of Dresser-Clark. As the gas approaches the blades of an expander, it is normally guided through a smooth annular passage whose cross-section changes gradually and continuously, to avoid perturbations in the flow. In the stumble-step concept, an abrupt discontinuity (a step) is introduced just ahead of the first blade row; the step introduces a minor cross flow or eddying of the hot gas, which diverts most of

the particulates away from the roots and tips of the blades, thus reducing the rate of erosion in this relatively highly stressed area. Prior to each succeeding stage, a step redistributes the particles away from critical areas where they would otherwise accumulate because of centrifugation. At least one expander that incorporated stumble-steps has reportedly accumulated approximately 40,000 hr of successful operation. Some erosion of the leading edges of the first row of stator blades was reported and is believed to have been because of the accidental omission of the first stumble-step.

Ingersoll-Rand representatives discussed results of developmental tests conducted on hot-gas expanders used for fluid catalytic cracking service and furnished copies of two papers.^{6,7} Ingersoll-Rand devised a method for observing stroboscopically the appearance of rotor blades during expander operation and followed the progress of deterioration caused by particulate-induced erosion. As a result of these tests, it was possible to modify the contours of the blades in critical areas and to increase their thickness, thus minimizing the adverse effects of erosion. Although the modifications reduce the operating efficiency of an expander with newly installed blades, a higher average efficiency can be obtained over a period of time because expander performance with the thickened blades deteriorates far less rapidly than with conventionally designed blades. Hard facing in critical blade areas also helped to reduce erosion rates.

A major problem in testing for the effects of particulates is the continuous provision of a representative supply of material. It is anticipated that attempts to recycle particulates in a test system will result in their degradation to the point that interpretation of test results will be difficult. It therefore seems probable that meaningful results can best be obtained through the continuous generation of a fresh supply of particulates. This would infer the need for a gasifier section to provide the required flow as well as a means of waste disposal.

Research and Development Needs

A consensus of suggestions made by the major potential vendors of hot-gas expanders includes:

1. study and improvement of materials for high-temperature expander components (especially blades),
2. further development and testing of proprietary and patented methods for reducing damage to expander components by entrained particulates, and
3. the provision of test facilities that can provide a continuous supply of representative particulates over a lengthy test period.

Additional data will be required before any of the manufacturers can formulate a realistic R&D program. This need is discussed in Sect. 5.4.

5. ANALYSIS AND DISCUSSION

In the preceding section, information received from the manufacturers was presented; this section presents the evaluation of that data. Arrangement of the presentation is the same as in the preceding section, with availability, problem areas and proposed solutions, and research and development needs being discussed in that order. Emphasis is on those applications for which equipment is not available or for which availability is questionable. Proposed solutions are also emphasized, and research and development needs are evaluated.

5.1 Pumps

Information received in response to the pump questionnaire and in follow-up discussions with manufacturers reveals that pumps are likely to be available for all clean-liquid applications specified. On the other hand, the availability of slurry pumps is much less clear, with erosion being the dominant problem.

Availability

The availability of equipment for each pump application in the questionnaire is summarized in Tables 11 through 15. For applications having readily available equipment, complete or nearly complete sets of data were used in compiling these summaries. Such sets of data are available for most clean-liquid applications. One entry is made for each type of pump currently available at capacities as large as or larger than that specified in the questionnaire. In the case of those applications for which the availability of equipment is questionable, as with most slurry pumps, poor agreement was found in the data collected. In such cases, several entries may be made to show the various levels of equipment availability along with opposing views as to the type of equipment proposed and its expected performance. In these situations, entries are sometimes made for equipment with capacities such that multiple units will be required to meet the specified capacities.

Table 11. Availability of pumps for low-pressure, low-head applications

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
<u>Liquid pumps</u>												
LL-1	1-A1	9,600		rotary		1-A	1-B	25	95		12	
	4-A1	4,000		cent	1	4-A	4-B	7.5	95.8	2-H	7	
	4-A2	19,675		cent	1	3-B 4-A 1-BCG	4-B 1-CD	5	98	1-BFG 1-BGH	12	
LL-2	1-A	9,600		rotary		1-A	1-B	10	98		8	
	1-A2	20,000		turbine	3	1-A	1-B	5	80	1-J	2	
	1-A1	4,800		cent	1	1-ABC		5	98	1-G	12	
	5-A2	26,400		cent	1	5-A 1-BC	5-B 1-CD	5	98	1-ABGH	13	
LL-3	1-A2	50,000		turbine	1+	1-A	1-B	10	98	1-FH	12	
	5-A2	117,600		cent	1	5-A 1-B	5-B	9	97.4	1-GF	21	
LL-4	1-A2	100,000		turbine	1+	1-AG	1-ABCDE	10	98	1-FH	18	
	4-A2	128,000		cent	1	4-A 1-B	4-B 1-D	10	97.25	1-GF	25	
LL-5	4-A2	209,300		cent	1	4-A 1-B	4-B	10	97.4	1-GF	25	
LL-6	1-A2	9,500		rotary		1-A	1-D	10	98		10	
	1-A2	20,000		turbine	1	1-A	1-B	5	80	1-J	4	
	2-A1	20,800		cent	1	2-A 1-BC	2-B	7.5	96.5	2-G 1-A	24	
	4-A2	25,500		cent	1	4-A	4-B	11.2	96.5	2-G 1-AB	16	
LL-7	1-A2	9,600		rotary		1-A	1-D	10	98		10	
	1-A1	39,000		cent	1	1-ABC	1-B	5	98	1-G	12	
	3-A2	35,666		cent	1	3-A	3-B	6.7	97	1-ABG	17	
LL-8	1-A2	9,600		rotary	1	1-AB	1-BE	5	98	1-A	6	
	1-A2	5,400		turbine	1+	1-AG	1-BCDE	10	98	1-AFH	12	
	3-A1	7,500		cent	1	3-A 2-BC	2-BE	8.3	96	1-FGH	8	
	3-A2	43,000		cent	1	3-A	3-B	11.7	97	1-A	16	

Table 11 (continued)

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
LL-9	1-A1	9,600		rotary	1	1-A	1-B	10	98		8	
	1-A2	9,000		rotary	1	1-A	1-B	10	95		12	
	1-A2	1,500		turbine	1+	1-AG	1-BCDE	10	98	1-AFH	12	
	5-A1	10,050		cent	1	5-A	4-B	7	96.2	2-H	8	
						2-BC	1-E			1-BGF		
	3-A2	30,000		cent	1	3-A	4-B	5	98	1-ABGH	12	
						2-B	1-CD					
LL-10	1-A1	9,600		rotary	1	1-A	1-B	10	98		8	
	1-A2	9,000		rotary	1	1-A	1-B	10	80		18	
	3-A1	4,033		cent	1	3-A	3-B	6.7	97	1-BFGH	8	
						2-BG						
	2-A2	20,500		cent	1	2-A	2-B	5	98		15	
LL-11	1-A1	9,600		rotary		1-A	1-B	10	98		8	
	1-A2	9,000		rotary	1	1-A	1-B	10	80		18	
	4-A2	14,662		cent	1	4-A		5	98	1-G	15	
						1-BC						
LL-12	1-A1	9,600		rotary		1-A	1-B	10	98		8	
	1-A2	9,000		rotary	1	1-A	1-B	10	95		18	
	3-A1	4,935		cent	1	3-A	3-B	8.3	96	1-FGH	8	
						2-BC						
	4-A2	23,800		cent	1	4-A	4-B	5	98	1-ABGH	13.5	
						1-BC	1-CD					
LL-13	2-A2	7,000		rotary	1	1-A	1-B	25	95	1-FH	16	
	2-A1	1,180		cent	1	2-A	2-B	5	98	1-G	12	
						1-BC						
	4-A2	10,000		cent	1	4-A	4-B	6.2	97.2	1-ABGHF	11	
						2-BC						
LL-14	4-A2	9,312		cent	1	4-A	4-B	6.2	97.2	1-G	15	
						1-BC						
Slurry pumps												
LL-15	1-A2	17,000		turbine	1+	1-AG	1-BCDE	10	98	1-AFH	12	
	1-A1	22,000		cent	1	1-A	1-E	25	80	1-BFG	24	
	2-A2	32,204		cent	1	2-A	2-B	10	95	2-B	18	
						1-BC						

Table 11 (continued)

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
LL-16	2-A2	17,500		cent	1	2-A 1-BC	1-BD	25	80	2-B 1-H	23.5	
LL-17	2-A1	16,000	temp % solids	cent	1	2-A 1-B	2-V belt 1-B	27.5	89	1-ABC	12	
	4-A2	15,450		cent	1	4-A 2-BC	3-B 1-D	30	78.8	4-B 2-H	18	
LL-18	3-A1	14,670		cent	1	3-A 1-B	3-belt	23.3	94.3	3-B	8	
	5-A2	12,920		cent	1	5-A 3-B	4-B 1-DE	47	82	1-AFG	16.6	
LL-19	1-A1	10,000		cent	1	1-AB	1-B 1-V belt	5	98		6	
	4-A2	14,675		cent	1	4-A 2-BC	3-B 2-D	46	78.8	3-B 2-EH	18	
LL-20	4-A1	9,475		cent	1	4-A 2-B	3-V belt 1-B	28.8	88.2	4-B 1-ACH	6	
	4-A2	15,031		cent	1	4-A 3-B	3-B 2-D	56.2	78.8	4-B 2-H	18	
LL-21	3-A1	14,670		cent	1	3-A 1-B	3-V belt 1-B	23.3	85	3-B 1-AC	6	
	4-A2	19,533		cent	1	4-A 3-B	3-B 2-D	56.2	78.8	4-B 2-H	18	
LL-22	2-A1	17,000		cent	1	2-A 1-B	2-V belt 1-B	30	87.5	2-B 1-AC	6	
	3-A2	13,575		cent	1	4-A 3-B	4-B 3-D	56.2	78.8	4-B 2-H	18	

^aSee Pump Questionnaire in Appendix B for equipment operating conditions.

^bRefer to Table 4 for explanation of Availability Codes.

^cA number followed by a dash before a code indicates the number of manufacturers listing that code.

^dRefer to Pump Questionnaire in Appendix B for listing of Driver, Transmission, and Problem Area Codes.

Table 12. Availability of pumps for medium-pressure, low-head applications

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
<u>Liquid pumps</u>												
ML-1	2-A1	2,100		cent	1	2-A 1-BC	2-B	5	98	1-G	12	
	3-A2	5,133		cent	1	3-A 1-BCG	3-B 1-CD	5	98	1-ABGH	10	
ML-2	1-A1	7,000		cent	1	1-ABC	1-B	5	98	1-G	12	
	4-A2	10,575		cent	1	4-A 1-BCG	4-B 1-CD	5	98	1-ABGH	12	
ML-3	2-A1	590		cent	1	2-A 1-BC	2-B	5	98	1-G	12	
	3-A2	11,166		cent	1	3-A 1-BCG	3-B 1-CD	8.3	96	3-A 2-B	10	
ML-4	1-A2	300		rotary	1	1-A	1-D	10	98	1-K	6	
	2-A1	345		cent	1	2-A 1-BC	2-B	5	98	1-G	12	
	3-A2	16,166		cent	1	3-A 1-BCG	3-B 1-CD	5	98	1-BGH	10	
ML-5	3-A1	383		cent	1	3-A 1-BC	2-B 1-E	6.7	97	1-GH	10	
	3-A2	18,333		cent	1	3-A 1-BCG	3-B 1-BCE	6.7	97	2-H 1-ABG	12	
	1-A2	9,000		rotary	1	1-A	1-B	10	95	1-H	18	
ML-6	2-A2	13,250		cent	1	2-A	2-B	5	98	1-G	16	
	1-A2	9,000		rotary	1	1-A	1-B	10	80	1-FHJ	18	
ML-7	2-A2	26,500		cent	1	2-A	2-B	5	98		15	
<u>Slurry pumps</u>												
ML-8	2-A2	24,000		cent	1	2-A 1-BC	2-B	25	80	2-B 1-C	18	
	3-B1	19,000	e	cent	1	3-A 2-BC	2-B 1-FDE	36.6	80	3-B 2-H	22	

Table 12 (continued)

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
ML-9	1-A2	26,000		cent	1	1-A	1-B	25	80	1-B	24	
	2-B1	21,000		cent	1	2-A 1-BC	1-DE	37.5	80	2-B 1-ACH	15	0.5
ML-10	1-A2	6,000		cent	1	1-ABC	1-B	25	80	all	12	
	1-B1		new	cent	2	1-A	1-B	50	60 ^f	1-B	24	1
	1-B1	20,000		cent	1	1-ABC	1-D	25	80	1-BH	12	1
	1-B1	22,000	g	cent	h	1-A	1-V belt	50	80	1-ABC	18	

^aSee Pump Questionnaire in Appendix B for equipment operating conditions.

^bRefer to Table 4 for explanation of Availability Codes.

^cA number followed by a dash before a code indicates the number of manufacturers listing that code.

^dRefer to Pump Questionnaire in Appendix B for listing of Driver, Transmission, and Problem Area Codes.

^eInlet and outlet pressure temperature.

^fAvailability can be improved with R&D.

^gInlet pressure and head.

^hFour single-stage centrifugal pumps in series.

Table 13. Availability of pumps for medium-pressure, medium-head applications

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
<u>Liquid pumps</u>												
MM-1	1-A1	7,200		cent	2	1-A	1-B	5	98			
	3-A2	11,166		cent	1	3-A	3-B	5	98	1-G	12	
MM-2	1-A1	5,400		cent	2	1-ABC	1-B	5	98	1-G	12	
	3-A2	10,833		cent	1-2	3-A	3-B	5	98		18	
	1-A2	4,500		turbine	multi	1-G	1-CDE	10	98	1-FH	18	
	1-A2	3,700	valving	plunger	e	1-AG to suit	1-BCDE to suit	10	95	f	12	
MM-3	1-A2	9,000		turbine	multi	1-AG	1-BCDE	10	98	1-FH	18	
	4-A2	11,325		cent	1-2	4-A 1-BC	4-B	5	98	1-G	17	
MM-4	1-A2	1,300		turbine	1+	1-AG	1-BCDE	10	98	1-AFH	18	
	1-A1	1,560		cent	3	1-ABC	1-B	5	98		12	
	4-A2	14,615		cent	1-2	3-A	4-B	6.2	96.5	2-ABG	14	
	1-A2	3,700		plunger		1-BCG to suit	1-CD to suit	10	95	1-H f		
MM-5	1-A1	9,600		cent	1	1-ABC	1-B	5	98	1-G	12	
	3-A2	13,467		cent	1-2	3-A	3-B	8.3	96	2-A 2-G	18	
MM-6	3-A2	17,000		cent	1-10	3-A	3-B	8.3	96	2-AG 1-BH	18	
MM-7	3-A2	12,333		cent	1	3-A	3-B	5	98	2-D	18	
	2-A2	9,300		rotary		2-A	2-B	25	80	1-FGHJ	13	

Table 13 (continued)

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
<u>Slurry pump</u>												
MM-8	1-A2	3,200		piston		1-ABC	1-D	5	93	1-M	18	
	1-A2	2,000		plunger		to suit	to suit	10	95	f	12	
	1-A2	741		g		1-A	1-D	5	80	1-B	12	1
	1-A2	200	180°F	h	e	1-A		5	93	i	6	0.25
	1-B1	1,000		cent	4	1-ABC	1-D	50	80	1-BH	12	1
	1-C1			cent	6	1-A	1-B	100	60	1-B	24	

^aSee Pump Questionnaire in Appendix B for equipment operating conditions.

^bRefer to Table 4 for explanation of Availability Codes.

^cA number followed by a dash before a code indicates the number of manufacturers listing that code.

^dRefer to Pump Questionnaire in Appendix B for listing of Driver, Transmission, and Problem Area Codes.

^eRequires multiple units in parallel.

^fPlunger, valving, and packing.

^gPositive displacement.

^hBag diaphragm.

ⁱBall check valves.

Table 14. Availability of pumps for high-pressure, low-head applications

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
<u>Liquid pumps</u>												
HL-1	1-A1	6,700		cent	1	1-ABC	1-B	5	98	1-G	12	
	3-A2	9,733		cent	1	3-A	3-B	6.6	97	1-FG	17	
HL-2	1-A1	9,600		cent	1	1-ABC	1-B	5	98	1-G	12	
	3-A2	10,670		cent	1	3-A	3-B	6.7	97	1-FG	15	
<u>Slurry pumps</u>												
HL-3	2-A2	13,950		cent	1	2-A	2-B	17.5	87.5	2-ABG	18	
	1-B1	12,000		cent	1	1-A	1-B	25	80	1-BFGH	15	0.5

^aSee Pump Questionnaire in Appendix B for equipment operating conditions.

^bRefer to Table 4 for explanation of Availability Codes.

^cA number followed by a dash before a code indicates the number of manufacturers listing that code.

^dRefer to Pump Questionnaire in Appendix B for listing of Driver, Transmission, and Problem Area Codes.

Table 15. Availability of pumps for high-pressure, high-head applications

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
<u>Liquid pumps</u>												
HH-1	3-A2	11,333		cent	2-4	1-A	1-B	6.7	97	1-GH	19	
	1-A2	3,700		plunger		to suit	to suit	10	95	e		
HH-2	3-A2	10,555		cent	2-4	1-A	1-B	6.7	97	1-GH	19	
HH-3	1-A1	18,700		cent	2	1-ABC	1-B	5	98	1-G	12	
	2-A2	19,000		cent	2-3	2-A 1-B	2-B 1-C	7.5	96.5	1-GH	17	
HH-4	1-A2	1,026		f	g	1-A	1-D	5	80	1-G	12	0.5
	1-B1 ^h	36,000	capacity	cent	3	1-A	1-B	10	95	1-GH	15	0.5
HH-5	1-A1	4,100		cent	4	1-ABC	1-B	5	98	1-G	12	
	3-A2	12,700		cent	2-4	3-A	3-B	13.3	96	2-AG 1-GH	19	
	1-A2	3,700		recip		to suit	to suit	10	95	e		
HH-6	2-A2	15,650		cent	1	2-B 1-AC	2-B	5	98	1-G	18	
	1-A2	32,000		cent	2	1-A	1-B	25	95	1-AGH	15	
HH-7	3-A2	11,333		cent	3-9	2-A 1-B	2-B 1-G	8.3	96	2-AG 1-BH	25	
	1-A2	3,700	valving	plunger	g	to suit	to suit	10	95	e	12	
HH-8	3-A2	10,667		cent	6-10	2-A 1-B	2-B 2-C	6.3	97	1-k	25	

Table 15 (continued)

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
<u>Slurry pumps</u>												
HH-9	1-A2	3,700	valving	plunger	g	to suit	to suit	10	95	e		
	1-A2	972		f	g	1-A	1-D	5	80		12	1
	1-C3	1,840	HP	plunger		1-ABC	1-D	5	98	1-H	18	2
	1-B1 ⁱ			cent	5±		1-B					
	1-A2 ^{i,j}			cent				10		1-B	15 ^k	
	1-C3/C4 ⁱ			cent						1-B	48	2
	1-D2 ⁱ			cent						1-B		
HH-10	1-A2	650	valving	plunger	g	to suit	to suit	10	95	e		
	1-B1	400		f	g	1-A	1-D	5	80	1-B	24	2
	1-C3	735	HP	plunger	g	1-ABC	1-C	5	98	1-H	18	2
	1-A2 ^{i,j}			cent				25		1-BCH	15 ^k	
	1-C3/C4 ⁱ			cent						1-B	48	2
	1-D2 ⁱ			cent						1-B		
HH-11	1-A2	650	valving	plunger		to suit	to suit	10	95	e		
	1-B1	400		f		1-A	1-D	5	80	1-B	24	2
	1-C3	735	HP	plunger		1-ABC	1-D	5	98	1-H	18	2
	1-A2 ^{i,j}			cent				25		1-BCH	15 ^k	
	1-C3/C4 ⁱ			cent						1-B	48	2
	1-D2 ⁱ			cent						1-B		
EH-12	1-A2	2,400	valving	plunger		to suit	to suit	10	95	e	12	
	1-C3	2,400	HP	plunger		1-ABC	1-D	5	98	1-H	18	2
	1-A2 ^{i,j}			cent				25		1-BCH	15 ^k	
	1-C3/C4 ⁱ			cent						1-B	48	2
	1-D2 ⁱ			cent						1-B		
HH-13	1-A2	2,400	valving	plunger	g	to suit	to suit	10	95	e	12	
	1-A2	1,195		f	g	1-A	1-D	10	80	1-B	18	1.5
	1-C3	2,700	HP	plunger	g	1-ABC	1-D	5	98	1-H	18	2
	1-A2 ^{i,j}			cent				25		1-BCH	15 ^k	
	1-C3/C4 ⁱ									1-B	48	2
	1-D2 ⁱ			cent						1-B		

Table 15 (continued)

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of pump	Stages	Driver ^{c,d}	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development time (years)
HH-14	1-A2	2,400	valving	plunger	<i>g</i>	to suit	to suit	10	95	<i>e</i>	12	
	1-A2	1,195		<i>f</i>	<i>g</i>	1-A	1-D	10	80	1-B	18	1.5
	1-C3	2,400	HP	plunger	<i>g</i>	1-ABC	1-D	5	98	1-H	18	2
	1-A2 ^{i,j}			cent				25		1-BCH	15 ^k	
	1-C3/C4 ⁱ									1-B	48	2
	1-D2 ⁱ									1-B		

^a See Pump Questionnaire in Appendix B for equipment operating conditions.

^b Refer to Table 4 for explanation of Availability Codes.

^c A number followed by a dash before a code indicates the number of manufacturers listing that code.

^d Refer to Pump Questionnaire in Appendix B for listing of Driver, Transmission, and Problem Area Codes.

^e Plungers, valving, and packing.

^f Positive displacement.

^g Requires multiple units in parallel.

^h Three other manufacturers stated B1 for availability and that development would be easy but provided no other data.

ⁱ Data received from manufacturers of pumps for EH liquid pump applications.

^j Follow-up discussions indicated A2 was overly optimistic.

^k Greater than 15 months.

Pumps are available from a number of manufacturers for each clean-liquid application specified in the pump questionnaire and would therefore also be available for all clean-liquid applications found in coal conversion facilities. Furthermore, in-house scale-up information is available to additional manufacturers for most of the clean-liquid applications. Few limiting factors of significance were listed for this equipment; when they were, they appeared to be from vendors who were commenting on pumps outside of their normal line of experience or interest. Thus pumps for clean-liquid applications are readily available and may be expected to perform according to the parameters in the summary tables.

The availability of slurry pumps, however, is questionable at best. Maintenance requirements are great, and slurry pumps generally have a reputation of unsatisfactory service.

Reciprocating pumps, which are very large and must often be installed in multiple units to meet capacity requirements, have been used satisfactorily for slurries; furthermore, additional capacity is required because frequent maintenance is necessary. High slurry concentrations can be handled by reciprocating machines, pump efficiency is good, and excellent system reliability can be attained with multiple units.

Centrifugal pumps are smaller and are often considered to be more advanced machines than reciprocating types. They also have a reputation for being smoother running and more reliable, based on excellent experience obtained in clean-liquid service. This reputation, however, is unfounded for slurry applications. Little experience is available for use by industry in the design of centrifugal slurry pumps for continuous service. Available information comes primarily from the mineral processing industry in which operation is intermittent and in which pumps are shut down for one or more shifts per week. During such time, maintenance can be performed without interrupting the process. Such frequent repairs are not desirable for the petrochemical and coal conversion industries; pumps are expected to run for several months between maintenance jobs. In general, centrifugal pumps are not available for such continuous service, based on information obtained not only from the manufacturers but also from architect-engineers and users. Furthermore, if centrifugal pumps were used, spare capacity would still be required because of frequent maintenance requirements.

Equipment for the low-pressure, low-head slurry applications (LL series*) appearing in the pump questionnaire is available from about two centrifugal pump manufacturers per application when considering only manufacturers who provided complete sets of data, including maintenance cost and in-service availability. This situation provides little depth in terms of alternate supplies for this equipment, even if in-house scale-up information is available as was indicated by several other manufacturers. Furthermore, the maintenance cost for these slurry pumps is several times that for similar pumps in clean-liquid service. Projected in-service availability is $\leq 80\%$ for slurry applications in most cases vs $\sim 95\%$ for clean-liquid pumps. Thus pump availability appears to be unsatisfactory for this group of pumps in continuous service applications unless spares are furnished. Because reciprocating pumps do not match such low-pressure, low-head applications, extensive research and development is needed to improve the performance of centrifugal slurry pumps for this service. A program for such research and development should draw on technology available from both ore-handling pump and refinery pump manufacturers. These same comments also apply to applications ML-8, ML-9, and ML-10. The data received for these latter applications do not mention reciprocating pumps.

Positive displacement pumps were generally specified and appear to be satisfactory for application MM-8. The specified horsepower, flow rate, pressure rise, and outlet pressure fall in ranges that match operating parameters of present-generation reciprocating pumps. The 60% solids content appears to be high for centrifugal pumps; furthermore, a 750-psi head requires multistage centrifugal pumps, which are not currently foreseen for slurry service.

The high-pressure, low-head application HL-3, which has a 10-psi pressure rise to 2500 psia, does not require the high head associated with reciprocating pumps. Thus currently available centrifugal pumps operated at very low speeds may, with some modifications, be suitable for this application.

* See Pump Questionnaire in Appendix B for equipment operating conditions.

The high-pressure, high-head slurry pumps required for applications HH-9 through HH-14 are the least available pumps considered in this survey. Only for HH-9 is equipment currently available at the flow rate specified. In this case two full-capacity reciprocating pumps* would be installed to provide continuous operation, although only one is needed to meet the capacity. Another option in this situation is to run both machines at one-half of their rated speed, that is, at 50% capacity. This would extend the time between repairs and also the life of the pumps. Such a procedure is not advisable for centrifugal pumps, however, in any situation; they are designed to run near peak efficiency, and deviation from this condition will increase wear and decrease pump life.

The other HH slurry applications require from 2 to 22 reciprocating pumps in parallel with from one to three spares. All of the information received on these reciprocating pumps, in essentially complete sets, appears in Table 15. Information received from manufacturers who have centrifugal pumps for one or more of the HH clean-liquid applications is also reported for the HH slurry applications. None of the HH slurry-pump applications can currently be satisfied with multistage centrifugal units; in fact, only one of the centrifugal pump manufacturers interviewed can foresee development of such pumps unless government funding is provided. The single company that indicated they could supply centrifugal pumps for these applications withdrew its projection during follow-up discussions. This company, which is initiating an active slurry pump development program, apparently has good in-house multistage slurry-pump technology but was overly optimistic on the near-term availability of such pumps for the HH-9 through HH-14 applications.

In summary, pumps are available for all clean-liquid applications. Single-stage centrifugal equipment for low-head slurry applications (LL, ML, and HL series) requires developmental work. The medium- to high-head slurry applications (MM and HH series) must be met in the near term by reciprocating machines.

* Three half-capacity units might also be used with two needed to meet capacity.

Problem Areas and Proposed Solutions

No problems that would substantially hinder availability and performance of pumps for clean-liquid applications were indicated. Problems that were noted are minor and may be overcome by careful specification and design of the pump based on as complete a knowledge of pump requirements as possible. For pumps in slurry applications, essentially all of the minor problems encountered with clean liquids may become significant. Furthermore, erosion becomes the dominant problem in slurry pumps.

Four basic solutions to counter erosion effects were identified as being common to both reciprocating and centrifugal slurry pumps. These solutions include installation of spare units to maintain continuous operation, replacement of worn parts, design of machines to run at slow speeds, and use of better construction materials. The last two solutions should reduce the erosion rate and prolong equipment life.

Repair of slurry pumps will be frequent, perhaps as often as every 3 weeks. Such frequent repair will necessitate installation of spare capacity, with the number of spare units required being dependent on the duration and frequency of repairs. Quicker maintenance turnaround can be accomplished by careful design of equipment, including easily replaceable inserts or subparts to facilitate rapid replacement of those parts subjected to the greatest erosion. In reciprocating pumps, these high-wear parts include cylinders, pistons or plungers, and, in particular, valves. Wear in centrifugal pumps is more severe than in the other pumps, affecting both impeller and casing. Sealing against back flow through worn areas, which results in decreased pump efficiency, will be difficult. The frequency of repair of both centrifugal and reciprocating slurry pumps is anticipated to be about the same; however, repair will be more extensive for centrifugal pumps.

Slow speeds are also recommended to reduce the rate of erosion in slurry pumps. In this area, reciprocating pumps appear to have an advantage; not only have they been slower running than centrifugal machines, but their outlet pressure is dependent on valve arrangement rather than on speed. Relative velocities of no more than 100 fps have been suggested by a number of manufacturers, and this suggestion appears

to be a good rule of thumb; however, examples provided indicated that many pumps run more slowly. This limitation keeps pressure rise per stage to a maximum of approximately 100 psi in centrifugal pumps; as rotational speed is decreased, the impeller diameter must be increased to maintain the desired head.

The fourth basic solution mentioned is the use of better construction materials, which would be more erosion resistant. Difficulties encountered in this approach are the availability of such materials and the limitations imposed on them. These limitations include resistance to thermal shock, pressure containment ability, and difficulty of machining. Such materials may be used for inserts or subparts in cases in which they would not be required to withstand high-pressure differentials. These inserts or subparts require only minimal machining. Surface hardening techniques that have been or are being developed should also be used when appropriate. Of the four basic solutions presented, appropriate construction materials could be the most critical to increasing pump life expectancy.

Other solutions mentioned for centrifugal pumps include better hydraulic design, provision of means for closing the gap between the wearing impeller and wear rings without opening the machine, and use of variable-speed drivers to maintain pump operation at its maximum possible efficiency regardless of the extent of wear. This last point on maintaining maximum efficiency is critical; running at lower efficiencies reduces pump life rapidly, whether a slurry or a clean liquid is handled.

The development of centrifugal slurry pumps is hindered not only by the physical limitations discussed above but also by dispersion of the necessary technology among various segments of the pump industry. The manufacturers of centrifugal pumps have tended to specialize their lines of pumps to meet the requirements of certain markets. As a result, existing slurry-pump technology is concentrated among several manufacturers who supply equipment primarily for low-pressure, low-head applications such as those found in the mineral beneficiation industry. Furthermore, existing high-pressure, high-temperature technology is found primarily among companies providing pumps to the petrochemical industries. With few exceptions, the experience gained by these various manufacturers cannot be used easily to develop multistage centrifugal slurry pumps.

Consequently, only reciprocating pumps remain for the high-head slurry applications. These machines are limited to about 3000 to 4000 hp per unit; thus multiple-unit installations will be required for high-flow applications. Although this requirement may be of concern to some, several multistage centrifugal slurry units in series (if they are developed) may be required to develop the high heads encountered in these applications. Furthermore, if several trains of such units were to be installed in parallel, the end result might be that as many units would be required by one type of pump as the other. In fact, unless some technological breakthrough is achieved that will permit development of a higher head per stage than 100 psi along with an increased acceptable life expectancy, centrifugal pumps may never be competitive in this high-pressure, high-head category.

Research and Development Needs

The current horsepower limitations of reciprocating pumps necessitates the use of multiple units in parallel to meet high-flow applications. Doubling of the current capacity of reciprocating pumps for use in first-generation commercial-scale liquefaction and gasification facilities is desirable. This double capacity will reduce the number of units required for a given application and may also lead to a reduction in initial and operating costs.

Centrifugal slurry pumps of both single and multistage design are in need of development. Single-stage units need to be improved to meet the demands of continuous operation; multistage units are, at the present time, essentially nonexistent. A development target for multistage slurry pumps is the provision of an outlet pressure in the range of 600 to 800 psia, a figure seen by some manufacturers as an upper pressure limit. This target, if achieved, would bridge the gap between existing single-stage centrifugal slurry pumps and reciprocating pumps; otherwise, the series installation of single-stage units may be required.

One of the keys to developing or improving slurry pumps, whether of centrifugal or reciprocating design, is the use of better construction materials. Research is needed in this area.

Another key to promoting the development of centrifugal slurry-pump technology is to establish clearly market demand. The present needs of the coal conversion industry are still hazy, and many manufacturers do not wish to risk research dollars on an undetermined market. Whether or not the market picture is resolved, test facilities are required. Many manufacturers do not have testing capabilities for slurries; however, several manufacturers have expressed reservations about common test facilities supported by the government because of possible disclosure requirements concerning pump design.

For the benefit of both markets, the development of pumps and hydraulic turbines to handle slurries should be coordinated.

5.2 Compressors

Compressors are available for most applications found in the coal conversion industry. There are, however, several significant exceptions: high-pressure oxygen compressors and high-flow low-head fans and blowers, particularly for streams containing entrained particulates. This section addresses primarily these exceptional items of equipment.

Availability

In addition to fan and blower and oxygen-compressor applications, the low-flow applications MH-1, VH-1, and VH-2,* for which compressors are available, are also considered below.

Fans and Blowers. As a class, the least readily available machines are the large fans or blowers in the "FB" classification (see Table 9). Only two companies, Elliott and American Demag, market these units in the relatively large sizes specified. For the five applications in which entrained particulates are either absent or in relatively low concentrations (indentifiers FB-1 through FB-5), both vendors offer axial flow blowers; the maximum capacity of the Elliott machines is 350,000 acfm; American Demag offers capacities up to 720,000 acfm.

* See Compressor Questionnaire in Appendix B for equipment operating conditions.

A single American Demag machine would satisfy the volumetric flow requirements for all of the applications except FB-4, in which the 800,000-acfm requirement exceeds the 720,000-acfm availability by about 11%; therefore, smaller machines in parallel would be required. With the Elliott 350,000-acfm limit, two or three parallel compressors would be required for applications FB-3, FB-4, and FB-5.

Although there were differences in the initial proposals of the two above-mentioned vendors for the applications in which particulate-laden gases are involved, both finally recommended the use of centrifugal blowers for all applications, primarily because centrifugal impellers can be built with impeller vanes that are relatively thicker and that have larger surface areas than axial-flow compressor blades. For these reasons, centrifugal units withstand abrasion by particulates for a longer time. Elliott stated that volumetric flow rates of about 350,000 acfm could be produced with double-flow centrifugal machines. American Demag specified maximum flows of 200,000 acfm for single-flow centrifugals and stated in a general note that greater levels could be obtained with double-flow construction.

If it is assumed that both vendors can produce 350,000-acfm blowers of double-flow construction, two parallel machines would be required for applications FB-6 and FB-9, and three blowers in parallel would be needed for identifier FB-7. The 360,000-acfm requirement for FB-8 is only slightly above the postulated maximum available capacity.

In an actual plant, reliability and maintenance considerations might frequently dictate the use of two or more parallel blowers or compressors. In drafting the questionnaires, it was decided that the entire flow requirement for a given application would be specified for a single machine in some cases. This would elicit information on maximum flows that could be handled by available equipment.

The relatively high (700°F) inlet temperature requirements for identifiers FB-6 and FB-7 will require improved materials and more sophisticated design; therefore, cost and delivery times for these particular units will be increased. Furthermore, for all cases involving particulates, the characteristics of the particle involved are important. Relatively soft particles will affect the life of a blower less

significantly than will sharp and highly abrasive ones. On the other hand, even soft particles can cause major problems if they adhere to the rotating components because imbalance and vibration can result.

Oxygen Compressors. As mentioned in Sect. 4.2, an initial misinterpretation of the process information for ML-4, ML-5, and ML-6 resulted in flow requirements being overstated by a factor of 32 (see Table 9); therefore, the largest volumetric flow should have been specified as about 28,000 acfm (for ML-6). The responses to the questionnaire indicate that this capacity should be available on a normal special-order basis, using a compressor of centrifugal design. The specified discharge pressure for each of these identifiers is 270 psia.

Specifications for the HH-4 and HH-5 oxygen compressors are identical in all respects except for volumetric flow, which differs by a factor of two. Several vendors offer to supply these compressors on a special-order basis, with the normal 18- to 24-month delivery. The 710-psia discharge pressure specified for these machines is relatively high. Although many oxygen compressors now in service operate with discharge pressures of as high as about 600 psia, two exceptions are known to be operating at higher pressures. These compressors were designed for operation at an outlet pressure of 960 psia; reportedly one of the compressors has been operated experimentally at pressures as high as 1500 psia.

Requirements for high-pressure oxygen compressors exist for several coal conversion processes. These requirements were not clearly identified in the equipment lists of reports mentioned in Sect. 3.1 and Appendix A. One such requirement for provision of 2000 tons per day of oxygen would demand an inlet volumetric flow of about 35,000 acfm at 80°F and 15 psia. The required outlet pressure for the process would be about 1250 psia; the required compressor-discharge pressure might be 50 to 100 psi higher.

Low-Volumetric Flow Applications. The following cases are worthy of special mention.

Identifier	Volume flow (acfm)	Pressures (psia)		Pressure ratio	Gas composition (mole %)
		Inlet	Outlet		
ML-1	400	18	470	26.1	42% H ₂ O, 31% H ₂ S, 27% NH ₃
VH-1	7000	1055	4268	4.0	99% H ₂ , 1% N ₂
VH-2	2000	550	2600	4.7	96% H ₂ , 4% CH ₄

The very low volumetric flow and high-pressure ratio of application MH-1 will definitely require the use of a reciprocating compressor according to seven of the eight vendors who furnished information for this application. A similar situation prevails for application VH-2 because of the low-flow and high-outlet pressure.

For application VH-1, two vendors estimated that from 40 to 65 centrifugal stages would be required for compression because of the thermodynamic characteristics of hydrogen. The responses for this application were evenly divided; three vendors recommended reciprocating compressors, and three others specified centrifugal machines. The ultimate selection would undoubtedly be based on an economic comparison, including costs not only for the compressors but also for the associated drive trains.

As mentioned earlier, centrifugal compressors can be built for volumetric flows as low as 500 acfm or lower. As the flow decreases, however, all dimensions of the centrifugal impeller must be reduced proportionately if excessive losses in efficiency are to be avoided. To produce a given pressure rise, however, the peripheral velocity (tip speed) of the impeller must be maintained approximately constant. As volume flow is reduced, therefore, the rotating speed of the impeller must be increased; hence the speeds for centrifugal compressors for applications MH-1 and VH-2 would be extremely high. For this reason, reciprocating compressors become more economical for low-volumetric flow applications, particularly when relatively high-outlet pressures or pressure ratios are involved.

Potential vendors of reciprocating compressors are probably under-represented in their input to this survey. When centrifugal and reciprocating compressors are built by the same company, they are often marketed by separate divisions. Because the questionnaire contained a

preponderance of centrifugal and axial flow applications, it was usually referred first to that division and probably arrived either late or not at all at the division that would handle reciprocating compressor inquiries. Future specific individual requests for information on low-volumetric flow compressors may be expected to receive a larger number of responses than was received in answer to this questionnaire.

Reciprocating compressors are a single species in the more general class of positive displacement compressors; several other types of positive displacement compressors are manufactured, of which rotary-lobe compressors are one example. These latter machines are widely used for a variety of applications but are not currently available for the relatively high pressures required for the low-volumetric flow cases specified in the questionnaire.

Problem Areas and Proposed Solutions

The applications expected to pose the most major problems in the successful specification of compressors are the four applications that involve particulate levels in the gas stream of 0.5 to 1.5 grains per acf (identifiers FB-6 through FB-9). As noted in the preceding section, these machines would normally be axial flow fans; however, two vendors have recommended that centrifugal blowers be used instead because their impellers are relatively thicker than the axial fan blades and thus should last longer. The maximum flow required by any of the process flow sheets (specifically, the Coalcon process) for any of these four applications is 410,000 acfm. Two 200,000-acfm centrifugal blowers in parallel will very nearly satisfy this requirement. It is conceivable that some of the techniques for handling particulates in hot-gas expanders (see Sect. 4.4) could also be applied to these particular applications.

Equipment suppliers and users express different opinions about the reliability and safety of high-pressure oxygen compressors, extending even to whether it is better to pump liquid oxygen or compress gaseous oxygen to the high pressures required by some processes. Questions of overall process economics and the relative sophistication of the compressors (including components and controls) supplied by various U.S. and foreign manufacturers are involved.

In the past, destruction of high-pressure oxygen compressors by burning or explosion has occurred because of the high reactivity of oxygen with metals in the presence of heat. The likelihood of such accidents is reported to increase with operating pressure; however, these chances can be minimized by the following combination of measures:

1. maintaining the maximum temperature of the oxygen stream below 200°C (392°F),
2. restricting temperatures to even lower levels in the higher pressure sections of the compressor,
3. adopting a conservative compressor design that will ensure against contact between rotating and stationary parts,
4. practicing stringent cleanliness control during system assembly, and
5. providing reliable temperature and other special monitoring devices.

The adoption of these measures reportedly permitted the successful experimental operation of the previously mentioned oxygen compressor at pressures as high as 1500 psia.

Many important questions that affect the initial and operating costs for compressors were not addressed in this brief survey. For example, many of the medium- and high-pressure ratio compressors have a number of variables that can affect both types of costs. Intercooling between compression stages, which can significantly reduce horsepower requirements, may increase overall equipment cost; in some cases intercooling may be mandatory for temperature control. There are other situations in which it is most economical and practical to build a compressor having as many as nine or ten stages in a single casing, even though overall efficiency and the range of stable operation are thereby decreased. In other cases, requirements for high efficiency and a wide range of stable operation may demand the use of several separate compressors in series.

The proper matching of compressors and drivers also warrants considerable study. In many coal conversion plants, steam turbines or hot-gas expanders will be installed as compressor drives to make use of

excess energy from the conversion process. It is often possible to tailor the speeds and other characteristics of compressors to match the preferred characteristics of the drivers and vice versa.

Past experience indicates that careful preparation of realistic compressor specifications can be a key factor in the procurement of equipment that will operate reliably and economically under actual process conditions. Such specifications should avoid restrictions often imposed by the use of existing industry codes prepared for conditions prevailing earlier; the main objective of the specifications should be to set forth the true operating conditions and other key parameters in a clear, unambiguous manner.

Research and Development Needs

One definite need is apparent, and a second one also probably exists. The first need is the development of techniques for dealing with particulate-laden gas streams in the large, low-pressure blowers or fans covered by identifiers FB-6 through FB-9. As is apparent from Sects. 4.4 and 5.4 dealing with hot-gas expanders, the problems caused by particulates will be a major source of concern for these expanders; these problems will require substantial research and development programs. It seems probable that many of the development activities for blowers can be an offshoot of the expander program; furthermore, additional specialized but limited efforts may be advisable for the development of these blowers.

Further study is required to define the optimum research and development program for the second area, high-pressure oxygen compressors. It seems possible that the most important function of such a program may be to assist major U.S. manufacturers of process compressors to advance their technology in the areas of stability and vibration analysis, mechanical rigidity and resilience of the compressor and drive train, and temperature and other fault-detection instrumentation.

This further study would include additional discussions with users of high-pressure oxygen compressors, with representatives of technology-intensive consulting and specialized compressor-manufacturing firms, and possibly with compressor manufacturers.

5.3 Hydraulic Turbines

As with pumps, hydraulic turbines are available for clean-liquid applications, but availability is questionable for slurry applications.

Availability

The availability of equipment for hydraulic turbine applications is summarized in Table 16. Several sets of data are presented for each application, the first having been received from the sole hydroturbine manufacturer responding. Data received from centrifugal pump manufacturers, who would generally use pumps operated in reverse rotation for these applications, is then presented; data for similar equipment is averaged. Information received from a hydraulic motor manufacturer for two applications is also tabulated. Turbines developed by the hydroturbine industry have efficiencies as high as 91 or 92% as opposed to efficiencies of approximately 80 to 85% obtained by operating pumps in reverse. Furthermore, the method for determining efficiencies in the hydroturbine industry is more demanding than the method used by pump manufacturers; therefore, results are more conservative.

Hydraulic turbines are available for the clean-liquid applications T-1 through T-17.* The very low slurry concentration of applications T-18 and T-19 is not expected to limit the availability of equipment; however, as slurry concentrations become greater, the availability of turbines will become much more limited than is the case with pumps. The one company indicating available equipment for T-20 through T-24 and scale-up information for T-25 and T-26 later qualified these projections as being overly optimistic. As a result, no equipment is immediately available for these last seven applications, although the design of equipment for applications T-20 through T-24 may be forthcoming if market demand is sufficient. The extremely high pressure of applications T-20 through T-22 is also limiting because of the need for multistage turbines. Development of equipment for slurry turbines, except for extremely low slurry concentrations, may require government funding.

* See Hydraulic Turbine Questionnaire in Appendix B for equipment operating conditions.

Table 16. Availability of equipment for hydraulic turbine applications

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of turbine ^{c,d}	Stages	Controls ^{c,d}	Efficiency (%)	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development lead time (years)
<u>Liquid hydraulic turbines</u>													
T-1	1-A2	6,050		C or E	1	1-CEFGJ	90+	1-B	20	87.5	2-ABD 1-J	14	0.5
	2-A2			L	2-4	2-D 1-CG	76.5	2-G 1-B				24	
T-2	1-A2	14,670		C or E	1	1-EF	90+	3-G 1-B	15	91	3-A 2-BD	14	0.5
	3-A2			L		2-DG 1-BCJ	81.6					22	
T-3	1-A2	27,500		C or E	1	1-EF	90+	2-G 1-C	17.5	89	2-A 1-BDGJ	14	0.5
	2-A2			L	1	1-BDGJ	82.5					21	
	1-A2	5,000		C	1	1-CDG	85	1-BG	10	95	1-ABD	24	
T-4	1-B1	4,600		C or L ^e	5-10	1-G	90+	2-G 1-B	25	87.5	stress ^f 2-ABD 1-J	20	2
	2-A2			L	12	2-D 1-CG	77.5					30	
	1-A2	50,000		L	8	1-BGD	86	1-G	5	98	1-AG	24	
T-5	1-B1	5,250		C or L ^e	5-10	1-G	90+	2-G 1-B	25	87.5	stress ^f 2-ABD 1-JO	20	2
	2-A2			L	6-10	2-D 1-CG	77.5					36	
	1-A2	50,000		L	8	1-BGD	86	1-G	5	98	1-AG	24	
T-6	1-A2	11,000		E	1	1-E	90+	2-G 1-B	20	87.5	2-ABD 1-JO	14	0.5
	2-A2			L	3-6	2-D 1-CG	81					24	
	1-A2	50,000		L	8	1-BGJ	83	1-G	10	95	1-AG	18	
T-7	1-A2	11,090		E	1	1-E	90+	2-G 1-B	25	87.5	2-ABD 1-JO	14	0.5
	2-A2			L	2	2-D 1-CG	81					24	
	1-A2	90,030		L	2	1-BGJ	81	1-G	10	95	1-AG	18	
T-8	1-A2	14,000		E	1	1-E	90+	1-C	30	80	1-ABDJ	14	0.5
	1-A2			L	4	1-D	75					24	
	1-A2	90,000		L	2	1-BGJ	78	1-C	10	95	1-AG	18	
	1-B1		new	L ^g	2	1-CDG	80	1-BG	10	95	1-ABD	36	

Table 16 (continued)

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of turbine ^{c,d}	Stages	Controls ^{c,d}	Efficiency (%)	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development lead time (years)
T-9	1-A2	17,000	new	E	1	1-E	90+					14	0.5
	2-A2			L	2	1-BDGJ	84	2-G	25	87.5	2-A	27	
	1-B1			L ^g	2	1-CDG	80	1-BG	10	95	1-BDGJ 1-ABD	36	
T-10	1-A2	32,500	new	E	1	1-E	90+					14	0.5
	2-A2			L	1	1-BDGJ	85	2-G	25	87.5	2-A		
	1-B1			L ^g	2	1-CDG	80	1-BG	10	95	1-BDGJ 1-ABD	36	
T-11	1-A2	50,000 28,000		C or E	1	1-EF	90+					14	0.5
	1-A2			C	1	1-CDG	85	1-BG	10	95	1-ABD	24	
	2-A2			L	1	1-BDGJ	85	2-G 1-C	20	87.5	2-A 1-BDGJ		
T-12	1-A2	40,000		C or E	1	1-EF	90+					20	0.5
	3-A2			L	1	2-DG 1-BCJ	84.7	3-G 1-BG	16.7	90	2-ABD 1-J		
T-13	1-B1	50,000 1,500 600	new	C or L ^e	5-10	1-G	90+				stress ^f	22	2
	1-A2			L	8	1-BGJ	78	1-G	5	98	1-AG	18	
	1-A2			L	6	1-D	60	1-CG	40	80	1-ABDJ	36	
	1-A2			K	1	1-L	90	1-B	10	95	h	18	
	1-B1			L	15	1-CDG	57	1-BG	5	98		36	
T-14	1-B1	50,000 15,000		C or L ^e	5-10	1-G	90+				stress ^f	24	2
	1-A2			L	8	1-BGJ	85	1-G	5	98	1-AG	18	
	2-A2			L	6-14	2-D 1-CG	75	2-G 1-BG	22.5	89	1-ABDJ		
	1-B1			K	1	1-L	93	1-B	10	95		18	
T-15	1-B1	50,000 4,000	new	C or L ^e	5-10	1-G	90+				stress ^f	24	2
	1-A2			L	8	1-BGJ	87	1-G	5	98	1-AG	18	
	1-A2			L	9	1-D	75	1-G	40	80	1-ABDJ	36	
	1-B1			L	12	1-CDG	80	1-BG	5	98		36	
T-16	1-B1	15,000 50,000	new	C or L ^e	5-10	1-G	90+				stress ^f	24	2
	1-A2			L	4	1-D	80	1-CG	40	80	1-ABDJ	36	
	1-A2			L	8	1-BGJ	88	1-C	5	98	1-AG	18	
	1-B1			L	8	1-CDG	80	1-BG	5	98		36	

Table 16 (continued)

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of turbine ^{c,d}	Stages	Controls ^{c,d}	Efficiency (%)	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development lead time (years)
T-17	1-B1			C or L ^e	5-10	1-G	90+				stress ^f	24	2
	1-A2	50,000	<i>i</i>	L	8	1-BGJ	88	1-G		98	1-AG	18	
	1-A2	15,000		L	4	1-D	80	1-CG	40	80	1-ABDJ	36	
<u>Slurry hydraulic turbines</u>													
T-18	1-A2			C	1	1-F	90+					14	0.5
	1-A2	30,000		L	1	1-CDG	75	1-BCG	25	80	1-B	24	
	1-B1	40,000	<i>j</i>	L	1	1-BGJ	80	1-G	10	95	1-AG	18	0.5
T-19	1-A2			E	1	1-E	90+					16	0.5
	1-A2	20,000		L	3-4	1-BGJ	80	1-G	5	98	1-AG	18	
	1-A2	4,500		L	6	1-CDE	80	1-BG	25	80	1-B		
T-20	1-B1		<i>k</i>	C or L ^e	5-10	1-G	90+				stress ^f	22	2
	1-A2 ^l	20,000		L	8	1-BGJ	80	1-G	10	95	1-ABG	18	
	1-D2					1-B					1-B		
T-21	1-B1		<i>k</i>	C or L ^e	5-10	1-G	90+				stress ^f	24	2
	1-A2 ^l	20,000		L	8	1-BGJ	82	1-G	10	95	1-ABG	18	
	1-D2										1-B		
T-22	1-B1		<i>k</i>	C or L ^e	5-10	1-G					stress ^f	24	2
	1-A2 ^l	20,000		L	6	1-BGJ	84	1-G	10	95	1-ABG	18	
T-23	1-B1		<i>k</i>	C or E	1	1-EF						14	0.5
	1-A2 ^l	40,000		L	1	1-BGJ	80	1-G	10	95	1-ABG	18	
	1-B1		new	L	2	1-CDG	70	1-BCG	50	60	1-B	24	1
T-24	1-B1		<i>k</i>	C or E	1	F						14	0.5
	1-A2 ^l	40,000		L	1	1-BGJ	84	1-G	10	95	1-ABG	18	
	1-B1		new	L	2	1-CDG	78	1-BGC	50	60	1-B	1	
T-25	1-C1/C3		<i>k</i>	E	1	1-E						14	0.5
	1-B1 ^l	9,000	solids	L	2-4	1-BGJ	75	1-G	25	85	1-ABG	18	0.5
	1-D2										1-B		

Table 16 (continued)

Identifier ^a	Availability ^{b,c}	Largest capacity (gpm)	Limiting factors	Type of turbine ^{c,d}	Stages	Controls ^{c,d}	Efficiency (%)	Transmission ^{c,d}	Maintenance cost (%)	In-service availability (%)	Problem areas ^{c,d}	Delivery time (months)	Development lead time (years)
T-26	1-C1/C3 1-B1 ^l 1-D	9,000	^k solids	E L	1 2-4	1-E 1-BGJ	75	1-G	25	85	1-ABG 1-B	14 18	0.5 0.5

^aSee Hydraulic Turbine Questionnaire in Appendix B for equipment operating conditions.

^bRefer to Table 4 for explanation of Availability Codes.

^cA number followed by a dash before a code indicates the number of manufacturers listing that code.

^dRefer to Hydraulic Turbine Questionnaire in Appendix E for listing of Driver, Transmission, and Problem Area Codes.

^eBarrel pump type construction required by high pressure.

^fStress is caused by high pressure.

^gSpecial design required to handle high dissolved gas content.

^hFilter required.

ⁱHigh horsepower requirement.

^jHigh head-to-capacity ratio.

^kLife expectancy.

^lAvailability stated is overly optimistic based on follow-up discussions.

Problems and Proposed Solutions

Most of the problems in hydraulic turbine applications are analogous to those for pumps; they therefore have similar solutions. Outlet pressure must be considered in turbine design, as would inlet pressure in pump design, as the critical parameter in avoiding cavitation problems. Erosion is likely to be more severe in turbines than in pumps if given the same slurry stream. Utilization of technology developed for slurry pumps will be beneficial to the turbine industry.

Research and Development Needs

Development programs for hydraulic turbines that must handle slurries should be coordinated with slurry pump programs so as to derive maximum benefits from each project. The reasons for higher turbine efficiencies should also be determined and investigated for their applicability to pump design. Resulting design modifications might be particularly beneficial because higher efficiencies lead to less wear.

The use of hydraulic turbines as pressure letdown devices, with power recovery being a side benefit, has been suggested for high-pressure slurries, based on the premise that they may last longer than throttling valves in this service. This approach should be investigated; favorable results would be an added incentive for developing hydraulic turbines.

Models have been used successfully by the hydroturbine manufacturers to obtain information for the design of full-scale units installed for hydroelectric generation. The modeling techniques developed by this industry should be investigated for their usefulness in development of both turbines and pumps for slurry applications.

5.4 Gas Expanders

Readily available equipment for power recovery from pressurized gas streams is limited to relatively clean applications below 1350°F. As temperature is decreased, the amount of entrained solids may be increased.

Availability

Expanders for the applications listed under identifiers E-1 through E-4* are expected to be available from several manufacturers; no major problems requiring appreciable research or development efforts are anticipated. The principal design task for these applications will be to match the operating speed and other characteristics of the expander to those of the compressor or other item of equipment that it will drive, to ensure optimum balance between performance, reliability, efficiency, and cost.

Applications E-5 and E-6 involve operating temperatures in excess of 1350°F and particulate-laden gas streams; equipment will not be available for these conditions until significant research, development, and testing have been successfully completed. Recommendations for these programs will be outlined in the following subsection.

Research and Development Needs

Several methods for reducing or eliminating the adverse effects of entrained particulates were discussed in Sect. 4.4 under problem areas and proposed solutions. All of these methods need considerable additional research and development before they can be used with confidence for the two high-particulate-level expander applications E-5 and E-6. Additional development and testing are also required to develop component cooling methods, select improved blade alloys, and verify other improvements needed for satisfactory operation at temperatures in the 1650 to 1750°F range specified for these same applications.

The recommended research and development effort can be divided into three principal phases:

1. a modest addition to the present survey effort leading to the formulation of criteria for future expander development,
2. a series of tests of the various concepts and designs, each directed toward a specific limited objective, and
3. testing of demonstration expanders under actual pilot-plant or demonstration-plant conditions.

* See Gas Turbine Questionnaire in Appendix B for equipment operating conditions.

The current survey was limited to manufacturers of industrial hot-gas expanders; therefore, data from one important area were not obtained. Expanders are used as integral components of aircraft gas turbines rather than being sold as end products. Substantially higher temperatures than those specified for any of the present survey applications are used for aircraft expanders (turbines).^{*} Some of the technology developed for these engines may be applicable to advanced hot-gas expanders for coal conversion applications.

In addition to the aircraft turbine industry, there are indications that some technology-intensive organizations may be developing expertise for hot-gas expanders; therefore, their suggestions should also be obtained.

To formulate optimum criteria for expander development projects, the requirements of the various processes and the advantages and disadvantages of alternate strategies should be carefully reviewed and analyzed. There are, for example, trade-offs between the costs of solids-gas separators and those of hot-gas expanders designed for various particulate levels. There are also possible trade-offs between expander inlet temperature and the extent of energy recovery; for instance, ref. 9 states that a reduction in expander inlet temperature from 1800 to 1300°F will reduce the direct-power output of the expander by only about 25%. This loss, which could be recovered in part by waste-heat boilers, might be economically acceptable if expanders for the higher temperatures were either unduly expensive or short-lived.

The parallel research and development contracts generated as a result of the establishment of these criteria would be directed initially toward specific objectives, which should be limited enough in scope to ensure that each succeeding step is based on a firm foundation. For example, "cold" tests of an expander design that included a particular separation concept might precede testing at higher temperatures; the initial high-temperature tests might then be made without particulates, and so on.

^{*} Reference 8 summarizes a proposed coal conversion method that will require a hot-gas expander designed to operate at gas temperatures as high as 3000°F.

It is anticipated that considerable progress in the development of processes and equipment technology for coal conversion processes will occur during the next several years. It will therefore be necessary to review and update continuously the optimum criteria for expander development and to guide the projects according to the updated criteria.

6. CONCLUSIONS AND RECOMMENDATIONS

This study was initiated with a twofold objective. First, the present capabilities of U.S. industry to supply the equipment needed for future coal conversion facilities was to be determined. Conclusions on these current capabilities are presented in the following subsection. Second, problem areas of the various types of required equipment were to be identified; if necessary, research and development needs, including lead-time requirements, were to be determined for producing equipment of advanced design. Research and development needs are presented in Subsect. 6.2. Unanswered questions raised by this study are considered briefly in Subsect. 6.3.

6.1 Availability

Equipment is available for all clean-stream applications considered in this study. Questions are raised only about oxygen compressors and, in a few cases, about equipment for high-temperature applications. The availability of all types of equipment used to handle solids is questionable. High erosion rates lead to short equipment lives; therefore, availability of equipment becomes a question of acceptable life expectancy, which is primarily concerned with economics. In this section, limitations of available equipment are first discussed, followed by the availability of questionable items in order of importance. Table 17 summarizes the limits of rotating equipment availability for coal conversion facilities.

Limitations of Available Equipment

In developing the various sets of equipment specifications that appear in Appendix B, information was obtained from several conceptual design reports that are based on coal conversion concepts believed to be representative of future coal conversion facilities in general. Because the more severe operating parameters in these reports were used in developing equipment specifications and because available equipment has been identified for all applications within certain limitations, it is concluded that equipment is available for almost all of the expected clean-stream

Table 17. Limits of rotating equipment availability

Operating parameter	Limit of specified operating parameter ^{a,b}							
	Pumps		Compressors				Hydraulic turbines	Gas expanders
	Centrifugal	Reciprocating	Axial	Centrifugal	Reciprocating	Oxygen		
Flow rate	200,000 ^c	<i>d</i>	<i>e</i>	<i>e</i>	<i>e</i>	350,000 ^f (2,000) ^g	<i>h</i>	100,000 ^f
Solids content	60 ⁱ	60 ⁱ	0.03 ^j	1.5 ^j		0	0	0.23 ^j @ 350°F 0.15 ^j @ 1,200°F 0.06 ^j @ 1,350°F 0 ^j @ 1,350°F
Temperature, °F	850		700	700		400	575	1,350
Pressure, psia	4,000	4,300	<i>e</i>	<i>e</i>	<i>e</i>	600 <i>k</i>	4,000	225 for clean stream 70 for dirty stream
Pressure head, psia ^l	4,000 ^m	<i>d</i>					4,000	
Pressure ratio ^l			48	270	270	40-65		15
Horsepower	36,000	3,000-4,000	60,000	60,000	10,000-12,000	60,000	<i>h</i>	80,000

^aSee Table 2 for limits of operating parameters encountered by rotating equipment in this study.

^bIn no case do all limits apply concurrently for a given type of equipment. Limits expressed numerically are upper limits based either on manufacturer's statements or, in the absence of such, the upper limit of the parameter in the equipment list for those items of equipment which are available. Figure 3 provides upper and lower limits.

^cGallons per minute.

^dSee Eq. (3.5).

^eSee Fig. 3.

^fActual cubic feet per minute.

^gTons per day.

^hHydroelectric power generation turbines are much larger in size than any industrial requirements.

ⁱWeight percent.

^jGrains per actual cubic foot.

^kOne oxygen compressor operates at 960 psia, and a sister unit has operated experimentally at 1500 psia.

^lMultiple unit installations may be required to meet the higher pressure heads or ratios required even if multistage equipment is used.

^mCentrifugal slurry pumps are limited to one stage with a maximum head of 100 psi.

applications likely to be found in future coal conversion facilities. The availability of oxygen compressors for pressures above 600 psia, however, is marginal. Restrictions on temperature may cause some minor difficulties with all types of equipment; these restrictions vary from one type of equipment to another. Careful specification of operating conditions and proper application of existing technology should minimize or prevent problems likely to be encountered with items of equipment used for clean-stream applications.

Oxygen Compressors. Oxygen compressors are readily available for compressing up to 2000 TPD of oxygen to discharge pressures of about 600 psia. One oxygen compressor is known to be operating with a discharge pressure of 960 psia, and a sister unit has reportedly been operated experimentally at 1500 psia; however, these cases are exceptional. Most oxygen compressors operating at these higher pressures have been destroyed by explosion or fire. Compressors capable of safely compressing 2000 TPD of oxygen to 1250 psia are yet to be developed; yet they are critical to a number of processes such as HYGAS and BI-GAS.

Temperature Limitations for Clean-Stream Applications. Although cooler operating temperatures are desirable from an equipment designer's point of view, pumps have been built for temperatures as high as 850°F and above. Compressors might also be designed for comparable temperatures; however, it is generally preferable to maintain lower temperatures because of equipment costs and operating efficiencies. It is recommended that the inlet temperature (600°F) of compressor MH-2* be reduced significantly inasmuch as gas temperatures increase during compression. Expander operation, even in the absence of particulates, is limited to about 1350°F unless blade and case cooling are employed.

Availability of Questionable Equipment

Slurry pumps are the most critical equipment items required for coal conversion facilities for which availability is questionable. Compressors (in particular, fans and blowers) for dirty-gas streams are also not readily

* See equipment questionnaires in Appendix B for equipment operating conditions.

available. Hot-gas expanders are critical to some coal conversion processes, and their development needs to be pursued. Hydraulic turbines for slurry applications are desirable but not currently available.

Slurry Pumps. Without reliable slurry pumps, coal conversion is impractical. Availability and reliability are really questions of acceptable equipment life expectancy and maintenance frequency. Because of high rates of erosion, maintenance work may be necessary as often as every 3 weeks and will frequently involve the replacement of severely eroded parts.

In the course of this study, no centrifugal slurry pumps were identified that operate continuously for more than 1 week at a time; however, maintenance does not normally disrupt the processes involved, primarily mineral beneficiation processes, inasmuch as these pumps were not required to be in operation around the clock. Current centrifugal pumps are of single-stage design and are limited to a pressure rise of <100 psi; if required, higher heads may be obtained by placing several single-stage units in series. If multistage centrifugal slurry pumps can be developed, manufacturers foresee a maximum outlet pressure of 600 to 800 psia.

High-head applications requiring pressure rises of greater than about 600 psi are handled currently by reciprocating pumps. Thus, if life expectancy and maintenance requirements are acceptable, equipment is available for low- and high-head applications. This situation either poses a need for intermediate-pressure-head multistage centrifugal slurry pumps or requires the installation of multiple single-stage units in series. The frequency of maintenance is expected to be about equal for centrifugal and reciprocating slurry pumps; however, maintenance will be more extensive for centrifugal pumps.

Slurry pumps need to be designed with easily replaceable subparts and liners for high erosion rate areas. Advanced construction materials should also be used, and velocities within the pump should be limited to a maximum of 100 fps. Centrifugal pumps must be operated at maximum efficiency to minimize wear.

Compressors for Dirty-Gas Streams. Compressors capable of handling particulate-laden streams may also be important; however, removing particulate matter by cyclones may solve the problems of severe particulate erosion of applications FB-6 through FB-9. FB-5 particulate loading is

already low inasmuch as the gas, as provided for in the flow sheet, has already passed through cyclones and an electrostatic precipitator. Axial flow compressors would normally be specified for the FB series of applications; if particulates are not removed, however, double-flow centrifugal compressors should be specified. Centrifugal compressors are more rugged than axial flow compressors and were recommended by several manufacturers. FB-6 and FB-7 require special construction materials not only because of the high temperature (700°F) but also because of aggregate erosion caused by this temperature. As temperature is increased, the tolerance of both compressors and expanders for particulates is decreased.

Expanders for High-Temperature, Dirty-Gas Streams. Expanders may or may not be required for first-generation coal conversion facilities, depending on the processes chosen for commercialization. Some processes require expanders to be justified economically; in other cases expanders may be desirable but are not absolutely necessary. Current technology limits expanders to a maximum temperature of about 1350°F, but design practice limits temperatures to about 1250°F. Higher temperatures will require blade and housing cooling as well as essentially complete particulate removal if present expander designs are used. Although a number of integrated particulate removal-expander processes are being studied, none have been demonstrated.

Hydraulic Turbines for Slurry Applications. Hydraulic turbines for slurry applications are not available; on the other hand, they do not appear to be critical. Slurry applications for turbines were postulated from the processes studied but were not included by those preparing the conceptual designs. Turbines may be desired for power recovery from high-pressure slurry streams, and some manufacturers have expressed the opinion that such units may serve better for pressure let-down purposes than valves. Anticipated problems with these units are expected to be more severe than analogous slurry-pump problems.

6.2 Research and Development Needs

The most critical items of equipment requiring research and development are slurry pumps and oxygen compressors, after which come fans and blowers

for low-pressure, dirty-gas streams. Next, and less critical except for a few processes, are expanders. Hydraulic turbines for slurry applications may be desirable, but are not necessary to justify a process. Particular areas of research and development work are discussed below.

Slurry Pumps

As previously discussed in Subsect. 6.1, single-stage centrifugal pumps for low-head applications and reciprocating pumps for high-head applications are available for slurry handling, although short pump life and frequent maintenance is to be expected. Both of these pumps need to be improved to operate for a longer time between maintenance and/or replacement. Multi-stage centrifugal slurry pumps are essentially nonexistent and need to be developed for heads as high as 600 to 800 psi (most manufacturers see 600 to 800 psia as a maximum outlet pressure from such pumps). These multi-stage pumps are needed to bridge the gap between single-stage centrifugal pumps and reciprocating units. The following items should be considered in designing slurry pumps.

1. Pump design should be based on a thorough knowledge of the specific application in which the pump will be used. It is essential that the pump be designed to operate at its highest efficiency to minimize wear, particularly if it is of centrifugal design.

2. Easily replaceable liners and subparts for high-wear areas should be incorporated in slurry-pump designs to reduce maintenance turnaround time.

3. Relative velocities in excess of 100 fps at no point should be included in slurry pump designs, unless erosion rates have been otherwise reduced significantly.

4. Advanced construction materials, such as hard metals and ceramics, should be developed for use in fabricating liners, subparts, and other parts of the pump such as the impeller to minimize the effects of erosion. Surface-hardening techniques also should be pursued.

Two additional matters must also be considered in establishing a research and development plan. First, the market demand for slurry pumps needs to be more firmly established. Inasmuch as the status and direction

of coal conversion commercialization is still unclear, most manufacturers are unwilling to commit research dollars to high-risk development projects for which they foresee no return on their investment. If the market picture remains unresolved, government funding of slurry-pump development will be required if these units are to be developed. The second matter is the need for slurry-pump testing facilities. Most manufacturers test pumps only with water, and those few manufacturers who have slurry-testing facilities have limited testing capabilities. Because of the difficulties of developing and maintaining adequate slurry test facilities, a testing center available to all manufacturers needs to be established; however, responding manufacturers have expressed concern about possible requirements leading to disclosures of proprietary information on pump design if government funding of such a center is involved.

Oxygen Compressors

Several coal conversion processes require high-pressure oxygen at about 1250 psig; one or more air-separation plants producing about 2000 TPD of oxygen are specified in the conceptual designs. Some compressor designers and operators prefer to limit outlet pressures for oxygen compressors to a maximum of about 600 psia to minimize the risk of explosion and/or fire, but others are willing to operate at pressures as high as 1500 psia. Because of the high reactivity of oxygen with metals in the presence of heat, the following measures are recommended.

1. Temperatures should not exceed 392°F in any part of the oxygen stream in the compressor and should be kept even lower as pressure is increased.
2. Design, construction, and installation of the compressor should preclude any rubbing contact between rotating and stationary parts which could lead to explosion and/or fire.
3. Strict cleanliness control should be practiced during manufacture, assembly, and maintenance of the compressor, the lack of which could also lead to explosion and/or fire.
4. Reliable temperature-monitoring and flash-detection devices should be used. Further development of the latter devices should be considered.

Fans and Blowers

Fans and blowers for particulate-laden streams need to be developed. Again, design and construction materials are important. The technology that is being considered or developed for handling particulates in hot-gas expanders should be reviewed for its applicability to fans and blowers.

Expanders

A number of particulate-removal techniques have been presented by their developers. Some of these techniques have been incorporated into actual expander designs, but others have not. All of them are discussed in Subsect. 4.4 and should be thoroughly investigated. Improved blade-cooling techniques and construction materials need to be developed for high-temperature applications.

Hydraulic Turbines

Hydraulic turbines for slurry applications are not critical items of equipment; however, technology developed for slurry pumps may also be used in developing slurry turbines. Development of these two types of equipment should be coordinated. The benefits of using hydraulic turbines for slurry pressure let-down should be considered.

6.3 Additional Areas of Study

In the course of this survey, a number of questions have been raised that could not be investigated in the time available. Several of these questions may have a significant effect on the course of research and development plans and should therefore be considered.

An important area of study not fully addressed is the adaptability of technology that has been developed for other industries to problems of equipment availability for the coal conversion industry. The experience of the mineral beneficiation and slurry pipeline industry should be thoroughly investigated, as well as the experience of coal conversion pilot plants, to establish more fully the level of existing technology and thereby to obtain a basis for future slurry-pump development. The aircraft turbine industry

may also be able to provide valuable high-temperature technology applicable to the design of hot-gas expanders.

The lead-time requirement for development of unavailable equipment was addressed briefly in the various questionnaires; however, the magnitude and nature of developmental work and the related costs were not considered. These aspects of development need to be determined to establish research and development programs, which we hope will lead to development of the required equipment by the time it is needed.

The information obtained during this study needs to be compared to equipment requirements for those processes most likely to be commercialized. In cases in which equipment availability is questionable, the possibility of modifying the process should be considered. The expenses involved in equipment development and use of the equipment afterward need to be compared to the economics and reliability of the modified process.

The availability of physical property data for slurries is limited. A program to expand this data base for the use of pump manufacturers needs to be considered.

The factors responsible for high hydroturbine efficiencies should be studied for their applicability to pump design. The modeling techniques that have been developed and successfully used by the hydroturbine industry for the design of the immense turbines installed in hydroelectric generating stations should also be investigated. These techniques may be particularly useful in the development of pumps and turbines for slurry applications.

Appendix A

PROCESSES FORMING A BASIS FOR EQUIPMENT SPECIFICATIONS

REFERENCES

1. R. J. McMahon, *Chemical Engineering Catalog*, Reinhold Publ. Co., Stamford, Conn., 1977.
2. Hydraulic Institute, *Hydraulic Institute Standards*, 13th ed., Cleveland, Ohio, 1975.
3. *Thomas Register of American Manufacturers and Thomas Register Catalogue File*, Thomas Publ. Co., New York, 1976.
4. Information Handling Service, *Visual Search Microfilm Plant Engineering Service*, Englewood, Colo., October 1976.
5. A. J. Miller, "Power Expander Centrifuge," U.S. Patent No. 3,905,197, Sept. 16, 1975.
6. J. P. Balfoort, "Power Recovery Systems and Hot Gas Expanders," pp. 1-7 in *Proceedings of the Third Turbomachinery Symposium, College Station, Texas, Oct. 15-17, 1974*, Texas A. & M. Univ. Press, College Station, Tex., 1974.
7. L. M. Stettenbenz, "Minimizing Erosion and Afterburn in the Power Recovery Gas Expander," presented at the Petroleum Mechanical Engineering and Pressure Vessels and Piping Conference, Denver, Colo., September 1970 (available as Form 3999 from Ingersoll-Rand, Phillipsburg, N.J.).
8. L. P. Harris and R. P. Shaw, *Energy Conversion Alternatives Study - ECAS - General Electric Phase II Final Report: Volume II, Advanced Energy Conversion Systems - Conceptual Designs: Part 3, Open Cycle Gas Turbines and Open Cycle MHD*, NASA-CR-134949, prepared by Corporate Research and Development, General Electric Company, for National Aeronautics and Space Administration, Energy Research and Development Administration, and National Science Foundation, Washington, D.C., December 1976, pp. 4.5-1 to 4.5-49.

9. A. L. Wilson, *Mechanical Development Recommendations, Interim Report*, FE-2240-44, C. F. Braun and Co., Alhambra, Calif., June 1977, pp. 156-67.

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Appendix A

PROCESSES FORMING A BASIS FOR EQUIPMENT SPECIFICATIONS

The seven processes forming a basis for equipment specifications are presented briefly in this appendix. The reference from which information was obtained on each process is cited along with basic information on coal feed and product flow rates obtained from the reference. The location and capacity of equipment serving as models for equipment specifications are also given. Simplified block flow diagrams show the arrangement of process units within the context of the overall process.

Information on processes forming bases for supplemental information is also provided.

BI-GAS Process

Reference

Energy Research and Development Administration, *250-Million-SCFD High-BTU Gas Plant*, ERDA 76-48, Process Evaluation Group — Mineral and Material Research and Development, Morgantown, W. Va., (March 1976).

Coal Feed

1. Western Kentucky #11 seam: 13,080 TPD (13,070 Btu/lb)
2. Montana subbituminous: 20,850 TPD (8,816 Btu/lb)

Products

1. Gas: 250 MM scfd (946 Btu/scf)
2. Gas: 250 MM scfd (951 Btu/scf)

Table A.1. Equipment included in survey - BI-GAS process

Identifier	Flow rate		Unit ^a
	Specified	Required	
<u>Pumps</u>	(gpm)	(gpm)	
LL-8	5,400	5,400	Flue Gas Processing (1)
LL-21	7,200	1,910	Slurry Preparation (2)
MM-1	6,000	1,900	Methanation (1)
HH-1	3,600	1,200	Methanation (1)
HH-5, 6	3,400	3,400	Purification (2)
	13,600		
HH-14	3,600	640	Slurry Preparation (2)
<u>Compressors</u>	(acfm)	(acfm)	
FB-2	260,000	44,000	Coal Preparation (2)
FB-3, 4	400,000	306,000	Coal Preparation (2)
	800,000		
HL-2, 3	14,000	12,000	Methanation (1, 2)
	40,000		

^aNumber in parantheses corresponds to 1 and 2 in above sections.

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Fig. A.1. Process unit flow sheet - BI-GAS process.

Coalcon Process

Reference

E. T. Coles, *Commercial Plant Process Evaluation Report*, report prepared under Contract No. E (49-18)-1736 with Energy Research and Development Administration, Coalcon, New York, N.Y., (August 1975).

Coal Feed

Illinois, Indiana, and Kentucky: 14,760 TPD (12,216 Btu/lb)

Products

Gas: 105 MM scfd (1,031 Btu/scf)

Heavy fuel oil: 2486 TPD (16,443 Btu/lb)

Light fuel oil: 926 TPD (18,614 Btu/lb)

Liquified petroleum gas: 415 TPD (21,474 Btu/lb)

Ammonia: 48 TPD (9,750 Btu/lb)

Sulfur: 353 TPD (3,980 Btu/lb)

Table A.2. Equipment included in survey - Coalcon process

Identifier	Flow rate		Unit
	Specified	Required	
<u>Pumps</u>	(gpm)	(gpm)	
LL-3, 4, 5	50,000 100,000 200,000	50,000	Cooling Water System
LL-9	1,500	250	Gas Cooling and Heavy Hydrocarbon Separation
LL-15	17,000	8,500	Coal Pressurization Steam System
LL-20	1,050	80	Hydrogen Production
LL-22	3,600	875	Hydrogen Production
ML-1	1,500	250	Gas Cooling and Heavy Hydrocarbon Separation
ML-6, 7	8,400 25,200	8,400	Gas Cooling and Heavy Hydrocarbon Separation
ML-8	9,000	1,400	Hydrogen Production
MM-2, 3	4,500 9,000	1,500	Hydrogen Production
MM-5, 6	8,000 16,000	8,000	Methanation
MM-8	700	700	Hydrogen Production
<u>Compressors</u>	(acfm)	(acfm)	
FB-6, 7	410,000 1,230,000	410,000	Coal Heating and Preparation
L-3	350,000	175,000	Oxygen Production
L-6	10,000	10,000	Deethanizer/Propane Refrigeration
MH-2	35,000	35,000	Deethanizer/Propane Refrigeration
HL-4	6,000	6,000	Methanation
HH-1	25,000	20,000	Methanation
HH-4, 5	35,000 70,000	34,000	Oxygen Production

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Fig. A.2. Process unit flow sheet — Coalcon process.

Fischer-Tropsch Process

Reference

R. M. Parsons Co., *Oil and SNG by Fischer-Tropsch Complex*, R&D Report No. 114, Interim Report No. 3 (Draft), under Contract No. E (49-18)-1775 with Energy Research and Development Administration, Pasadena, Calif. (no date).

Coal Feed

Illinois, Indiana, and Kentucky: 40,000 TPD (12,550 Btu/lb)

Products

Gas: 260 MM scfd (1,035 Btu/scf)

Naptha: 2,378 TPD (20,000 BPD) (20,625 Btu/lb)

Diesel fuel: 2,105 TPD (16,000 BPD) (20,255 Btu/lb)

Fuel oil: 713 TPD (5,000 BPD) (19,865 Btu/lb)

Alcohols: 458 TPD (4,000 BPD) (12,505 Btu/lb)

Liquified petroleum gas: 343 TPD (3,500 BPD) (21,035 Btu/lb)

Sulfur: 1,000 TPD (3,990 Btu/lb)

Table A.3. Equipment included in survey — Fischer-Tropsch process

Identifier	Flow rate		Unit
	Specified	Required	
<u>Pumps</u>	(gpm)	(gpm)	
LL-1	2,500	1,200	Water Reclamation
LL-3, 4, 5	50,000 100,000 200,000	50,000	Raw Water System
LL-18	8,000	4,031	Coal Preparation
ML-2	5,800	2,900	Process Gasification
ML-3	440	220	Fischer-Tropsch Synthesis
ML-4	300	150	Fischer-Tropsch Synthesis
ML-5	620	310	Fischer-Tropsch Synthesis
ML-9	10,000	4,620	Process Gasification
ML-10	5,000	1,335	Process Gasification
HH-3, 4	15,600 31,200	4,600	Power Generation
HH-9	2,500	1,250	Water Reclamation
<u>Compressors</u>	(acfm)	(acfm)	
ML-1	82,000	41,000	Fischer-Tropsch Synthesis
ML-3	20,000	10,000	Methanation
MH-1	400	180	Water Reclamation
HL-6	10,000	3,600	Methanation
<u>Hydraulic Turbines</u>	(gpm)		
T-19	2,168		Water Reclamation

Fig. A.3. Process unit flow sheet — Fischer-Tropsch process.

Hydrocarbonization ProcessReference

J. M. Holmes et al., *Hydrocarbonization Process Evaluation Report*, ORNL-5212 (Draft), Oak Ridge National Laboratory, (September 1976).

Coal Feed

Illinois No. 6: 46,210 TPD (12,705 Btu/lb)

Products

Fuel oil: 22,930 bbl/day (6.31 MM Btu/bbl)*

Gas: 63.67 MM scfd (985 Btu/scf)

Char: 18,178 TPD (14,821 Btu/lb)

Sulfur: 519 TPD (3,990 Btu/lb)

Ammonia: 193 TPD (9,800 Btu/lb)

* Naptha, 2,174 bbl/day; fuel oil, 20,756 bbl/day.

Table A.4. Equipment included in survey — Hydrocarbonization process

Identifier	Flow rate		Unit
	Specified	Required	
<u>Pumps</u>	(gpm)	(gpm)	
LL-3, 4, 5	50,000 100,000 200,000	60,000	Raw Water Treatment Plant
LL-10, 11	2,600 7,800	2,600	Hydrocarbonization; Char and Tar Recovery
LL-16	15,000	3,400	Hydrocarbonization; Char and Tar Recovery
LL-20	1,050	470	Coal Beneficiation
MM-4	1,300	1,300	Hydrocarbonizer Make Gas Treating
HL-3	4,500	4,500	Tar Hydrotreater
HH-13	5,400	1,800	Char Recovery and Storage
<u>Compressors</u>	(acfm)	(acfm)	
FB-5	600,000	575,000	Fluidized Bed Combustion System
FR-8, 9	360,000 720,000	357,000	Coal Beneficiation
L-1	270,000	90,000	Hydrocarbonization; Char and Tar Recovery
HH-2	30,000	27,000	Cryogenic Separation
VH-2	2,000	1,500	Tar Hydrotreater
VH-3	80,000	80,000	Tar Hydrotreater
<u>Hydraulic Turbines</u>	(gpm)		
T-1	1,172		Hydrocarbonizer Make Gas Treating
T-2	2,787		Hydrogen Preparation Plant
T-3	4,405		Acid Gas Separation and Recycle
T-18	8,592		Fluidized Bed Combustion System

Table A.4 (continued)

Identifier	Flow rate		Unit
	Specified	Required	
<u>Gas Expanders</u>	(acfm)		
E-1	60		Tar Hydrotreater
E-2	16,000		Fluidized Bed Combustion System
E-3	85,000		Fluidized Bed Combustion System

Fig. A.4. Process unit flow sheet - Hydrocarbonization process.

HYGAS Process

Reference

Energy Research and Development Administration, *IGT HYGAS Hydrogasification Process*, ERDA 76-47, Process Evaluation Group - Mineral and Material Research and Development, Morgantown, W. Va., (March 1976).

Coal Feed

1. Pittsburgh seam: 16,200 TPD (13,053 Btu/lb)
2. Montana subbituminous: 22,200 TPD (8,806 Btu/lb)

Products

1. Gas: 250 MM scfd (965 Btu/scf)
B-T-X: 25,300 lb/hr (136,000 Btu/gal)
2. Gas: 250 MM scfd (965 Btu/scf)
B-T-X: 23,200 lb/hr (136,000 Btu/gal)

Table A.5. Equipment included in survey — HYGAS process

Identifier	Flow rate		Unit ^a
	Specified	Required	
<u>Pumps</u>	(gpm)	(gpm)	
LL-21	7,200	578	Slurry Preparation (2)
HL-2	8,000	4,800	Dust Removal (1)
HH-12	4,800	400	Slurry Preparation (1)
HH-14	3,600	290	Slurry Preparation (2)
<u>Compressors</u>	(acfm)	(acfm)	
L-2	220,000	70,000	Coal Pretreatment (1)
HL-1	10,000	7,620	Methanation (1)

^aNumber in parentheses corresponds to 1 and 2 in above section.

NOTE: FOR MONTANA SUBBITUMINOUS COAL, THE COAL PRETREATMENT UNIT IS NOT REQUIRED. ALSO, WATER IS USED FOR SLURRY MAKE-UP; THEREFORE, WATER IS RECYCLED FROM THE DUST REMOVAL UNIT TO SLURRY PREPARATION WITH EXCESS WATER GOING TO WASTE WATER TREATMENT. PRODUCT B-T-X IS RECOVERED DIRECTLY FROM SHIFT CONVERSION AND B-T-X RECOVERY UNITS.

Fig. A.5. Process unit flow sheet — HYGAS process.

Lurgi Process

Reference

Energy Research and Development Administration, *250-Million-SCFD Gas Plant*, ERDA 76-7, Process Evaluation Group — Mineral and Material Research and Development, Morgantown, W. Va., (August 1975).

Coal Feed

New Mexico: 23,904 TPD (8,664 Btu/lb)

Products

Gas: 250 MM scfd (934 Btu/scf)

Ammonia: 104.7 TPD (9,800 Btu/lb)

Tar oil: 68,600 gpd (17,920 Btu/lb)

Naptha: 36,000 gpd (19,150 Btu/lb)

Sulfur: 126.04 TPD (3,990 Btu/lb)

Table A.6. Equipment included in survey — Lurgi process

Identifier	Flow rate		Unit
	Specified	Required	
<u>Pumps</u>	(gpm)	(gpm)	
LL-14	4,800	1,600	Methanation
MM-7	7,200	800	Tar, Tar Oil, and Naptha Separation
<u>Compressors</u>	(acfm)	(acfm)	
FB-2	260,000	127,000	Flue Gas Processing
ML-2	11,000	1,200	Methanation
HL-5	10,000	7,100	Methanation

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Fig. A.6. Process unit flow sheet — Lurgi process.

Synthoil Process

Reference

R. Salmon et al., *Evaluation of the Synthoil Process*, ORNL-5209 (Draft), Oak Ridge National Laboratory (September 1976).

Coal Feed

Western Kentucky: 50,133 TPD (10,445 Btu/lb)

Products

Heavy fuel oil: 97,200 bbl/day (6.4 MM Btu/bbl)^a

Sulfur: 2,128 ton/day (3,990 Btu/lb)

Ammonia: 180 ton/day (9,800 Btu/lb)

^aNaptha, 2,110 bbl/day; light gas oil, 665; heavy fuel oil, 94,425.

Table A.7. Equipment included in survey - Synthoil process

Identifier	Flow rate		Unit
	Specified	Required	
<u>Pumps</u>	(gpm)	(gpm)	
LL-2	4,000	3,300	Industrial Water System
LL-3, 4, 5	50,000 100,000 200,000	102,200	Industrial Water System
LL-6, 7	16,300 32,600	16,300	Raw Gas Treating
LL-12	4,000	2,000	Low Temperature Carboniza- tion
LL-13	800	660	Product Distillation
LL-17	9,000	4,500	Synthoil Reaction and Pro- duct Filtration
LL-19	6,400	2,150	Synthoil Reaction and Pro- duct Filtration
HL-1	5,600	1,700	High Temperature Shift Con- version
HH-2	4,400	1,100	High Temperature Shift Con- version
HH-5, 6	3,400 13,600	3,100	Low Temperature Shift Feed Gas Treating; Low Tempera- ture Shift Product Gas CO ₂ Removal
HH-7	5,600	1,400	Recycle Gas and Fuel Gas Treating
HH-8	4,500	1,500	Synthoil Reaction and Pro- duct Filtration
HH-10, 11	3,600 14,400	865	Synthoil Reaction and Pro- duct Filtration
<u>Compressors</u>	(acfm)	(acfm)	
FB-1	220,000	73,000	Gasification
FB-3, 4	400,000 800,000	115,000	Coal Preparation
L-4	910,000	151,000	Oxygen Plant
L-5	75,000	75,000	Low Temperature Carboniza- tion

Table A.7 (continued)

Identifier	Flow rate		Unit
	Specified	Required	
<u>Compressors</u>	(acfm)	(acfm)	
ML-4, 5, 6	150,000 300,000 900,000	30,000	Oxygen Plant
MH-3	16,000	8,000	Gasification
HH-3	30,000	28,000	High Temperature Shift Conversion
VH-1	7,000	6,300	Synthoil Reaction and Product Filtration
VH-4, 5	7,000 28,000	6,600	Synthoil Reaction and Product Filtration
<u>Hydraulic turbines</u>	(gpm)	(gpm)	
T-4, 5	1,296 5,182		Recycle Gas and Fuel Gas Treating
T-6, 7	1,467 5,870		Low Temperature Shift Feed Gas Treating
T-8, 9, 10	3,126 12,506 25,012		Low Temperature Shift Feed Gas Treating
T-11, 12	7,750 31,000		Raw Gas Treating
T-13	404	101	Synthoil Reaction and Product Filtration
T-14, 15, 16, 17	1,428 4,284 8,567 17,134	1,428	Synthoil Reaction and Product Filtration
T-20,21,22	1,042 4,170 16,680		Synthoil Reaction and Product Filtration
T-23, 24	4,124 16,497		Synthoil Reaction and Product Filtration

Fig. A.7. Process unit flow sheet - Synthoil process.

Supplemental Sources

Two additional conceptual design reports were reviewed for hydraulic-turbine and gas-expander applications. Information on these sources is provided below. Information was also obtained from Stearns-Roger concerning expanders for the CO₂ Acceptor process.

CO₂ Acceptor ProcessReference

Personal communication to authors from Stearns-Roger personnel during visit in Denver, Colo., on Apr. 27, 1977.

HYGAS ProcessReference

Institute of Gas Technology, *HYGAS: 1964 to 1974, Pipeline Gas from Coal - Hydrogenation (IGT Hydrogasification Process)*, FE-381-T9-P4, vol. 4, part 8, Chicago, Ill. (July 1975).

HYGAS (Steam-Iron) ProcessReference

R. Detman, *Factored Estimates for Western Coal Commercial Concepts, Technical Appendix II*, FE-2240-5, IR, App. I, C. F. Braun and Company, Alhambra, Calif. (October 1976).

Table A.8. Equipment included in survey — Supplemental sources

Identifier	Flow rate		Process/unit
	Specified	Required	
<u>Hydraulic Turbines</u>			
	(gpm)	(gpm)	
T-25, 26	1,039 3,117		HYGAS/Char Recovery
<u>Gas Expanders</u>			
	(acfm)	(acfm)	
E-4	85,000	85,000	CO ₂ Acceptor
E-5-A,B,C	15,000	15,000	HYGAS (Steam-Iron)
E-6-A,B,C	310,000	310,000	HYGAS (Steam-Iron)

Appendix B
QUESTIONNAIRES

Appendix B
QUESTIONNAIRES

Four questionnaires, one each on pumps, compressors, hydraulic turbines, and gas expanders, were prepared and sent to industry. These questionnaires and their cover letter comprise this appendix. Cross-reference listings giving the processes and required flow rates of equipment which serve as models for equipment specifications shown in these questionnaires may be found in Appendix C. Additional information on equipment location within the processes is available by consulting Appendix A, once the process is determined.

The following errata were noted in the questionnaires after they had been sent to industry.

1. Pumps, page 6 of 10
LL-3, correct horsepower, 1459 hp
LL-4, correct horsepower, 2917 hp
LL-5, correct horsepower, 5834 hp
LL-21, correct horsepower, 357 hp
LL-22, correct horsepower, 126 hp
2. Pumps, page 7 of 10
ML-5, correct pressure head, 74 psi
3. Pumps, page 8 of 10
MM-7, correct horsepower, 1890 hp
4. Compressors, page 7 of 8
ML-4 through ML-6. Divide flow rate and horsepower by 32 to obtain correct values; correct inlet pressure is about 15 psia.
5. Compressors, page 8 of 8
VH-3, correct molecular weight, 5.6 lb/lb mole
6. Gas Expanders, page 6 of 6
E-1, correct composition, 79% H₂, 19% CH₄, 2% C₂H₆

UNION CARBIDE CORPORATION

NUCLEAR DIVISION

P.O. BOX X, OAK RIDGE, TENNESSEE 37830

Date

Company Name
and
Address

COVER LETTER INTRODUCING
QUESTIONNAIRE(S) TO INDUSTRY

Gentlemen:

Investigation of Industrial Coal Conversion
Equipment Capability

An investigation of United States industry's ability to provide rotating equipment for coal conversion facilities of demonstration and commercial scale is being performed at the Oak Ridge National Laboratory by Union Carbide Nuclear Division. This work is being sponsored by the United States Energy Research and Development Administration/Fossil Energy, Major Facilities Project Management Division. Industry input is desired in two areas:

1. defining the present capability of industry to supply the equipment needed;
2. determining research and development needs, including lead time requirements, for producing equipment of advanced design.

Appreciation is expressed to those firms who have responded to our request for information article in the *Commerce Business Daily* of January 28, 1977. The attached package represents our next activity in this study.

The study deals with fluid transport and power recovery devices for handling air, liquids, oils, gases, and slurries in coal conversion plants. Equipment of interest includes turbines, expanders, pumps, compressors, and associated drive trains.

Would you please help us by providing information on the following specific equipment.

Pumps and Associated Drive Trains
Compressors and Associated Drive Trains
Hydraulic Turbines and Associated Drive Trains
Gas Expanders and Associated Drive Trains

*Only lines
applicable to
the manufacturer
were listed.*

This is not a request for proposal; nor may it serve as a basis for any claim for reimbursement of costs for efforts expended. It is likely, however, that this study will directly benefit the rotating equipment industry as well as the Government and the public. The names of the participating companies, as well as their addresses, will be listed in the final report along with the answers supplied to Questions 1 and 2. Other information supplied will be published on a statistical basis only. A copy of the final report will be sent directly to the responding firms. The report summarizing this study will be available to the public through normal Government publication channels. Therefore, please do not supply any proprietary information; such information will not be accepted.

An attachment, including an objective questionnaire, has been developed for each specific type of equipment listed above. We hope that this will help you provide the necessary information with a minimum of time and effort. Two copies of each attachment are enclosed, one to keep for your information and one for your response. We would appreciate receiving your input in the format of the questionnaire. We are hoping to accumulate the data by *response date*. Your cooperation in meeting this date would be most helpful.

Your ideas or suggestions which may help in making this investigation more beneficial to both governmental and industrial planners are welcomed. If additional information or clarification is needed, please call me collect at (615) 483-8611, ext. 3-0172 or W. Reid Williams at ext. 3-0321.

Your help in this effort is appreciated.

Very truly yours,

Joel R. Horton
UCC-ND Engineering

JRH:blm

Attachment: Pumps
Compressors
Hydraulic Turbines
Gas Expanders

As appropriate

ATTACHMENT

Investigation of Coal Conversion Equipment Capability

Pumps

This attachment includes a list of typical applications for pumps in proposed coal conversion plants and a questionnaire for determining the availability of pumps for these applications.

Sheets 2 and 3 of this attachment list general instructions for completing the questionnaire.

Sheet 4 lists the availability code to use in completing item 1 of the instructions.

Sheet 5 is an address and reference form which should be completed to properly reference your firm and point of contact. One individual should be named on this form for further contact by telephone during this study if necessary.

Sheets 6, 7, 8, 9, and 10 list the typical applications for pumps in coal conversion plants and provide blank columns for inserting the information requested by this questionnaire.

We recognize that some of the questions may be too difficult or time consuming to answer. We will appreciate your effort in answering these questions to the extent possible.

GENERAL INSTRUCTIONS

1. Pump Availability

Please choose the most appropriate availability code from the list on sheet 4 and insert it in column 1.

2. Largest Available Capacity

Please indicate in column 2 the largest capacity pump which you do make for the process conditions listed.

3. Limiting Factors

If your availability code in column 1 is not A1 or A2, please indicate the particular characteristics which are the limiting factors. Expand on this with additional sheets, if necessary, and reference footnotes in column 3.

Please answer the remaining questions based on the larger of the capacities listed in columns 2 and 3.

4. Type of Pump for Each Application

Please indicate in column 4 the recommended type of pump for the specified service: piston, plunger, diaphragm, blow case, rotary, centrifugal, peripheral, or other.

5. Stages

Please insert in column 5 the estimated number of stages.

6. Recommended Driver

Please indicate the recommended driver by inserting the appropriate code in column 6 from the following list.

A. Electric motor	E. Hydraulic turbine
B. Steam turbine	F. Steam (reciprocating)
C. Gas turbine	G. Other
D. Gas expander	

7. Recommended Intermediate Transmission

Please indicate the recommended intermediate transmission by inserting the appropriate code in column 7 from the following list.

- A. Direct-drive, common-shaft
- B. Direct-drive, coupled-shaft
- C. Speed - increasing gear
- D. Speed - reducing gear
- E. Other (Please indicate with footnote.)

8. Catalogs

Please provide two copies of catalogs on your pump equipment for the following:

- a. pumps for the more difficult applications;
- b. the most advanced line of pumps presently manufactured by your company.

Catalog numbers and/or other identifying information may be added in column 8.

9. Anticipated Maintenance Cost

Please consider the average annual repair and maintenance cost during the first ten years of the life of the pump when used in the service indicated. Please insert in column 9 the number which best represents your estimate of the average annual maintenance cost as a percentage of the initial cost of the pump: <5%, <10%, <25%, <50%, <100%, or >100%.

10. Projected In-Service Availability

Please provide in column 10 your projection of available in-service time: 98%+, 95%+, 80%+, 60%+, <60%.

11. Problem Areas

For the equipment specified for this application, please identify the most severe problems anticipated by inserting the most appropriate code(s) in column 11 from the following list.

A. Corrosion	H. Seals
B. Erosion	I. Couplings
C. Pitting	J. Vibration
D. Deposits	K. Drivers
E. Plugging	L. Intermediate Transmissions
F. Bearings	M. Other
G. Cavitation	

12. Delivery Time

For equipment which you make or anticipate making, please insert in column 12 the number below which best represents the anticipated lead time in months required from order placement through installation and check out: <6, <12, <18, <24, <36, or >36. (Delivery time does not include development time which should be included in item 13.)

13. Development Lead Time

For equipment not yet available but specified for applications listed, please state the total anticipated time for research, development, and testing required to provide the first unit of reliable equipment. Please state in years in column 13.

14. Additional Comments

Additional comments on specific applications are welcomed. These may be stated or footnoted in column 14. Attach additional sheets, if necessary.

15. Industry Capabilities and Quantities

Please provide your general comments and your assessment of industry's capability to supply pumps of advanced design in sufficient quantities for demonstration and commercial coal conversion plants. This is assuming that coal conversion will become a major industry within the next ten to fifteen years.

Pumps

Sheet 4 of 10

AVAILABILITY CODES FOR USE IN COMPLETING ITEM 1

<u>Code</u>	<u>Description</u>
<u>Available Equipment</u>	
A1	Available off-the-shelf equipment produced by <u>our company</u> .
A2	Equipment available by special order through <u>our company</u> .
A3	Equipment not presently available through our company but believed to be available within the <u>industry</u> .
<u>Technology Available for Scale-up</u>	
B1	Equipment is not presently available through our company but technology is available <u>in-house</u> which will likely be used if market forces are attractive.
B2	Equipment is not presently available through our company but technology is available within the <u>industry</u> which will likely be used by one or more companies if market forces are attractive.
<u>Anticipated Technology by 1982</u>	
C1	Anticipated technology requiring R&D which will likely be funded by <u>our company</u> if market forces are attractive.
C2	Anticipated technology requiring R&D which can be funded by <u>industry</u> if market forces are attractive.
C3	Anticipated technology requiring R&D which can be handled through <u>our company</u> provided governmental assistance is available.
C4	Anticipated technology requiring R&D which can be handled <u>within the industry</u> provided <u>governmental assistance</u> is available.
<u>Anticipated Technology: 1982 to 1987</u>	
D1	Very advanced future technology requiring extensive R&D which is likely to be handled by industry by 1987 <u>without governmental assistance</u> .
D2	Very advanced future technology requiring extensive R&D which requires governmental assistance for development by 1987.
<u>Questionable Technology</u>	
E1	Technology not believed possible before 1987.
E2	Technology not believed possible for these conditions.
<u>Inapplicable</u>	
F1	None of the above codes are applicable or appropriate for our firm to use. Insert a footnote in column 14 for additional comments, if so desired.

Pumps

Sheet 5 of 10

To: Joel R. Horton
Union Carbide Corporation-
Nuclear Division
MS 241-A, Bldg. 1000
Post Office Box X
Oak Ridge, TN 37830

Investigation of Industrial Coal Conversion
Equipment Capability

Address and Reference Form for Manufacturers
of
Pumps

1. Please indicate below the name and address of your company as you would like to have it listed in the final report.

COMPANY _____
AND _____
DIVISION _____
STREET _____
CITY _____ STATE _____ ZIP _____

2. Please indicate below an individual's name and address available for additional communication, if necessary, during the period of this study.

NAME _____
COMPANY _____
AND _____
DIVISION _____
STREET _____
CITY _____ STATE _____ ZIP _____

3. Please indicate below the name and address of a person (or position) you would like to have the final report mailed to.

NAME _____
COMPANY _____
AND _____
DIVISION _____
STREET _____
CITY _____ STATE _____ ZIP _____

Respectfully submitted,

Date _____

Please return this sheet together with sheets 6, 7, 8, 9, and 10 of this attachment for pumps.

PROCESS CONDITIONS										RESPONSE MATRIX													
A	B	C	D	E	F	G	H	I	J	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Identifier	Flow Rate	*Solids Content	Specific Gravity	Inlet Temperature	Inlet Pressure	Outlet Pressure	Pressure Head	Fluid Horsepower	Composition	Pump Availability	Largest Capacity	Limiting Factors	Type of Pump	Stages	Driver	Transmission	Catalogs	Maintenance Cost	In-Service Availability	Problem Areas	Delivery Time	Development Time	Additional Comments
-	CPM	Weight %	-	°F	psia	psia	psi	hp	Weight %	-	GPM	-	-	-	-	-	-	%	%	-	Months	Years	-
LL-1	2,500		1.0	215	19	63	44	65	Water														
LL-2	4,000		1.0	80	15	145	130	305	Water														
LL-3	50,000		1.0	120	15	65	50	875	Water														
LL-4	100,000		1.0	120	15	65	50	1,750	Water														
LL-5	200,000		1.0	120	15	65	50	2,920	Water														
LL-6	16,300		1.13	240	15	60	45	430	5 mole % K ₂ CO ₃ in water														
LL-7	32,600		1.13	240	15	60	45	860	5 mole % K ₂ CO ₃ in water														
LL-8	5,400		1.0	125	15	37	22	70	9.5% citrate sol'n.														
LL-9	1,500			104	15	37	22	20	Oil (MW ≈ 100)														
LL-10	2,600		0.87	412	114	133	19	30	Oil (54.9% LGO, 39.1% HGO)														
LL-11	7,800		0.87	412	114	133	19	90	Oil (54.9% LGO, 39.1% HGO)														
LL-12	4,000		0.9	110	15	60	45	105	Oil (MW ≈ 210)														
LL-13	800		0.9	660	23	90	67	35	Oil (MW ≈ 410)														
LL-14	4,800		-	716	68	112	44	125	Dowtherm														
LL-15	17,000	low	1.0	125	15	25	10	100	Solids contaminated condensate														
LL-16	15,000	5.2	0.74	620	115	130	15	135	5.2% solids, 94.8% oil and residue (MW ≈ 350)														
LL-17	9,000	11	1.0	550	15	40	25	135	11% solids, 89% C ₅ ⁺														
LL-18	8,000	15	1.07	100	65	110	45	210	15% solids, 85% H ₂ O														
LL-19	6,400	35	1.15	360	15	50	35	135	35% solids, 65% C ₅ ⁺ or B-T-X														
LL-20	1,050	40	1.3	140	15	30	15	10	40% solids, 60% H ₂ O														
LL-21	7,200	55	1.15	250	15	100	85	120	55% solids, 45% H ₂ O														
LL-22	3,600	60	1.1	180	15	75	60	45	60% solids, 40% H ₂ O														

*1/8 in. maximum particle size in slurry.

*1/8 in. maximum particle size in slurry.

[illegible]

*1/8 in. maximum particle size in slurry.

ATTACHMENT

Investigation of Coal Conversion Equipment Capability

Compressors

This attachment includes a list of typical applications for compressors in proposed coal conversion plants and a questionnaire for determining the availability of compressors for these applications.

Sheets 2 and 3 of this attachment list general instructions for completing the questionnaire.

Sheet 4 lists the availability code to use in completing item 1 of the instructions.

Sheet 5 is an address and reference form which should be completed to properly reference your firm and point of contact. One individual should be named on this form for further contact by telephone during this study if necessary.

Sheets 6, 7, and 8 list the typical applications for compressors in coal conversion plants and provide blank columns for inserting the information requested by this questionnaire.

We recognize that some of the questions may be too difficult or time consuming to answer. We will appreciate your effort in answering these questions to the extent possible.

NOTE: The isothermal horsepower in column I is expressed as ideal. It is realized that few, if any, compressors will operate under isothermal conditions. This quantity is simply a measure of the minimum horsepower under ideal conditions.

GENERAL INSTRUCTIONS

1. Compressor Availability

Please choose the most appropriate availability code from the list on sheet 4 and insert it in column 1.

2. Largest Available Capacity

Please indicate in column 2 the largest capacity compressor which you do make for the process conditions listed.

3. Limiting Factors

If your availability code in column 1 is not A1 or A2, please indicate the particular characteristics which are the limiting factors. Expand on this with additional sheets, if necessary, and reference footnotes in column 3.

Please answer the remaining questions based on the larger of the capacities listed in columns 2 and B.

4. Type of Compressor for Each Application

Please indicate in column 4 the recommended type of compressor for the specified service.

A. Reciprocating	F. Centrifugal
B. Sliding vane	G. Axial flow
C. Straight lobe	H. Mixed flow
D. Helical lobe	I. Other
E. Liquid piston	

5. Stages

Please insert in column 5 the estimated number of stages.

6. Recommended Driver

Please indicate the recommended driver by inserting the appropriate code in column 6 from the following list. Assume that any of the below is available.

A. Electric motor	E. Hydraulic turbine
B. Steam turbine	F. Steam (reciprocating)
C. Gas turbine	G. Other
D. Gas expander	

7. Recommended Intermediate Transmission

Please indicate the recommended intermediate transmission by inserting the appropriate code in column 7 from the following list.

- A. Direct-drive, common-shaft
- B. Direct-drive, coupled-shaft
- C. Speed - increasing gear
- D. Speed - reducing gear
- E. Other (Please indicate with footnote.)

8. Catalogs

Please provide two copies of catalogs on your compressor equipment for the following:

- a. compressors for the more difficult applications;
- b. the most advanced line of compressors presently manufactured by your company.

Catalog numbers and/or other identifying information may be added in column 8.

Compressors

Sheet 3 of 8

9. Anticipated Maintenance Cost

Please consider the average annual repair and maintenance cost during the first ten years of the life of the compressor when used in the service indicated. Please insert in column 9 the number which best represents your estimate of the average annual maintenance cost as a percentage of the initial cost of the compressor: <5%, <10%, <25%, <50%, <100%, or >100%.

10. Projected In-Service Availability

Please provide in column 10 your projection of available in-service time: 98%+, 95%+, 80%+, 60%+, <60%.

11. Problem Areas

For the equipment specified for this application, please identify the most severe problems anticipated by inserting the most appropriate code(s) in column 11 from the following list.

A. Corrosion	H. Gas cleaning
B. Erosion	I. Couplings
C. Pitting	J. Vibration
D. Deposits	K. Drivers
E. Plugging	L. Intermediate transmissions
F. Bearings	M. Other
G. Seals	

12. Delivery Time

For equipment which you make or anticipate making, please insert in column 12 the number below which best represents the anticipated lead time in months required from order placement through installation and check out: <6, <12, <18, <24, <36, or >36. (Delivery time does not include development time which should be included in item 13.)

13. Development Lead Time

For equipment not yet available but specified for applications listed, please state the total anticipated time for research, development, and testing required to provide the first unit of reliable equipment. Please state in years in column 13.

14. Additional Comments

An indication of limits on particulate loading would be appreciated. Other comments on specific applications are welcomed. These may be stated or footnoted in column 14. Attach additional sheets, if necessary.

15. Industry Capabilities and Quantities

Please provide your general comments and your assessment of industry's capability to supply compressors of advanced design in sufficient quantities for demonstration and commercial coal conversion plants. This is assuming that coal conversion will become a major industry within the next ten to fifteen years.

AVAILABILITY CODES FOR USE IN COMPLETING ITEM 1

<u>Code</u>	<u>Description</u>
<u>Available Equipment</u>	
A1	Available off-the-shelf equipment produced by <u>our company</u> .
A2	Equipment available by special order through <u>our company</u> .
A3	Equipment not presently available through our company but believed to be available within the <u>industry</u> .
<u>Technology Available for Scale-up</u>	
B1	Equipment is not presently available through our company but technology is available <u>in-house</u> which will likely be used if market forces are attractive.
B2	Equipment is not presently available through our company but technology is available within the <u>industry</u> which will likely be used by one or more companies if market forces are attractive.
<u>Anticipated Technology by 1982</u>	
C1	Anticipated technology requiring R&D which will likely be funded by <u>our company</u> if market forces are attractive.
C2	Anticipated technology requiring R&D which can be funded by <u>industry</u> if market forces are attractive.
C3	Anticipated technology requiring R&D which can be handled through <u>our company</u> provided governmental assistance is available.
C4	Anticipated technology requiring R&D which can be handled <u>within the industry</u> provided <u>governmental assistance</u> is available.
<u>Anticipated Technology: 1982 to 1987</u>	
D1	Very advanced future technology requiring extensive R&D which is likely to be handled by industry by 1987 <u>without governmental assistance</u> .
D2	Very advanced future technology requiring extensive R&D which requires governmental assistance for development by 1987.
<u>Questionable Technology</u>	
E1	Technology not believed possible before 1987.
E2	Technology not believed possible for these conditions.
<u>Inapplicable</u>	
F1	None of the above codes are applicable or appropriate for our firm to use. Insert a footnote in column 14 for additional comments, if so desired.

Compressors

Sheet 5 of 8

To: Joel R. Horton
Union Carbide Corporation-
Nuclear Division
MS 241-A, Bldg. 1000
Post Office Box X
Oak Ridge, TN 37830

Investigation of Industrial Coal Conversion
Equipment Capability

Address and Reference Form for Manufacturers
of
Compressors

1. Please indicate below the name and address of your company as you would like to have it listed in the final report.

COMPANY _____
AND _____
DIVISION _____

STREET _____

CITY _____ STATE _____ ZIP _____

2. Please indicate below an individual's name and address available for additional communication, if necessary, during the period of this study.

NAME _____

COMPANY _____
AND _____
DIVISION _____

STREET _____

CITY _____ STATE _____ ZIP _____

3. Please indicate below the name and address of a person (or position) you would like to have the final report mailed to.

NAME _____

COMPANY _____
AND _____
DIVISION _____

STREET _____

CITY _____ STATE _____ ZIP _____

Respectfully submitted,

Date _____

Please return this sheet together with sheets 6, 7, and 8 of this attachment for compressors.

[illegible]

[illegible]

ATTACHMENT

Investigation of Coal Conversion Equipment Capability

Hydraulic Turbines

This attachment includes a list of typical applications for hydraulic turbines in proposed coal conversion plants and a questionnaire for determining the availability of hydraulic turbines for these applications.

Sheets 2, 3, and 4 of this attachment list general instructions for completing the questionnaire.

Sheet 5 lists the availability code to use in completing item 1 of the instructions.

Sheet 6 is an address and reference form which should be completed to properly reference your firm and point of contact. One individual should be named on this form for further contact by telephone during this study if necessary.

Sheet 7 lists the typical applications for hydraulic turbines in coal conversion plants and provides blank columns for inserting the information requested by this questionnaire.

We recognize that some of the questions may be too difficult or time consuming to answer. We will appreciate your effort in answering these questions to the extent possible.

NOTE: The fluid horsepower appearing in columns I and L are expressed as ideal. It is realized that few, if any, hydraulic turbines or pumps will operate under ideal conditions. The quantity in column I is simply a measure of the maximum horsepower available to the hydraulic turbine under ideal conditions, while the quantity in column L is the minimum required by the pump.

Hydraulic Turbines

Sheet 2 of 7

GENERAL INSTRUCTIONS

1. Turbine Availability

Please choose the most appropriate availability code from the list on sheet 5 and insert it in column 1.

2. Largest Available Capacity

Please indicate in column 2 the largest capacity turbine which you do make for the process conditions listed.

3. Limiting Factors

If your availability code in column 1 is not A1 or A2, please indicate the particular characteristics which are the limiting factors. Expand on this with additional sheets, if necessary, and reference footnotes in column 3.

4. Type of Turbine for Each Application

Please indicate in column 4 the recommended type of unit for the specified service.

- A. Reaction turbine - axial (propeller), fixed blades
- B. Reaction turbine - Kaplan (axial (propeller), adjustable blades)
- C. Reaction turbine - Francis (axial-radial)
- D. Reaction turbine - diagonal flow
- E. Impulse turbine - Pelton
- F. Impulse turbine - inclined jet
- G. Impulse turbine - double jet
- H. Impulse turbine - multi-jet
- I. Hydraulic motor - crank and piston type
- J. Hydraulic motor - vane type
- K. Hydraulic motor - piston type rotory
- L. Pump - centrifugal (in reverse)
- M. Pump - axial flow (in reverse)
- N. Other

5. Stages

Please insert in column 5 the estimated number of stages.

6. Load and Speed Control

Please indicate the recommended controls by inserting the appropriate code(s) in column 6 from the following list.

- A. Mechanical break
- B. Electric break
- C. Synchronous motor-generator
- D. Driven unit load
- E. Needle valves in jets
- F. Wicket gates
- G. Inlet flow control
- H. Discharge flow control
- J. Governor
- K. Adjustable blades
- L. Variable displacement
- M. Other

7. Estimated Turbine Efficiency

Please indicate in column 7 the estimated efficiency.

Hydraulic Turbines

Sheet 3 of 7

8. Recommended Intermediate Transmission

Please indicate the recommended intermediate transmission by inserting the appropriate code(s) in column 8 from the following list.

A. Direct-drive, common-shaft	E. Fluid coupling
B. Direct-drive, coupled-shaft	F. Ratchet coupling
C. Speed - increasing gear	G. Clutch
D. Speed - reducing gear	H. Other (Please indicate with footnote.)

9. Catalogs

Please provide two copies of catalogs on your equipment for the following:

- equipment for the more difficult applications;
- the most advanced line of equipment presently manufactured by your company.

Catalog numbers and/or other identifying information may be added in column 9.

10. Anticipated Maintenance Cost

Please consider the average annual repair and maintenance cost during the first ten years of the life of the turbine when used in the service indicated. Please insert in column 10 the number which best represents your estimate of the average annual maintenance cost as a percentage of the initial cost of the hydraulic turbine: <5%, <10%, <25%, <50%, <100%, or >100%.

11. Projected In-Service Availability

Please provide in column 11 your projection of available in-service time: 98%+, 95%+, 80%+, 60%+, <60%.

12. Problem Areas

For the equipment specified for this application, please identify the most severe problems anticipated by inserting the most appropriate code(s) in column 12 from the following list.

A. Corrosion	H. Clutches
B. Erosion	I. Couplings
C. Pitting	J. Vibration
D. Cavitation	K. Governors
E. Plugging	L. Intermediate transmission
F. Bearings	M. Control
G. Seals	N. Valves
	O. Other

13. Delivery Time

For equipment which you make or anticipate making, please insert in column 13 the number below which best represents the anticipated lead time in months required from order placement through installation and check out: <6, <12, <18, <24, <36, or >36. (Delivery time does not include development time which should be included in item 14.)

14. Development Lead Time

For equipment not yet available but specified for applications listed, please state the total anticipated time for research, development, and testing required to provide the first unit of reliable equipment. Please state in years in column 14.

Hydraulic Turbines

Sheet 4 of 7

15. Additional Comments

Other comments on specific applications are welcomed. These may be stated or footnoted in column 15. Attach additional sheets, if necessary.

16. Industry Capabilities and Quantities

Please provide your general comments and your assessment of industry's capability to supply hydraulic turbines of advanced design in sufficient quantities for demonstration and commercial coal conversion plants. This is assuming that coal conversion will become a major industry within the next ten to fifteen years.

AVAILABILITY CODES FOR USE IN COMPLETING ITEM 1

<u>Code</u>	<u>Description</u>
<u>Available Equipment</u>	
A1	Available off-the-shelf equipment produced by <u>our company</u> .
A2	Equipment available by special order through <u>our company</u> .
A3	Equipment not presently available through our company but believed to be available within the <u>industry</u> .
<u>Technology Available for Scale-up</u>	
B1	Equipment is not presently available through our company but technology is available <u>in-house</u> which will likely be used if market forces are attractive.
B2	Equipment is not presently available through our company but technology is available within the <u>industry</u> which will likely be used by one or more companies if market forces are attractive.
<u>Anticipated Technology by 1982</u>	
C1	Anticipated technology requiring R&D which will likely be funded by <u>our company</u> if market forces are attractive.
C2	Anticipated technology requiring R&D which can be funded by <u>industry</u> if market forces are attractive.
C3	Anticipated technology requiring R&D which can be handled through <u>our company</u> provided governmental assistance is available.
C4	Anticipated technology requiring R&D which can be handled <u>within the industry</u> provided <u>governmental assistance</u> is available.
<u>Anticipated Technology: 1982 to 1987</u>	
D1	Very advanced future technology requiring extensive R&D which is likely to be handled by industry by 1987 <u>without governmental assistance</u> .
D2	Very advanced future technology requiring extensive R&D which requires governmental assistance for development by 1987.
<u>Questionable Technology</u>	
E1	Technology not believed possible before 1987.
E2	Technology not believed possible for these conditions.
<u>Inapplicable</u>	
F1	None of the above codes are applicable or appropriate for our firm to use. Insert a footnote in column 15 for additional comments, if so desired.

Hydraulic Turbines

Sheet 6 of 7

To: Joel R. Horton
 Union Carbide Corporation-
 Nuclear Division
 MS 241-A, Bldg. 1000
 Post Office Box X
 Oak Ridge, TN 37830

Investigation of Industrial Coal Conversion
Equipment Capability

Address and Reference Form for Manufacturers
of
Hydraulic Turbines

1. Please indicate below the name and address of your company as you would like to have it listed in the final report.

COMPANY _____
 AND _____
 DIVISION _____
 STREET _____
 CITY _____ STATE _____ ZIP _____

2. Please indicate below an individual's name and address available for additional communication, if necessary, during the period of this study.

NAME _____
 COMPANY _____
 AND _____
 DIVISION _____
 STREET _____
 CITY _____ STATE _____ ZIP _____

3. Please indicate below the name and address of a person (or position) you would like to have the final report mailed to.

NAME _____
 COMPANY _____
 AND _____
 DIVISION _____
 STREET _____
 CITY _____ STATE _____ ZIP _____

Respectfully submitted,

 Date _____

Please return this sheet together with sheet 7 of this attachment for hydraulic turbines.

TURBINE PROCESS CONDITIONS										Pump Specification**		RESPONSE MATRIX															
A	B	C	D	E	F	G	H	I	J	K	L	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Identifier	Flow Rate	Solids Content*	Specific Gravity	Temperature	Inlet Pressure	Outlet Pressure	Pressure Head	Fluid Horsepower	Stream Composition	Flow Rate	Horsepower	Availability	Largest Capacity	Limiting Factors	Type of Turbine	Stages	Controls	Efficiency	Transmission	Catalogs	Maintenance Cost	In-Service Availability	Problem Areas	Delivery Time	Development Lead Time	Additional Comments	
-	GPM	Weight %	-	°F	psia	psia	psi	hp	Weight %	GPM	hp	-	GPM	-	-	-	-	%	-	-	%	%	-	Months	Years	-	
T-1	1,172		1.04	140	560	20	540	369	68% H2O, 29% DEA, 3% CO2	1,172	362																
T-2	2,787		1.04	230	432	50	382	621	68% H2O, 29% DEA, 3% CO2	2,698	606																
T-3	4,405		1.04	130	172	25	147	378	66% H2O, 30% DEA, 4% CO2 + H2S	4,329	328																
T-4	1,296		1.04	120	3,985	200	3,785	2,861	68% H2O, 29% DEA, 3% H2S	1,254	2,925																
T-5	5,182		1.04	120	3,985	200	3,785	11,443	68% H2O, 29% DEA, 3% H2S	5,014	11,700																
T-6	1,467		1.13	201	1,075	23	1,052	901	68% H2O, 29% K2CO3, 3% CO2	1,466	880																
T-7	5,870		1.13	201	1,075	23	1,052	3,602	68% H2O, 29% K2CO3, 3% CO2	5,864	3,520																
T-8	3,126		1.13	273	1,075	23	1,052	1,919	63%H2O, 27% K2CO3, 10% CO2	2,820	1,728																
T-9	12,506		1.13	273	1,075	23	1,052	7,676	63% H2O, 27% K2CO3, 10% CO2	11,281	6,911																
T-10	25,012		1.13	273	1,075	23	1,052	15,352	63% H2O, 27% K2CO3, 10% CO2	22,562	13,822																
T-11	7,750		1.13	233	240	22	218	986	67% H2O, 29% K2CO3, 4% CO2 + H2S	1,848	291																
T-12	31,000		1.13	233	240	22	218	3,943	67% H2O, 29% K2CO3, 4% CO2 + H2S	7,394	1,164																
T-13	404		0.89	100	3,990	16	3,974	937	70% Oil [B.Pt. 400-650°F], 18% [650-850], 10% [C5H12 - 400], 2% [CH4 - C4H10]	***																	
T-14	1,428		0.89	100	3,980	60	3,920	3,266	98% Oil [B.Pt. 400-650°F], 2% [CH4 - C4H10]	1,400	3,235																
T-15	4,284		0.89	100	3,980	60	3,920	9,796	98% Oil [B.Pt. 400-650°F], 2% [CH4 - C4H10]	4,201	9,706																
T-16	8,567		0.89	100	3,980	60	3,920	19,593	98% Oil [B.Pt. 400-650°F], 2% [CH4 - C4H10]	8,402	19,412																
T-17	17,134		0.89	100	3,980	60	3,920	39,186	98% Oil [B.Pt. 400-650°F], 2% [CH4 - CH10]	16,804	38,823																
T-18	8,592	0.01	0.97	184	130	20	110	551	H2O, 0.01% solids	***																	
T-19	2,168	0.01	0.94	253	1,515	35	1,480	1,872	H2O, 0.01% solids	***																	
T-20	1,042	8	0.84	550	4,000	203	3,797	2,309	8% Ash, 5% residue, 70% [B.Pt. 850-1050+°F], 16% [C5H12 - 850], 1% dissolved gas	***																	
T-21	4,170	8	0.84	550	4,000	203	3,797	9,238	8% Ash, 5% residue, 70% [B.Pt. 850-1050+°F], 16% [C5H12 - 850], 1% dissolved gas	***																	
T-22	16,680	8	0.84	550	4,000	203	3,797	36,951	8% Ash, 5% residue, 70% [B.Pt. 850-1050+°F], 16% [C5H12 - 850], 1% dissolved gas	***																	
T-23	4,124	8	0.84	540	203	16	187	450	8% Ash, 5% residue, 71% [B.Pt. 850-1050+°F], 16% [C5H12 - 850]	***																	
T-24	16,497	8	0.84	540	203	16	187	1,800	8% Ash, 5% residue, 71% [B.Pt. 850-1050+°F], 16% [C5H12 - 850]	***																	
T-25	1,039	25	0.92	573-212	1,285	15	1,270	770	25% solids, 75% H2O	***																	
T-26	3,117	25	0.92	573-212	1,285	15	1,270	2,310	25% solids, 75% H2O	***																	

*1/8 in. maximum particle size in slurry.

**Pumps are specified only when they appear with the hydraulic turbine on the flow sheets. For most applications, pumps deliver lean solutions to stripping towers, while turbines recover the energy from the rich solution being returned to the regeneration tower.

***Assume that the turbine drives a generator.

ATTACHMENT

Investigation of Coal Conversion Equipment Capability

Gas Expanders

This attachment includes specifications for gas expanders found in recent conceptual designs of coal conversion plants and a questionnaire for determining the availability of these expanders.

Sheets 2 and 3 of this attachment list general instructions for completing the questionnaire.

Sheet 4 lists the availability code to use in completing item 1 of the instructions.

Sheet 5 is an address and reference form which should be completed to properly reference your firm and point of contact. One individual should be named on this form for further contact by telephone during this study if necessary.

Sheet 6 lists specifications for expanders in coal conversion plants and provides blank columns for inserting the information requested by this questionnaire.

We recognize that some of the questions may be too difficult or time consuming to answer. We will appreciate your effort in answering these questions to the extent possible.

NOTE: The horsepower appearing in column I is expressed as ideal. It is realized that few, if any, expanders will operate under ideal conditions. The quantity in column I is simply a measure of the maximum horsepower available to the expander under ideal conditions.

Expanders

Sheet 2 of 6

GENERAL INSTRUCTIONS

1. Expander Availability

Please choose the most appropriate availability code from the list on sheet 4 and insert it in column 1.

2. Largest Available Capacity

Please indicate in column 2 the largest capacity expander which you do make for the process conditions listed.

3. Limiting Factors

If your availability code in column 1 is not A1 or A2, please indicate the particular characteristics which are the limiting factors. Expand on this with additional sheets, if necessary, and reference footnotes in column 3.

4. Type of Expander for Each Application

Please indicate in column 4 the recommended type of unit for the specified service.

A. Radial - inflow	C. Lobe type	E. Other
B. Radial - outward flow	D. Axial	

5. Stages

Please insert in column 5 the estimated number of stages.

6. Load and Speed Control

Please indicate the recommended controls by inserting the appropriate code(s) in column 6 from the following list.

A. Mechanical break	E. Inlet flow control
B. Electric break	F. Discharge flow control
C. Synchronous motor-generator	G. Governors
D. Driven unit (i.e., pump, compressor)	H. Adjustable nozzles
	I. Other

7. Estimated Expander Efficiency

Please indicate in column 7 the estimated efficiency of the expander.

8. Recommended Intermediate Transmission

Please indicate the recommended intermediate transmission by inserting the appropriate code(s) in column 8 from the following list.

A. Direct-drive, common-shaft	E. Fluid coupling
B. Direct-drive, coupled-shaft	F. Ratchet coupling
C. Speed - increasing gear	G. Clutch
D. Speed - reducing gear	H. Other (Please indicate with footnote.)

9. Catalogs

Please provide two copies of catalogs on your equipment for the following:

- a. equipment for the more difficult applications;
- b. the most advanced line of equipment presently manufactured by your company.

Catalog numbers and/or other identifying information may be added in column 9.

Expanders

Sheet 3 of 6

10. Anticipated Maintenance Cost

Please consider the average annual repair and maintenance cost during the first ten years of the life of the expander when used in the service indicated. Please insert in column 10 the number which best represents your estimate of the average annual maintenance cost as a percentage of the initial cost of the expanders: <5%, <10%, <25%, <50%, <100%, or >100%.

11. Projected In-Service Availability

Please provide in column 11 your projection of available in-service time: 98%+, 95%+, 80%+, 60%+, <60%.

12. Problem Areas

For the equipment specified for this application, please identify the most severe problems anticipated by inserting the most appropriate code(s) in column 12 from the following list.

A. Corrosion	H. Clutches
B. Erosion	I. Couplings
C. Pitting	J. Vibration
D. Deposits	K. Governors
E. Plugging	L. Intermediate transmission
F. Bearings	M. Control
G. Seals	N. Other

13. Delivery Time

For equipment which you make or anticipate making, please insert in column 13 the number below which best represents the anticipated lead time in months required from order placement through installation and check out: <6, <12, <18, <24, <36, or >36. (Delivery time does not include development time which should be included in item 14.)

14. Development Lead Time

For equipment not yet available but specified for applications listed, please state the total anticipated time for research, development, and testing required to provide the first unit of reliable equipment. Please state in years in column 14.

15. Additional Comments

Other comments on specific applications are welcomed. These may be stated or footnoted in column 15. Attach additional sheets, if necessary.

16. Industry Capabilities and Quantities

Please provide your general comments and your assessment of industry's capability to supply expanders of advanced design in sufficient quantities for demonstration and commercial coal conversion plants. This is assuming that coal conversion will become a major industry within the next ten to fifteen years.

AVAILABILITY CODES FOR USE IN COMPLETING ITEM 1

<u>Code</u>	<u>Description</u>
<u>Available Equipment</u>	
A1	Available off-the-shelf equipment produced by <u>our company</u> .
A2	Equipment available by special order through <u>our company</u> .
A3	Equipment not presently available through our company but believed to be available within the <u>industry</u> .
<u>Technology Available for Scale-up</u>	
B1	Equipment is not presently available through our company but technology is available <u>in-house</u> which will likely be used if market forces are attractive.
B2	Equipment is not presently available through our company but technology is available within the <u>industry</u> which will likely be used by one or more companies if market forces are attractive.
<u>Anticipated Technology by 1982</u>	
C1	Anticipated technology requiring R&D which will likely be funded by <u>our company</u> if market forces are attractive.
C2	Anticipated technology requiring R&D which can be funded by <u>industry</u> if market forces are attractive.
C3	Anticipated technology requiring R&D which can be handled through <u>our company</u> provided governmental assistance is available.
C4	Anticipated technology requiring R&D which can be handled <u>within the industry</u> provided <u>governmental assistance</u> is available.
<u>Anticipated Technology: 1982 to 1987</u>	
D1	Very advanced future technology requiring extensive R&D which is likely to be handled by industry by 1987 <u>without governmental assistance</u> .
D2	Very advanced future technology requiring extensive R&D which requires governmental assistance for development by 1987.
<u>Questionable Technology</u>	
E1	Technology not believed possible before 1987.
E2	Technology not believed possible for these conditions.
<u>Inapplicable</u>	
F1	None of the above codes are applicable or appropriate for our firm to use. Insert a footnote in column 15 for additional comments, if so desired.

Expanders

Sheet 5 of 6

To: Joel R. Horton
Union Carbide Corporation-
Nuclear Division
MS 241-A, Bldg. 1000
Post Office Box X
Oak Ridge, TN 37830

Investigation of Industrial Coal Conversion
Equipment Capability

Address and Reference Form for Manufacturers
of
Expanders

1. Please indicate below the name and address of your company as you would like to have it listed in the final report.

COMPANY _____
AND _____
DIVISION _____

STREET _____

CITY _____ STATE _____ ZIP _____

2. Please indicate below an individual's name and address available for additional communication, if necessary, during the period of this study.

NAME _____

COMPANY _____
AND _____
DIVISION _____

STREET _____

CITY _____ STATE _____ ZIP _____

3. Please indicate below the name and address of a person (or position) you would like to have the final report mailed to.

NAME _____

COMPANY _____
AND _____
DIVISION _____

STREET _____

CITY _____ STATE _____ ZIP _____

Respectfully submitted,

Date _____

Please return this sheet together with sheet 6 of this attachment for hydraulic turbines.

EXPANDER PROCESS CONDITIONS											RESPONSE MATRIX																	
A	B	C	D	E	F	G	H	I	J	K	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15			
Identifier	Flow Rate acfm (inlet)	Particulate Loading grains acf (inlet)	Molecular Weight lbs lb mole	Inlet Temperature °F	Inlet Pressure psia	Outlet Pressure psia	Pressure Ratio	Isothermal Horsepower hp	Gas Composition Mole %	Particulate Characteristics Weight %	Availability	Largest Capacity acfm (inlet)	Limiting Factors	Type of Expander	Stages	Controls	Efficiency %	Transmission	Catalogs	Maintenance Cost %	In-Service Availability	Problem Areas	Delivery Time Months	Development Lead Time Years	Additional Comments			
E-1	60		5.3	120	2400	500	4.8	1,000	79% N ₂ , 19% CH ₄ , 2% C ₂ H ₆																			
E-2	16,000		28.2	135	106	20	5.3	12,400	90% N ₂ , 7% O ₂ , 2% H ₂ O, 1% Ar																			
E-3	85,000	0.23	26.7	348	120	20	6.0	80,400	77% N ₂ , 16% H ₂ O, 6% O ₂ , 1% Ar	Coal dust																		
E-4	85,000	0.15	33.3	1200	113	25	4.5	63,800	65% N ₂ , 34% CO ₂ , 1% H ₂ O	Ash and coal fines: 4% 20 µm x 10 µm, 13% 10 µm x 5 µm, 58% 5 µm x 2.5 µm, 25% 2.5 µm																		
E-5-A	15,000	3.15	28.0	1657	1095	66	16.6	203,000	45% N ₂ , 25% H ₂ O, 22% CO ₂ , 4% CO, 3% H ₂ , 1% CH ₄	36% Fe _{0.9470} , 33% Fe ₃ O ₄ , 31% inerts																		
E-5-B	15,000	0.16	28.0	1657	1095	66	16.6	203,000	45% N ₂ , 25% H ₂ O, 22% CO ₂ , 4% CO, 3% H ₂ , 1% CH ₄	36% Fe _{0.9470} , 33% Fe ₃ O ₄ , 31% inerts																		
E-5-C	15,000	0.016	28.0	1657	1095	66	16.6	203,000	45% N ₂ , 25% H ₂ O, 22% CO ₂ , 4% CO, 3% H ₂ , 1% CH ₄	36% Fe _{0.9470} , 33% Fe ₃ O ₄ , 31% inerts																		
E-6-A	310,000	0.15	29.0	1744	66	25	2.6	87,400	53% N ₂ , 25% H ₂ O, 22% CO ₂	36% Fe _{0.9470} , 33% Fe ₃ O ₄ , 31% inerts																		
E-6-B	310,000	0.0075	29.0	1744	66	25	2.6	87,400	53% N ₂ , 25% H ₂ O, 22% CO ₂	36% Fe _{0.9470} , 33% Fe ₃ O ₄ , 31% inerts																		
E-6-C	310,000	0.00075	29.0	1744	66	25	2.6	87,400	53% N ₂ , 25% H ₂ O, 22% CO ₂	36% Fe _{0.9470} , 33% Fe ₃ O ₄ , 31% inerts																		
<p>Because of the limited number of applications found in the conceptual designs for coal conversion facilities which were surveyed, it would be of benefit to this study to obtain additional information which would help us more fully understand the present state of expander technology. If time permits, please indicate the upper limit of the process condition specified in Column A of each row below which can be tolerated by your present expander designs along with the other conditions compatible with this upper limit. Your response to questions 1, 4-8, 10-13 and 15 of the questionnaire as they relate to <u>your</u> specifications would be appreciated.</p>																												
Maximum Flow Rate	*							**				NOT APPLICABLE	NOT APPLICABLE						NOT APPLICABLE					NOT APPLICABLE				
Maximum Particulate Loading		*						**																				
Maximum Inlet Temperature				*				**																				
Maximum Inlet Pressure					*			**																				
Maximum Pressure Ratio							*	**																				
Maximum Horsepower (actual)								*,**																				

*Maximum value of this process condition available through your company.

**Actual horsepower.

Appendix C

LOCATION OF MODELS FOR EQUIPMENT SPECIFICATIONS

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Appendix C

LOCATION OF MODELS FOR EQUIPMENT SPECIFICATIONS

This appendix is provided to facilitate the reader's further investigation of equipment applications that are characterized in the foldout pages of Appendix B. These applications are identified by alphanumeric codes consisting of one or two letters and a number separated by a hyphen. (The alphabetic portion of the code is explained in Table 3, Sect. 3.3.) The identifier and the specified flow rate for each application are given in the following tables along with the process(es) that provide the model and the flow rate specified for that process. Additional information on the process which will assist in locating desired data on the model may be found in Appendix A. No spacing between identifiers (such as LL-3, LL-4, and LL-5), in Appendix A indicates that the specified operating parameters are identical except for flow rates.

Table C.1. Location of models for pump specifications

Identifier	Specified flow rate (gpm)	Process	Required flow rate (gpm)
LL-1	2,500	Fischer-Tropsch	1,200
LL-2	4,000	Synthoil	3,300
LL-3	50,000	Coalcon	50,000
LL-4	100,000	Fischer-Tropsch	50,000
LL-5	200,000	Hydrocarbonization Synthoil	60,000 102,200
LL-6	16,300	Synthoil	16,300
LL-7	32,600	Synthoil	16,300
LL-8	5,400	BI-GAS	5,400
LL-9	1,500	Coalcon	250
LL-10	2,600	Hydrocarbonization	2,600
LL-11	7,800	Hydrocarbonization	2,600
LL-12	4,000	Synthoil	2,000
LL-13	800	Synthoil	660
LL-14	4,800	Lurgi	1,600
LL-15	17,000	Coalcon	8,500
LL-16	15,000	Hydrocarbonization	3,400
LL-17	9,000	Synthoil	4,500
LL-18	8,000	Fischer-Tropsch	4,031
LL-19	6,400	Synthoil	2,150
LL-20	1,050	Coalcon Hydrocarbonization	80 466
LL-21	7,200	BI-GAS HYGAS	1,910 578
LL-22	3,600	Coalcon	875
ML-1	1,500	Coalcon	250
ML-2	5,800	Fischer-Tropsch	2,900
ML-3	440	Fischer-Tropsch	220
ML-4	300	Fischer-Tropsch	150
ML-5	620	Fischer-Tropsch	310
ML-6	8,400	Coalcon	8,400
ML-7	25,200	Coalcon	8,400
ML-8	9,000	Coalcon	1,400

Table C.1 (continued)

Identifier	Specified flow rate (gpm)	Process	Required flow rate (gpm)
ML-9	10,000	Fischer-Tropsch	4,620
ML-10	5,000	Fischer-Tropsch	1,335
		Synthoil	2,420
MM-1	6,000	BI-GAS	1,900
MM-2	4,500	Coalcon	1,500
MM-3	9,000	Coalcon	1,500
MM-4	1,300	Hydrocarbonization	1,300
MM-5	8,000	Coalcon	8,000
MM-6	16,000	Coalcon	8,000
MM-7	7,200	Lurgi	800
MM-8	700	Coalcon	700
HL-1	5,600	Synthoil	1,700
HL-2	8,000	HYGAS	4,800
HL-3	4,500	Hydrocarbonization	4,500
HH-1	3,600	BI-GAS	1,200
HH-2	4,400	Synthoil	1,100
HH-3	15,600	Fischer-Tropsch	4,600
HH-4	31,200	Fischer-Tropsch	4,600
HH-5	3,400	BI-GAS	3,400
HH-6	13,600	Synthoil	3,100
HH-7	5,600	Synthoil	1,400
HH-8	4,500	Synthoil	1,500
HH-9	2,500	Fischer-Tropsch	1,250
HH-10	3,600	Synthoil	865
HH-11	14,400	Synthoil	865
HH-12	4,800	HYGAS	400
HH-13	5,400	Hydrocarbonization	1,800
HH-14	3,600	BI-GAS	640
		HYGAS	290

Table C.2. Location of models for compressor specifications

Identifier	Specified flow rate (acfm)	Process	Required flow rate (acfm)
FB-1	220,000	Synthoil	73,000
FB-2	260,000	BI-GAS ($P_o = 15.4$) Lurgi	44,000 127,000
FB-3	400,000	BI-GAS	306,000
FB-4	800,000	BI-GAS Synthoil	220,000 115,000
FB-5	600,000	Hydrocarbonization	575,000
FB-6	410,000	Coalcon	410,000
FB-7	1,230,000	Coalcon	410,000
FB-8	360,000	Hydrocarbonization	357,000
FB-9	720,000	Hydrocarbonization	357,000
L-1	270,000	Hydrocarbonization	90,000
L-2	220,000	HYGAS	70,000
L-3	350,000	Coalcon	175,000
L-4	910,000	Synthoil	151,000
L-5	75,000	Synthoil	75,000
L-6	10,000	Coalcon	10,000
ML-1	82,000	Fischer-Tropsch	41,000
ML-2	11,000	Lurgi	1,200
ML-3	20,000	Fischer-Tropsch	10,000
ML-4	150,000	Synthoil	150,000
ML-5	300,000	Synthoil	150,000
ML-6	900,000	Synthoil	150,000
MH-1	400	Fischer-Tropsch	180
MH-2	35,000	Coalcon	35,000
MH-3	16,000	Synthoil	8,000
HL-1	10,000	HYGAS	8,000
HL-2	14,000	BI-GAS	12,000
HL-3	40,000	BI-GAS	12,000
HL-4	6,000	Coalcon	6,000
HL-5	10,000	Lurgi	7,100
HL-6	10,000	Fischer-Tropsch	3,600
HH-1	25,000	Coalcon	20,000

Table C.2 (continued)

Identifier	Specified flow rate (acfm)	Process	Required flow rate (acfm)
HH-2	30,000	Hydrocarbonization	27,000
HH-3	30,000	Synthoil	28,000
HH-4	35,000	Coalcon	34,000
HH-5	70,000	Coalcon	34,000
VH-1	7,000	Synthoil	6,300
VH-2	2,000	Hydrocarbonization	1,500
VH-3	80,000	Hydrocarbonization	80,000
VH-4	7,000	Synthoil	6,600
VH-5	28,000	Synthoil	6,600

Table C.3. Location of models for hydraulic turbine specifications

Identifier	Specified flow rate (gpm)	Process	Required flow rate (gpm)
T-1	1,172	Hydrocarbonization	
T-2	2,787	Hydrocarbonization	
T-3	4,405	Hydrocarbonization	
T-4	1,296	Synthoil	
T-5	5,182	Synthoil	
T-6	1,467	Synthoil	
T-7	5,870	Synthoil	
T-8	3,126	Synthoil	
T-9	12,506	Synthoil	
T-10	25,012	Synthoil	
T-11	7,750	Synthoil	
T-12	31,000	Synthoil	
T-13	404	Synthoil	101
T-14	1,428	Synthoil	1,428
T-15	4,284	Synthoil	1,428
T-16	8,567	Synthoil	1,428
T-17	17,134	Synthoil	1,428
T-18	8,592	Hydrocarbonization	
T-19	2,168	Fischer-Tropsch	
T-20	1,042	Synthoil	
T-21	4,170	Synthoil	
T-22	16,680	Synthoil	
T-23	4,124	Synthoil	
T-24	16,497	Synthoil	
T-25	1,039	HYGAS	
T-26	3,117	HYGAS	

Table C.4. Location of models for expander specifications

Identifier	Specified flow rate (acfm)	Process	Required flow rate (acfm)
E-1	60	Hydrocarbonization	
E-2	16,000	Hydrocarbonization	
E-3	85,000	Hydrocarbonization	
E-4	85,000	CO ₂ Acceptor	85,000
E-5 ^a	15,000	HYGAS (Steam-Iron)	15,000
E-6 ^a	310,000	HYGAS (Steam-Iron)	310,000

^aA represents no cleanup of gas; B represents 95% cleanup of gas;
C represents 99.9% cleanup of gas.

Appendix D

MANUFACTURERS RESPONDING TO ROTATING EQUIPMENT QUESTIONNAIRES

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Appendix D

MANUFACTURERS RESPONDING TO ROTATING EQUIPMENT QUESTIONNAIRES

The manufacturers listed in this section have provided information on rotating equipment for coal conversion facilities in response to the questionnaires (see Appendix B). The names and addresses appearing below have been supplied by the manufacturers themselves. Their responses to the first two questions of the questionnaire on availability and largest capacities are given in Appendix E.

Pump Manufacturers

Barrett, Haentjens & Co.
Box 488
Hazleton, Pa. 18201

Delaval Turbine, Inc.
Turbine Division
P.O. Box 251
Trenton, N.J. 08602

Bingham-Williamette Co.
2800 Northwest Front Avenue
Portland, Oreg. 97210

Dover Corp.
Blackmer Pump Division
1809 Century
Grand Rapids, Mich. 49506

Buffalo Forge Co.
Pump Division
P.O. Box 985
Buffalo, N.Y. 14240

Dresser Industries, Inc.
Pacific Pump Division
5715 Bickett Street
Huntington Park, Calif. 90255

Byron Jackson Pump Division
Borg-Warner Corp.
P.O. Box 2017 Terminal Annex
Los Angeles, Calif. 90051

The Duriron Co., Inc.
Central Division
425 North Findlay Street
Dayton, Ohio 45401

Colt Industries Operating Corp.
Fairbanks Morse Pump Division
3601 Kansas Avenue
Kansas City, Kans. 66110

Galigher Co.
Baker International
440 West 8th South
Salt Lake City, Utah 84110

Delaval Turbine, Inc.
IMO Pump Division
P.O. Box 321
Trenton, N.J. 08602

Ingersoll-Rand Co.
Cameron Pump Division
P.O. Box 486
Phillipsburg, N.J. 08865

Ingersoll-Rand Co.
Standard Pump — Aldrich Division
Allentown, Pa. 18105

LaBour Pump Co.
P.O. Box 1187
Elkhart, Ind. 46514

Lawrence Pumps, Inc.
371 Market Street
Lawrence, Mass. 01843

Morris Pumps, Inc.
31 East Genesee Street
Baldwinsville, N.Y. 13027

National Supply Co.
Division of Armco Steel Corp.
1455 West Loop South
Houston, Tex. 77027

Peabody Floway, Inc.
P.O. Box 164
Fresno, Calif. 93707

Roper Pump Co.
Box 269
Commerce, Ga. 30529

Tuthill Pump Co.
Chicago Division
12500 South Crawford Avenue
Chicago, Ill. 60658

United Centrifugal Pumps
1132 North Seventh Street
San Jose, Calif. 95112

Warren Pumps, Inc.
Subsidiary of Houdaille Industries,
Inc.
Warren, Mass. 01083

A. R. Wilfley & Sons, Inc.
P.O. Box 2330
Denver, Colo. 80201

Wilson-Snyder Pumps
United States Steel Corp.
2001 N. Lamar Street, Box 478
Dallas, Tex. 75221

Worthington (Canada) Ltd.
P.O. Box 40
Brantford, Ontario N3T 5M5
Canada

Zimpro, Inc.
Subsidiary of Sterling Drug
Military Road
Rothschild, Wis. 54474

Compressor Manufacturers

Airco Cryogenics
1900 Main Street
Irvine, Calif. 92716

Allis-Chalmers Corp.
Compressor Division
P.O. Box 512
Milwaukee, Wis. 53201

American Demag Corp.
Compression Equipment Division
450 Park Avenue
New York, N.Y. 10022

Beloit Power Systems, Inc.
Tang Industries
555 Lawton Avenue
Beloit, Wis. 53511

Delaval Turbine, Inc.
Centrifugal Compressor Division
P.O. Box 251
Trenton, N.J. 08602

Diebold, Inc.
Lamson Division
685 Lamson Street
Syracuse, N.Y. 13201

Dresser Industries, Inc.
Dresser Clark Division
P.O. Box 560
Olean, N.Y. 14760

Elliot Company
Division of Carrier Corp.
North Fourth Street
Jeannette, Pa. 15644

Gardner-Denver Co.
Industrial Machinery Division
1800 Gardner Expressway
Quincy, Ill. 62301

Ingersoll-Rand Co.
Turbo Products Division
942 Memorial Parkway
Phillipsburg, N.J. 08865

Joy Manufacturing Co.
3101 Broadway
Buffalo, N.Y. 14225

Mechanical Equipment Co., Inc.
861 Carondelet Street
New Orleans, La. 70130

Rotoflow Corp.
2235 Carmelina Avenue
Los Angeles, Calif. 90064

The Spencer Turbine Co.
Turbo Compressor Division
600 Day Hill Road
Windsor, Conn. 06095

Sulzer Brothers, Inc.
19 Rector Street
New York, N.Y. 10006

Turbonetics, Inc.
968 Albany-Shaker Road
Latham, N.Y. 12110

Westinghouse Electric Corp.
Marine Marketing Division
Hendy Avenue
Sunnyvale, Calif. 94088

York Division
Borg-Warner Corp.
P.O. Box 1592
York, Pa. 17405

Hydraulic Turbine Manufacturers

Abex Corp.
Denison Division
1160 Dublin Road
Columbus, Ohio 43216

Allis-Chalmers Corp.
Hydro-Turbine Division
Box 712
York, Pa. 17405

Bingham-Willamette Co.
2800 Northwest Front Avenue
Portland, Oreg. 97210

Byron Jackson Pump Division
Borg-Warner Corp.
P.O. Box 2017 Terminal Annex
Los Angeles, Calif. 90051

Dresser Industries, Inc.
Pacific Pumps Division
5715 Bickett Street
Huntington Park, Calif. 90255

Expander Manufacturers

Airco Cryogenics
1900 Main Street
Irvine, Calif. 92716

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Tang Industries
555 Lawton Avenue
Beloit, Wis. 53511

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Turbine Division
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Dresser Clark Division
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Ingersoll-Rand Co.
Turbo Products Division
942 Memorial Parkway
Phillipsburg, N.J. 08865

Rotoflow Corp.
Engineering I
2235 Carmelina Avenue
Los Angeles, Calif. 90064

Westinghouse Electric Corp.
Marine Marketing Division
Hendy Avenue
Sunnyvale, Calif. 94088

Appendix E

RESPONSES FROM MANUFACTURERS TO QUESTIONS ON
AVAILABILITY AND CAPACITY

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Appendix E
RESPONSES FROM MANUFACTURERS TO QUESTIONS ON
AVAILABILITY AND CAPACITY

This appendix is a tabulation of responses from manufacturers to questions on availability and capacity (see Appendix B, questions 1 and 2 of each questionnaire). These data are presented exactly as they were provided by the manufacturers. Section 4 of this report provides a summary of the responses on availability and capacity as well as a summary of the responses to the remaining questions asked in the questionnaires and of additional information obtained from the manufacturers. Section 5 should be consulted for an analysis of the data.

The following tables are arranged first in the order of type of equipment (pump, compressors, hydraulic turbines, and gas expanders) and second by series (pumps: LL, ML and MM, and HL and HH series; compressors: FB, L, ML, and MH; and HL, HH, and VH series). Information within these latter subdivisions is then arranged alphabetically by manufacturers.

Table E.1. Responses from manufacturers to questions on availability and capacity

Pumps: LL series

Identifier	Manufacturer							
	Barrett, Haentjens & Co.		Bingham-Willamette Co.		Buffalo Forge Co.		Byron Jackson	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
LL-1	A2	25,000	A2	10,000	A2	4,500	A2	3,700
LL-2	A2		A2	12,000	A2	9,000	A2	5,000
LL-3	A2		A2	200,000	A3		A2	73,000
LL-4			A2	200,000	A3		A2	130,000
LL-5			A2	200,000	A3		A2	238,000
LL-6	A2		A2	25,000	A3		A2	24,000
LL-7	A2		A2	35,000	A3		A2	37,000
LL-8	A2		A2	25,000	A2	6,600	A2	64,000
LL-9	A2		A2	25,000	A2	2,200	A1	27,000
LL-10	A2		A2	25,000	A2	4,000	A2	2,800
LL-11	A2		A2	25,000	A2	8,400	A2	8,300
LL-12	A2		A2	25,000	A2	5,000	A2	5,200
LL-13	A2		A2	15,000	A2	1,400	A1	1,400
				8,000				
LL-14	A2		A2	10,000	A3		A2	5,500
LL-15	A2		A2	40,000	A3			
LL-16	A2		A2	15,000	A3			
LL-17	A2		A2	15,000	A2	12,000		
LL-18	A2		A2	15,000	A2	8,500		
LL-19	A2		A2	15,000	A3			
LL-20	A2		A2	20,000	A2	1,250		
LL-21	A2		A2	10,000	A3			
LL-22	A2		A2	10,000	A3			

Table E.7. Responses from manufacturers to questions on availability and capacity

Gas expanders

Identifier	Manufacturer							
	Airco Cryogenics		Beloit		Delaval		Dresser Industries	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
E-1	A2		F		A3	90,000	A3	
E-2	A2		A2	16,000	B1	90,000	A3	
E-3	A2		B1	16,000	B1	90,000	A2	70,000
E-4	A2		F		B1	90,000	A2	85,000
E-5-A	B1		F				B2	
E-5-B	B1		F				B2	
E-5-C	B1		F				B2	
E-6-A	C3		F				A3	
E-6-B	C3		F				A3	
E-6-C	C3		F				A3	

Manufacturer

Identifier	Manufacturer							
	Elliott Co.		Ingersoll Rand Co. Turbo Products Division		Rotoflow Corp.		Westinghouse Electric Corp.	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
E-1	A2		B2		A2	78		
E-2	A2		B2	30,000	A2	20,800		
E-3	B1		B2	125,000	A2	110,500		
E-4	B1		C1	125,000	E2			
E-5-A	D2		D2	35,000	E2		B1	15,000
E-5-B	D2		D2	35,000	E2		B1	15,000
E-5-C	D2		D2	35,000	E2		B1	15,000
E-6-A	C3		C3	310,000	E2		B1	310,000
E-6-B	A2		C3	310,000	E2		B1	310,000
E-6-C	A2		C3	310,000	E2		B1	310,000

Table E.1 (continued)

Identifier	Manufacturer							
	Colt Industries Fairbanks Morse		Delaval IMO Division		Delaval Turbine Division		Dover Corp.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
LL-1			A1	9,600	A2	50,000		
LL-2			A1	9,600	A2	50,000		
LL-3	A2	50,000			A2	210,000		
LL-4	A2	100,000			A2	210,000		
LL-5					A2	210,000		
LL-6			A2	9,600	A2	35,000		
LL-7			A2	9,600	A2	35,000		
LL-8	A2	5,400	A2	9,600	A3			
LL-9	A2	1,500	A1	9,600			A1	750
LL-10			A1	9,600			A1	1,175
LL-11			A1	9,600				
LL-12	A2	4,800	A1	9,600				
LL-13			A2	5,000				
LL-14			B1	5,000				
LL-15	A2	17,000	A3					
LL-16			A3					
LL-17			A3					
LL-18			A3					
LL-19			A3					
LL-20			A3					
LL-21			C2					
LL-22			C2					

Table E.1 (continued)

Identifier	Manufacturer							
	Dresser Industries Pacific Pump		The Duriron Co., Inc.		Galigher Co.		Ingersoll-Rand Co. Cameron Pump Division	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
LL-1	A2	40,000	A1	6,000	A1	4,000	A1, A2	as req'd
LL-2	A2	40,000	A3		A3		A1, A2	as req'd
LL-3	A2	55,000	A3		A3		A2	as req'd
LL-4	B1		A3		A3		A2	as req'd
LL-5	B1		A3		A3		A2	as req'd
LL-6	A2	18,000	A3		A3		A2, B1, B2	
LL-7	B1		A3		A3		A2, B1, B2	
LL-8	A2	40,000	A1	6,000	A1	10,000	A2	8,000
LL-9	A2	40,000	A1	6,000	A1	2,400	A2	8,000
LL-10	A2	16,000	A1	6,000	A3		A2	8,000
LL-11	A2	16,000	B1		A3		A2	8,000
LL-12	A2	40,000	A1	6,000	A1	4,000	A2	8,000
LL-13	A2	16,000	A2	6,000	A3		A2	8,000
LL-14	A2	16,000	A3		A3		A2	8,000
LL-15	A2	40,000	A3		A3		A2	
LL-16	B1	18,000	B2		A3		B1, B2	
LL-17	A2	16,000	B2		A3		B1, B2	
LL-18	A2	16,000	B1		A1	10,000	A2	
LL-19	A2	16,000	B1		A3		B1, B2	
LL-20	B1		A1	1,500	A1	2,400	A2	
LL-21	B1		B1		A1	10,000	B1	
LL-22	B1		B1		A1	4,000	A2	

Table E.1 (continued)

Identifier	Manufacturer							
	Ingersoll Rand Co. SPAD		LaBour Pump Co.		Lawrence Pumps, Inc.		Morris Pumps, Inc.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
LL-1			A1	3,000	A3		A3	
LL-2			A3, B1		A3		A3	
LL-3			A3		A3		A3	
LL-4			A3		A3		A3	
LL-5			A3		A3		A3	
LL-6			A3		A3		A3	
LL-7			A3		A3		A3	
LL-8			A3, B1		A3		A3	
LL-9			A1	3,000	A3		A3	
LL-10			A1	3,000	A3		A3	
LL-11			A3, B1		A3		A3	
LL-12			A3, B1		A3		A3	
LL-13			A1	3,000	A3		A3	
LL-14			A3, B1		A2	5,000	A3	
LL-15			A3		A2	20,000	A2	70,000
LL-16			A3		A2	20,000	B1	70,000
LL-17			A3		A2	20,000	B1	20,000
LL-18			A3		A2	20,000	A2	20,000
LL-19			A3		A2	20,000	B1	20,000
LL-20			A3		A2	20,000	A2	20,000
LL-21			A3		A2	20,000	A2	20,000
LL-22			A3		A2	20,000	A2	20,000

Table E.1 (continued)

Identifier	Manufacturer							
	National Supply Co.		Peabody Floway, Inc.		Foper Pump Co.		Tuthill Pump Co.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
LL-1	A3		A2		F1		A3	
LL-2	A3		A2	20,000	F1		A3	
LL-3	A3		A3		F1			
LL-4	A3		A3		F1			
LL-5	A3		A3		F1			
LL-6	A3		A2	20,000	F1			
LL-7	A3		A3		F1			
LL-8	A3		A2		F1			
LL-9	A3		A2		B1	900	A3	
LL-10	A3		A2		A3	3,000	A3	
LL-11	A3		A2		B2		A3	
LL-12	A3		A2		A3	5,000	A3	
LL-13	A3		A2		F1		A3	
LL-14	A3		A2		F1		A3	
LL-15	A3		A2		F1		A3	
LL-16	A3		A3		F1		A3	
LL-17	A3		A3		F1		A3	
LL-18	A3		A3		F1		A3	
LL-19	A3		A3		F1		A3	
LL-20	A3		A3		F1		A3	
LL-21	A3		A3		F1		A3	
LL-22	A3		A3		F1		A3	

Table E.1 (continued)

Identifier	Manufacturer							
	United		Warren Pumps, Inc.		Wilfley		Wilson-Snyder Pumps	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
LL-1	A1	3,000	A2	100,000	A3		A2	25,000
LL-2	A1	4,800	A2	100,000	A3		A2	25,000
LL-3	B1		A2	100,000	A3		A3	25,000
LL-4	A3		A2	100,000	A3		A3	25,000
LL-5	A3				A3		A3	25,000
LL-6	A1	19,600	A2	100,000	B1		A3	25,000
LL-7	A1	39,000	A2	100,000	B1		A3	25,000
LL-8	A1	6,500	A2	100,000	A1	12,000	A3	25,000
LL-9	A1	1,800	A2	4,000	A3		A2	25,000
LL-10	A1	3,100	A2	4,000	A3		A3	25,000
LL-11	A2	9,350			A3		A3	25,000
LL-12	A1	4,800	A2	4,000	A3		A2	25,000
LL-13	A1	960	A2	4,000	A3		A2	10,000
LL-14	A2	5,750			A3		A3	10,000
LL-15	A2	20,400			B1		A3	
LL-16	B1				B1		A3	
LL-17	A2	10,800			A1	10,000	A3	
LL-18	A2	9,600			A1	12,000	A3	
LL-19	A2	7,700			A1	10,000	A3	
LL-20	A2	1,260	A2	6,000	A1	12,000	A3	
LL-21	A2	8,600			A1	12,000	A3	
LL-22	A2	4,300	A2	6,000	A1	12,000	A3	

Table E.1 (continued)

Identifier	Manufacturer			
	Werthington		Zimpro, Inc.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
LL-1	A1		F1	200
LL-2	A1		F1	200
LL-3	A1		F1	200
LL-4	A2		F1	200
LL-5	A2		F1	200
LL-6	A1	22,000	F1	200
LL-7	A2		F1	200
LL-8	A2		F1	200
LL-9	A2	9,000	F1	200
LL-10	A2	9,000	F1	200
LL-11	A2	9,000	F1	200
LL-12	A2	9,000	F1	200
LL-13	A2	9,000	F1	200
LL-14	B2		F1	200
LL-15	A1	22,000	F1	200
LL-16	B1	50	F1	200
LL-17	A1	22,000	F1	200
LL-18	A1	22,000	F1	200
LL-19	A1	22,000	F1	200
LL-20	A1	22,000	A2	200
LL-21	A1	22,000	F1	200
LL-22	A1	20,000	F1	200

Table E.2. Responses from manufacturers to questions on availability and capacity

Pumps: ML and MM series

Identifier	Manufacturer							
	Barrett, Haentjens & Co.		Bingham-Willamette Co.		Buffalo Forge Co.		Byron Jackson	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
ML-1	A2		A2	3,000	A3		A1	2,400
ML-2	A2		A2	6,500	A3		A2	9,800
ML-3	A2		A2	7,500	A3		A1	650
ML-4	A2		A2	7,500	A3		A1	330
ML-5	A2		A2	7,500	A3		A1	700
ML-6	A2		A2	22,500	A3		A2	10,500
ML-7	A2		A2	26,000	A3		A2	27,000
ML-8	A2		A2	32,000	A3			
ML-9	A2		A2	26,000	A3			
ML-10	A2		B1		A3			
MM-1	A2		A2	13,000	A3		A2	6,500
MM-2	A2		A2	11,000	A3		A2	7,000
MM-3	A2		A2	9,000	A3		A2	9,000
MM-4	A2		A2	16,000	A3		A2	1,460
MM-5	A2		A2	8,000	A3		A2	8,400
MM-6	A2		A2	16,000	A3		A2	19,000
MM-7	A2		A2	16,000	A3		A2	9,000
MM-8	A2		A3, C1	12,000	A3			

Table E.2 (continued)

Identifier	Manufacturer							
	Colt Industries Fairbanks Morse		Delaval IMO Division		Delaval Turbine Division		Dover Corp.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
ML-1			A3		A3			
ML-2			A3		A3			
ML-3			A3		A3			
ML-4			A3		A3			
ML-5			A2	560	A3			
ML-6			A2	560	A3			
ML-7			A2	560	A3			
ML-8			A3		A3			
ML-9			A3		A3			
ML-10			A3		A3			
MM-1			A3		A3, B1			
MM-1	A2	4,500	A3		A3, B1			
MM-3	A2	9,000	A3		A3, B1			
MM-4	A2	1,300	A3		A3			
MM-5			A3		A3			
MM-6			A3		A3			
MM-7			A2	9,600				
MM-8			C2					

Table E.2 (continued)

Identifier	Manufacturer							
	Dresser Industries Pacific Pump		The Duriron Co., Inc.		Galigher Co.		Ingersoll-Rand Co. Cameron Pump Division	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
ML-1	A2	16,000	A3		A3		A1, A2	as req'd.
ML-2	A2	16,000	A3		A3		A1, A2	as req'd.
ML-3	A2	16,000	A3		A1	1,200	A1, A2	as req'd.
ML-4	A2	16,000	A3		A3		A1, A2	as req'd.
ML-5	A2	16,000	A3		A1	1,200	A1, A2	14,000
ML-6	A2	16,000	A3		A3		A1, A2	14,000
ML-7	C1	32,000	A3		A3		B1	8,000
ML-8	A2	16,000	A3		A3		B1, B2	15,000
ML-9	A2	16,000	A3		A3		A3	15,000
ML-10	A2	32,000	B1		A3		A3	15,000
MM-1	A2	16,000	A3		A3		A2	14,000
MM-2	A2	9,500	A3		A3		A3	14,000
MM-3	A2	9,500	A3		A3		A3	14,000
MM-4	A2	16,000	A3		A3		A2, A3	14,000
MM-5	A2	16,000	A3		A3		A2, A3	14,000
MM-6	A2	16,000	A3		A3		A2, A3	14,000
MM-7	A2	16,000	A3				A2, A3	14,000
MM-8	B1	16,000	A3		A3		C3, C4	

Table E.2 (continued)

Identifier	Manufacturer							
	Ingersoll Rand Co. SPAD		LaBour Pump Co.		Lawrence Pumps, Inc.		Morris Pumps, Inc.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
ML-1			A3		A2		A3	
ML-2			A3		A2		A3	
ML-3			A3		A3		A3	
ML-4			A3		A3		A3	
ML-5			A3		A3		A3	
ML-6			A3		A3		A3	
ML-7			A3		A3		A3	
ML-8			A3		B1	20,000	C4	20,000
ML-9			A3		B1	20,000	C4	20,000
ML-10			A3, B1		B1	20,000	C4	10,000
MM-1			A3				A3	
MM-2	A2	3,700	A3				A3	
MM-3			A3				A3	
MM-4	A2	3,700	A3				A3	
MM-5			A3				A3	
MM-6			A3				A3	
MM-7			A3				A3	
MM-8	A2	2,000	A3				C4	

Table E.2 (continued)

Identifier	Manufacturer							
	National Supply Co.		Peabody Floway, Inc.		Roper Pump Co.		Tuthill Pump Co.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
ML-1	A3		A2		F1		A3	
ML-2	A3		A2		F1		A3	
ML-3	A3		A2		F1		A3	300
ML-4	A3		A2		F1		A2	300
ML-5	A3		A2		A3		A2	600
ML-6	A3		A2		F1		A3	600
ML-7	A3		A2		F1		A3	600
ML-8	A3		A2		F1		A3	
ML-9	A3		A3		F1		A3	
ML-10	A3		A3		F1		A3	
MM-1	A3		A2		F1		A3	
MM-2	A3		A2		F1		A3	
MM-3	A3		A3		F1		A3	
MM-4	A2	1,212	A2		F1		A3	
MM-5	A3		A3		F1		A3	
MM-6	A3		A3		F1		A3	
MM-7	A3		A3		B1, B2		A3	
MM-8	A2	741	A3		F1		A3	

Table E.2 (continued)

Identifier	Manufacturer							
	United		Warren Pumps, Inc.		Wilfley		Wilson-Snyder Pumps	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
ML-1	A1	1,800			A3		A2	10,000
ML-2	A1	7,000			A3		A2	10,000
ML-3	A1	530			A3		A2	10,000
ML-4	A1	360			A3		A2	25,000
ML-5	A1	750	A2	4,000	A3		A2	25,000
ML-6	B1				A3		A3	10,000
ML-7	B1				A3		A3	10,000
ML-8	B1				B2		A3	
ML-9	B1				B2		A3	
ML-10	A2	6,000			C1		A3	
MM-1	A1	7,200			A3		A3	25,000
MM-2	A1	5,400			A3		A3	25,000
MM-3	A2	10,800			A3		A3	25,000
MM-4	A1	1,560			A3		A2	25,000
MM-5	A1	9,600					A3	25,000
MM-6	B1						A3	25,000
MM-7	A1	8,600					A3	10,000
MM-8	A2	840			A3		A2	3,200

Table E.2 (continued)

Identifier	Manufacturer			
	Worthington		Zimpro, Inc.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
ML-1			F1	200
ML-2			F1	200
ML-3			A2	200
ML-4			A2	200
ML-5	A2	9,000	F1	200
ML-6	A2	9,000	F1	200
ML-7	A2	9,000	F1	200
ML-8	B1	22,000	F1	200
ML-9	B1	22,000	F1	200
ML-10	B1	22,000	F1	200
MM-1			F1	200
MM-2			F1	200
MM-3			F1	200
MM-4			A2	200
MM-5			F1	200
MM-6			F1	200
MM-7	A2	9,000	F1	200
MM-8	C1		A2	200

Table E.3. Responses from manufacturers to questions on availability and capacity

Pumps: HL and HH series

Identifier	Manufacturer							
	Barrett, Haentjens & Co.		Bingham-Willamette Co.		Buffalo Forge Co.		Byron Jackson	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
HL-1	A2		A2	10,500	A3		A2	6,700
HL-2			A2	10,000	A3		A2	10,000
HL-3			A2	22,500	A3			
HH-1			A2	4,000	A3		A2	4,000
HH-2			A2	10,000	A3		A2	4,700
HH-3				4,500				
HH-4			B1	7,000	A3		A2	18,000
HH-5	A2		A3	16,000	A3		B1	
HH-6			A2	5,500	A3		A2	4,100
HH-7				14,000				
HH-8			B1	16,000	A3		A2	1,500
HH-9			A2	14,000				
HH-10			A2	6,500	A3		A2	15,000
HH-11			A2	6,500	A3		A2	5,500
HH-12								
HH-13	A2		D2		A3			
HH-14	A2		D2		A3			

Table E.3 (continued)

Identifier	Manufacturer							
	Colt Industries Fairbanks Morse		Delaval IMO Division		Delaval Turbine Division		Dover Corp.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
HL-1			A3		A3			
HL-2			A3		A3			
HL-3			A3					
HH-1			A3		A3, B1			
HH-2			A3		A3, B1			
HH-3			A3		B1			
HH-4			A3		B1			
HH-5			A3		A3			
HH-6			A3		A3, B1			
HH-7			B2		A2	10,000		
HH-8			C3		A2	10,000		
HH-9			A3		A3, B1			
HH-10			E1					
HH-11			E1					
HH-12			D2					
HH-13			D2					
HH-14			D2					

Table E.3 (continued)

Identifier	Manufacturer							
	Dresser Industries Pacific Pump		The Furiron Co., Inc.		Galigher Co.		Ingersoll Rand Co. Cameron Pump Division	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
HL-1	A2	12,000	A3		A3		A3	14,000
HL-2	A2	12,000	A3		A3		A3	14,000
HL-3	B1	12,000	A3		A3		C3, C4	
HH-1	A2	20,000	A3		A3		A2	
HH-2	A2	20,000	A3		A3		A3, B1	
HH-3	A2	20,000	A3		A3		A3, B1	
HH-4	B1	36,000	A3		A3		A3, B1	
HH-5	A2	20,000	A3		A3		A2	
HH-6	A2	32,000	A3		A3		A2	
HH-7	A2	20,000	A3		A3		A2, A3	
HH-8	A2	20,000	A3		A3		A2, A3	
HH-9	A2	20,000	A3		A3		C3, C4	
HH-10	A2	20,000	A3		A3		C3, C4	
HH-11	A2	36,000	A3		A3		C3, C4	
HH-12	A2	20,000	A3		A3		C3, C4	
HH-13	A2	20,000	A3		A3		C3, C4	
HH-14	A2	20,000	A3		A3		C3, C4	

Table E.3 (continued)

Identifier	Manufacturer							
	Ingersoll Rand Co. SPAD		LaBour Pump Co.		Lawrence Pumps, Inc.		Morris Pumps, Inc.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
HL-1			A3		B1	10,000	A3	
HL-2			A3		B1	1,000	A3	
HL-3			A3		A3		C4	
HH-1	A2	3,700	A3		A3		A3	
HH-2			A3		A3		A3	
HH-3			A3		A3		A3	
HH-4			A3		A3		A3	
HH-5	A2	3,700	A3		A3		A3	
HH-6			A3		A3		A3	
HH-7	A2	3,700	A3		A3		A3	
HH-8			A3		A3		A3	
HH-9	A2	3,700	A3		A3		C4	
HH-10	A2	650	F1		C4		C4	
HH-11	A2	650	F1		A3		C4	
HH-12	A2	2,400	F1		C4		C4	
HH-13	A2	2,400	F1		C4		C4	
HH-14	A2	2,400	F1		C4		C4	

Table E.3 (continued)

Identifier	Manufacturer							
	National Supply Co.		Peabody Floway, Inc.		Roper Pump Co.		Tuthill Pump Co.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
HL-1	A3		A2		F1		A3	
HL-2	A3		A2		F1		A3	
HL-3	A3		A2		F1			
HH-1	A2	1,204	A3		F1		A3	
HH-2	A2	1,195	A3		F1		A3	
HH-3	A2	1,026	A3		F1			
HH-4	A2	1,026	A3		F1			
HH-5	A2	1,195	A3		F1		A3	
HH-6	A2	1,195	A3		F1		A3	
HH-7	A2	435	A3		F1			
HH-8	A2	435	A3		F1			
HH-9	A2	972	A3		F1			
HH-10	B1	400	A3		F1			
HH-11	B1	400	A3		F1			
HH-12			A3		F1			
HH-13	A2	1,195	A3		F1			
HH-14	A2	1,195	A3		F1			

Table E.3 (continued)

Identifier	Manufacturer							
	United		Warren Pumps, Inc.		Wilfley		Wilson-Snyder Pumps	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
HL-1	A1	6,700			A3		A3	10,000
HL-2	A1	9,600					A3	25,000
HL-3	A2	5,400			D1		A3	25,000
HH-1	B1				A3		A3	10,000
HH-2	B1				A3		A3	25,000
HH-3	A1	18,700			A3		A3	10,000
HH-4	B2				A3		A3	10,000
HH-5	A1	4,100			A3, D1		A3	10,000
HH-6	A2	16,300			D1		A3	10,000
HH-7	B2						C3	735
HH-8	B2						C3	735
HH-9							C3	1,840
HH-10					D1		C3	735
HH-11					D1		C3	735
HH-12							C3	2,400
HH-13					A3		C3	2,700
HH-14					A3		C3	2,400

Table E.3 (continued)

Identifier	Manufacturer			
	Worthington		Zimpro, Inc.	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
HL-1			F1	200
HL-2			F1	200
HL-3	C1		F1	200
HH-1			F1	200
HH-2			F1	200
HH-3			F1	200
HH-4			F1	200
HH-5			F1	200
HH-6			F1	200
HH-7			F1	200
HH-8			F1	200
HH-9			F1	200
HH-10			F1	200
HH-11			F1	200
HH-12			F1	200
HH-13			F1	200
HH-14			F1	200

Table E.4. Responses from manufacturers to questions on availability and capacity

Compressors: FB, L, ML, and, MH series

Identifier	Manufacturer							
	Airco Cryogenics		Allis-Chalmers Corp.		American Demag Corp.		Beloit	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
FB-1	A3		A3		A2	720,000	F	25,000
FB-2	A3		A3		A2	720,000	F	25,000
FB-3	A3		A3		A2	720,000	F	25,000
FB-4	A3		A3		A2	720,000	F	25,000
FB-5	A3		A3		A2	720,000	F	25,000
FB-6	A3		C2		B1	200,000	F	25,000
FB-7	A3		C2		B2		F	25,000
FB-8	A3		A3		B1	200,000	F	25,000
FB-9	A3		A3		B2		F	25,000
L-1	B1		B1	70,000	A2	100,000	F	25,000
L-2	B1		B1	150,000	A3		F	25,000
L-3	A2		B1	320,000	A2	550,000	F	25,000
L-4	B1		D2	320,000	C3	1,000,000	F	25,000
L-5	A2		A2	170,000	A2	100,000	A2, B1	25,000
L-6	A2		A2	170,000	A2	125,000	A2	16,000
ML-1	A3		B1	50,000	A2	100,000	B1	1,000
ML-2	A3		B1	50,000	A2	100,000	B1	1,000
ML-3	A3		B1	50,000	A2	100,000	B1	1,000
ML-4	F1		D2		B2	300,000	B1	6,000
ML-5	F1		E1		B1	300,000	B1	6,000
ML-6	F1		E2		C3	1,000,000	B1	6,000
MH-1	A3		A3		A2	13,000	F1	
MH-2	A2		D2		A2	125,000	B1	25,000
MH-3	A2		A2	170,000	A2	125,000	A2	25,000

Table E.4 (continued)

Identifier	Manufacturer							
	Delaval Turbine, Inc.		Diebold, Inc.		Dresser Clark		Elliott Co.	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
FB-1	A3				A3		A2	350,000
FB-2	A3				A3		A2	350,000
FB-3	A3				A3		B1	350,000
FB-4	A3				A3		A3	350,000
FB-5	A3				A3		B2	350,000
FB-6	A3				A3		B1	350,000
FB-7					A3		B2	350,000
FB-8	A3				A3		B1	350,000
FB-9	A3				A3		B2	350,000
L-1	A2	541,000			A2	360,000	A2	280,000
L-2	A2	541,000			A3		A2	350,000
L-3	A2	541,000			A2	550,000	A2	350,000
L-4	C4				C1		A3	350,000
L-5	A2	541,000			A2	360,000	A2	140,000
L-6	A2	150,000			A2	150,000	A2	130,000
ML-1	A2	150,000			A2	360,000	A2	110,000
ML-2	A2	150,000			A2	360,000	A2	30,000
ML-3	A2	150,000			A2	360,000	A2	30,000
ML-4	B2				B1		A2	280,000
ML-5	B2				B1		B1	300,000
ML-6	C4				E1		D2	
MH-1	A3				A3		A3	
MH-2	B1	150,000			B2		B1	140,000
MH-3	A2	150,000			A2	150,000	A2	140,000

Table E.4 (continued)

Identifier	Manufacturer							
	Gardner-Denver Co.		Ingersoll Rand Co. Turbo Products Division		Joy Manufacturing Co.		Mechanical Equipment Co.	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
FB-1	A2	6,000			B2		B1	
FB-2	A2	6,000			B2		B1	
FB-3	A2	6,000			A3		B1	
FB-4	A2	6,000			A3		B1	
FB-5	A2	6,000			B2		B1	
FB-6	A2	6,000			B2		B1	
FB-7	A2	6,000			B2		B1	
FB-8	A2	6,000			B2		B1	
FB-9	A2	6,000			B2		B1	
L-1	A2	3,000			B2		B1	
L-2	A2	5,800			A3	35,000	B1	
L-3	A2	3,500			A3	35,000	B2	
L-4	A2	3,500			B2	35,000	B2	
L-5	A2				B2		B1	
L-6	A2	4,500			A3		B1	
ML-1	A2	2,000			B2		A2	
ML-2	A2	2,000			B2		A2	
ML-3	A2	2,000			B2		A3	
ML-4	A2	3,000	C3		C2		B1	
ML-5	A2	3,000	C3		C2		B1	
ML-6	A2	3,000	C3		C2		B1	
MH-1	A2	2,000			B2			
MH-2	A2	2,000	C3		A3			
MH-3	A2	3,000			A3			

Table E.4 (continued)

Identifier	Manufacturer							
	Rotoflow Corp.		The Spencer Turbine Co.		Sulzer Brothers, Inc.		Turbonetics, Inc.	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
FB-1			A2	25,000			A3	
FB-2			A2	20,000			A3	
FB-3			A2	25,000			A3	
FB-4			A2	25,000			A3	
FB-5			A2	25,000			A3	
FB-6			A2	10,000			A3	
FB-7			A2	10,000			A3	
FB-8			A2	20,000			A3	
FB-9			A2	20,000			A3	
L-1	A2	114,000	A3		A2	270,000	A3	
L-2	A2	110,000	A2	25,000	A2	540,000	A3	
L-3	A2	175,000	A3		A1	260,000	A3	
L-4	A2	455,000	A3		A2	260,000		
L-5	A2	75,000	A2	10,000	A2	120,000	A3	
L-6	A2	10,000	A3		A2	95,000		
ML-1	A2	82,000	A3		B1	120,000	A3	
ML-2	A2	11,000	A3		A2	120,000	A2	30,000
ML-3	A2	20,000	A3		B1	120,000	B1	30,000
ML-4	A2	150,000	A3		A2	65,000	A3	
ML-5	A2	150,000	A3		A2	65,000		
ML-6	A2	150,000	A3		A2	65,000		
MH-1	A2	150,000	A3				A3	
MH-2	A2	35,000	A3		B1		A3	
MH-3	A2	16,000	A3		A2	65,000	A3	

Table E.4 (continued)

Identifier	Manufacturer			
	Westinghouse Electric Corp.		York Division Borg-Warner Corp.	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
FB-1			A3	
FB-2				
FB-3				
FB-4				
FB-5				
FB-6				
FB-7				
FB-8				
FB-9				
L-1	B1	300,000	A3	
L-2	A2	400,000	A2	22,000
L-3	A2	400,000	A2	22,000
L-4	A2	1,000,000	A2	22,000
L-5			A2	21,000
L-6			A2	10,000
ML-1			A3	
ML-2			A3	
ML-3			A2	1,370
ML-4			A3	
ML-5	B1	300,000	A3	
ML-6	B1	900,000	A3	
MH-1			A3	
MH-2			A3	
MH-3			A2	16,000

Table E.5. Responses from manufacturers to questions on availability and capacity

Compressors: HL, HH, and VH series

Identifier	Manufacturer							
	Airco Cryogenics		Allis-Chalmers Corp.		American Demag Corp.		Beloit	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
HL-1	A3		B1	50,000	A2	100,000	C1	25,000
HL-2	A3		A2	50,000	A2	100,000	C1	25,000
HL-3	A3		B1	50,000	A2	100,000	C3	40,000-50,000
HL-4	A3		A2	50,000	A2	100,000	C1	25,000
HL-5	B1, A2		A2	68,000	A2	125,000	F	
HL-6	B1, A2		A2	68,000	A2	125,000	F	
HH-1	A2		A2	30,000	A2	125,000	F	
HH-2	A2		A2	60,000	A2	125,000	F	
HH-3	B1		C4		A2	125,000	F	
HH-4	F1		A3		A2	150,000	F	
HH-5	F1		B2		A2	150,000	F	
VH-1	B1		D2		A2	13,000	F	
VH-2	A2		A3		A2	13,000	F	
VH-3	A3		D2	65,000	A2	100,000	F	
VH-4	A3		B1	50,000	A2	100,000	F	
VH-5	A3		B1	50,000	A2	100,000	F	

Table E.5 (continued)

Identifier	Manufacturer							
	Delaval Turbine, Inc.		Diebold, Inc.		Dresser Clark		Elliott Co.	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
HL-1	A2	30,000			A2	66,000	A2	55,000
HL-2	A2	30,000			A2	66,000	A2	55,000
HL-3	A2	60,000			A2	66,000	A2	55,000
HL-4	A2	30,000			A2	66,000	A2	55,000
HL-5	B2, A2	150,000			A2	66,000	A2	55,000
HL-6	A2	150,000			A2	66,000	A2	55,000
HH-1	A2	150,000			A2	180,000	A2	55,000
HH-2	A2	150,000			A2	180,000	A2	55,000
HH-3	A2	150,000			A2	180,000	A2	55,000
HH-4	B1	150,000			A2	45,000	A2	55,000
HH-5	B1	150,000			A3	45,000	A2	75,000
VH-1	B2				A2		A2	11,000
VH-2	B2				A2		A3	
VH-3	B2				C2		C2	
VH-4	B2				A2	14,000	B1	
VH-5	B2				B1		C2	

Table E.5 (continued)

Identifier	Manufacturer							
	Gardner-Denver Co.		Ingersoll Rand Co. Turbo Products Division		Joy Manufacturing Co.		Mechanical Equipment Co.	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
HL-1	A2	4,000	A2		C2		B1	
HL-2	A2	800	A2		C2		B1	
HL-3	A2	800	A2		C2		B2	
HL-4	A2	1,200	A2		A3		B1	
HL-5	A2	600	A2		C2		B2	
HL-6	A2	600	A2		C2		B2	
HH-1	A2	1,000	A2		B2			
HH-2	A2	800	A2		C2			
HH-3	A2	500	A2		C3			
HH-4	A2	1,200	C3		C2			
HH-5	A2	1,200	C3		C2			
VH-1			A2		C3		B2	
VH-2			A2		C3		B1	
VH-3			A2	20,000	C3		B2	
VH-4			A2		C3		B1	
VH-5			A2	7,000	C3		B2	

Table E.5 (continued)

Identifier	Manufacturer							
	Rotoflow Corp.		The Spencer Turbine Co.		Sulzer Brothers, Inc.		Turbonetrics, Inc.	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
HL-1			A3		A2	56,000	B1	10,500
HL-2			A3		A2	100,000	B1	30,000
HL-3			A3		B1	100,000	A3	
HL-4			A3		A2	85,000	B1	10,500
HL-5			A3		A2	120,000	B1	10,500
HL-6			A3		A2	120,000	B1	10,500
HH-1	A2	25,000	A3		A2	120,000	A3	
HH-2	A2		A3		A2	120,000	A3	
HH-3	A2	30,000	A3		A2	120,000	A3	
HH-4	A2	35,000	A3		A2	60,000	A3	
HH-5	A2	70,000	A3		A2	60,000	A3	
VH-1			A3					
VH-2			A3					
VH-3	A2	40,000	A3		B1	45,000		
VH-4	A2	7,000	A3		A2	55,000		
VH-5	A2	28,000	A3		B1	55,000		

Table E.5 (continued)

Identifier	Manufacturer			
	Westinghouse Electric Corp.		York Division Bcrg-Warner Corp.	
	Availability	Largest capacity (acfm)	Availability	Largest capacity (acfm)
HL-1			A2	1,200
HL-2			A2	2,000
HL-3			A2	2,100
HL-4			A2	1,800
HL-5			A2	2,300
HL-6			A2	2,300
HH-1			A3	
HH-2			A2	15,000
HH-3			A3	
HH-4			A3	
HH-5			A3	
VH-1			A3	
VH-2				
VH-3			A3	
VH-4			A3	
VH-5				

Table E.6. Responses from manufacturers to questions on availability and capacity
Hydraulic turbines

Identifier	Manufacturer							
	Abex Corp.		Allis-Chalmers Corp.		Bingham-Willamette Co.		Byron-Jackson	
	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)	Availability	Largest capacity (gpm)
T-1			A2		A2	4,100	A2	8,000
T-2			A2		A2	10,000	A2	14,000
T-3			A2		A2	5,000	A2	15,000
T-4			B1		A2	3,500	A2	4,500
T-5			B1		A2	6,000	A2	4,500
T-6			A2		A2	8,000	A2	14,000
T-7			A2		A2	8,000	A2	14,000
T-8			A2		B1		A2	14,000
T-9			A2		B1		A2	14,000
T-10			A2		B1		A2	25,000
T-11			A2		A2	50,000	A2	16,000
T-12			A2		A2	50,000	A2	30,000
T-13	A1, A2	600	B1		B1		A2	1,500
T-14	B1	1,400	B1		A2	1,500	A2	1,500
T-15			B1		B1		A2	4,000
T-16			B1		B1		A2	15,000
T-17			B1		B2		A2	15,000
T-18			A2		A2	30,000	B2	
T-19			A2		A2	4,500	B2	
T-20			B1		D2		B2	
T-21			B1		D2		B2	
T-22			B1		D2		B2	
T-23			B1		B1		B2	
T-24			B1		B1		B2	
T-25			C1, C3		D2		B2	
T-26			C1, C3		D2		B2	

Table E.6 (continued)

Identifier	Manufacturer	
	Dresser Industries	
	Availability	Largest capacity (gpm)
T-1	A2	700
T-2	A2	20,000
T-3	A2	40,000
T-4	A2	50,000
T-5	A2	50,000
T-6	A2	50,000
T-7	A2	90,000
T-8	A2	90,000
T-9	A2	20,000
T-10	A2	40,000
T-11	A2	40,000
T-12	A2	40,000
T-13	A2	50,000
T-14	A2	50,000
T-15	A2	50,000
T-16	A2	50,000
T-17	A2	50,000
T-18	B1	40,000
T-19	A2	20,000
T-20	A2	20,000
T-21	A2	20,000
T-22	A2	20,000
T-23	A2	40,000
T-24	A2	40,000
T-25	B1	9,000
T-26	B1	9,000

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