EPA-600/2-76-178
July 1976

Environmental Protection Technology Series

FEASIBILITY STUDY FOR A DIRECT, AIR-COOLED CONDENSATION SYSTEM

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

EPA REVIEW NOTICE

This report has been reviewed by the U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policy of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/2-76-178
July 1976

FEASIBILITY STUDY FOR A DIRECT, AIR-COOLED CONDENSATION SYSTEM

by

Michael D. Henderson

R.W. Beck and Associates
400 Prudential Plaza
Denver, Colorado 80202

Grant No. R803207-01
ROAP No. 21AZU-034
Program Element No. 1BB392

EPA Project Officer: James P. Chasse (EPA/Corvallis)

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

CONTENTS

FIGURES

FIGURES (cont)

TABLES

ACKNOWLEDGEMENTS

The cooperation of C-E Lummus Heat Transfer Division and GEA Airexchangers, Inc. is gratefully acknowledged for their assistance in arranging the European itinerary.

Three other manufacturers of air-cooled heat exchangers have also been of great help in documenting the experience of American manufacturers in this field. Special recognition is due to Hudson Products Corporation, Ecodyne MRM Division and The Marley Company.

Personnel at the Neil Simpson Station of Black Hills Power and Light Company and Rugeley Station "A" of the Central Electricity Generating Board were also gracious hosts to the research team.

Contributions from Battelle Pacific Northwest Laboratories and the Aluminum Company of America have been of special value in preparing this report.

J. P. Rossie, C. H. Armstrong and R. D. Mitchell have been associated with numerous dry cooling tower studies performed by R. W. Beck and Associates since 1969. Their editorial assistance has been invaluable. R. D. Mitchell was also responsible for the performance study of the Braintree installation described in Section IX.

SECTION I

CONCLUSIONS

The experience of owners of direct, air-cooled condensing systems indicates that the systems are feasible. Three special areas of concern were freezing during severe weather, corrosion in a marine or industrial atmosphere and noise attenuation. The present investigation indicates that:

1. Fintube bundle freezing can be prevented by proper system design and strict attention to operating procedures.

2. The service life required of power plants can be achieved, even in corrosive environments, by careful selection of fin-type materials and manufacture of the cooling coils.

3. Special design considerations can attenuate dry tower fan noise to meet very stringent requirements.

The performance of direct, air-cooled condensing systems can also be optimized to minimize the cost of energy to consumers. In the particular case of an 85 MW combined-cycle unit being constructed for the Braintree, Massachusetts Electric Light Department, the dry tower is subject to only a minor cost (capital and bus-bar) penalty compared to alternative cooling methods. A case-by-case analysis is necessary, however, to determine the economic feasibility of direct, air-cooled condensing systems.

SECTION II

RECOMMENDATIONS

Based on the results of the present investigation, it is recommended that a multi-year performance study of the dry cooling tower for the 85 MW combined-cycle electric generating unit under construction by the Braintree, Massachusetts Electric Light Department be undertaken to substantiate the feasibility of this unit. The study should include collection of tower thermal, meteorological and ambient air quality data; fintube corrosion and noise surveys; laboratory analyses (for particulates, salts, halogens, etc.); and studies of fluid distribution within the cooling coils. Statistical analyses should then be used to determine which parameters most influence the steam plant/air-cooled condenser performance, and to determine the mode of operation required for optimum performance.

SECTION III

INTRODUCTION

The purpose of this report is to present the results of research conducted by R. W. Beck and Associates to determine the feasibility of utilizing air-cooled condensation systems in coastal environments. Direct-cycle dry cooling towers transfer the heat of condensation of the turbine exhaust steam directly to the atmosphere by means of air-cooled heat exchangers, with no evaporation loss of circulating water. In this respect, a major siting obstacle to the construction of thermal and nuclear power stations is mitigated. Dry cooling towers are also beneficial from the standpoint of environmental protection.

R. W. Beck and Associates is the consulting engineer to the Braintree, Massachusetts Electric Light Department for the design and construction of an 85 MW combined-cycle unit with associated dry cooling tower. The exhaust heat from a 65 MW gas turbine will be utilized in an unfired heat recovery boiler to produce steam for a 20 MW steam turbine. Specific site considerations include subfreezing weather (down to a low temperature of -22 C), a marine and industrial environment, and noise attenuation required by the Commonwealth of Massachusetts to 51 dB(A) within the plant boundary (400 feet from the dry tower).

Armstrong and Schermerhorn[1] have recently studied this application of a direct, air-cooled condensing system to a combined-cycle electric generating unit. In this particular case, the dry tower is subject to only a minor cost (capital and bus-bar) penalty compared to alternative cooling methods. In addition, the use of a dry tower allows a significant reduction in the total time required to complete the project (vis a vis environmental issues associated with alternative cooling systems), thus reducing indirect costs and partially offsetting the fuel cost penalty. The study revealed the necessity of making a careful and extensive analysis of how ambient air temperature will affect plant performance characteristics and, in turn, fuel costs.

Major aspects of this study include selection of materials and fin types to prevent external corrosion of fintube surfaces due to marine or industrial environments, prevention of coil freezing during severe weather and noise attenuation. Five manufacturers have been contacted in order to ascertain the extent of their experience in providing this equipment. On-site visits with owners and operators of dry towers have also been made to determine whether the equipment can operate satisfactorily under a wide range of load and atmospheric conditions, and to detail necessary maintenance procedures. General information relative to these visits is presented in Table 1. At many of these locations corrosion and noise surveys were also conducted.

Table 1. DRY COOLING TOWER INSTALLATIONS VISITED BY R. W. BECK PERSONNEL IN 1973, 1974, AND 1975

No.	Location	Owner	Service/Designer Manufacturer	Year Installed	Duty (G cal/hr /MM Btu/hr)	Date of Visit
1	Wyodak, Wyoming	Black Hills Power and Light	vacuum steam condensing GEA	1965 1969	5/20 40/160	April, 1973
2	Rotterdam, Netherlands	A. Z. C. Zoutchemie	steam condensing GEA	1970	N/A	June, 1974
3	Rotterdam, Netherlands	Esso Refinery	vacuum steam condensing GEA	1970	10/40	June, 1974
4	Rotterdam, Netherlands	Esso Refinery	steam and hydrocarbon condensing/Lummus	1964	N/A	June, 1974
5	Antwerp, Belgium	Albatross Refinery	vacuum steam condensing GEA	1967	20/70	June, 1974
6	Brunsbuttelkoog, West Germany	Condea Refinery	vacuum steam condensing GEA	1963 1971	N/A N/A	June, 1974
7	Zurich, Switzerland	Municipal incinerator	vacuum steam condensing GEA	1972	50/210	June, 1974 July, 1975
8	Nuremburg, West Germany	Linde/air separation plant	vacuum steam condensing Lummus	1972	30/110	June, 1974
9	Green Springs, Ohio	Columbia Gas S.N.G. plant	vacuum steam condensing Ecodyne MRM	1972	70/290	August, 1974
10	Baytown, Texas	Celanese Chemical	steam condensing/Hudson Products Corporation	1971	30/120	August, 1974
11	Freeport, Texas	Dow Chemical	hydrocarbon and vacuum-steam condensing/Hudson Products Corporation	1963 1971	6/25 3/12	August, 1974

Table 1. (Continued)

No.	Location	Owner	Service/Designer Manufacturer	Year Installed	Duty (G cal/hr /MM Btu/hr)	Date of Visit
12	St. Croix, Virgin Islands	Hess Refinery	steam and hydrocarbon condensing/Ecodyne	1966	N/A	August, 1974
13	Penuelas, Puerto Rico	Puerto Rico Olefins	steam condensing Marfab	1971	10/45	August, 1974
14	Donawitz, Austria	Voest-Alpine Steel Works	vacuum steam condensing Lummus	1975	40/150	July, 1975
15	Florence, Italy	Nuovo Pignone manufacturing plant	vacuum steam condensing Lummus	1967	15/60	July, 1975
16	Nangis, France	Grande Paroisse C.D.F. Chemie	vacuum steam condensing Lummus	1967	25/100	July, 1975
17	Feluy, Belgium	S.A. Chevron Belgium N.V.	vacuum steam condensing Lummus	1975	15/60	July, 1975
18	Rugeley England	C.E.G.B.	circulating water cooling English Electric Co.	1961	150/590	July, 1975
19	Wolfsburg, West Germany	Volkswagenwerk A. G.	vacuum steam condensing GEA	1961 1966 1972	120/460 60/230 60/230	July, 1975
20	Ibbenburen West Germany	Preussag A. G.	circulating water cooling GEA-Heller	1967	180/740	July, 1975
21	Schmehausen West Germany	Hochtemperatur Kernkraftwerk	circulating water cooling Balcke-Durr GEA	under construction	380/1500	July, 1975
22	Utrillas Spain	Union Termica S. A.	vacuum steam condensing GEA	1970	275/1100	July, 1975
23	Nangis, France	S.E.I.F.	vacuum steam condensing Hudson Products Corp.	1967	40/180	
24	Paris, France	R.A.T.P. Arbor Station	freon condensing Hudson Products Corp.	1972	60/240	

N.B. The numbers used to designate various installations in this table will be used throughout the report.

Finally, a computer program has been developed to evaluate the annual performance and bus-bar energy costs of the Braintree installation.

SECTION IV

AIR-COOLED CONDENSER SYSTEMS

The familiarity of five different designers/manufacturers with the production of air-cooled vacuum steam condensers has been determined from their literature and discussions with engineering personnel. These five are GEA Airexchangers, Inc., C-E Lummus Heat Transfer Division, Hudson Products Corporation, Ecodyne MRM Division and The Marley Company. The following paragraphs summarize the results of this investigation.

GEA is the parent company for several branches that design and manufacture air coolers for various industries. The basic engineering design for the Braintree dry tower was performed by personnel at the home office in Bochum, West Germany. The actual contractual arrangement however, was with GEA Airexchangers, Inc., a U. S. corporation based near St. Louis, Missouri. This company processed materials and subassemblies from both domestic and foreign sources in conformance with the engineering design generated in Bochum. GEA can document over 200 air-cooled vacuum steam condensers which are currently in service. The oldest was installed in 1939. Although only a few of these units are as large as the Braintree unit, they are all of basically the same design, with improvements in structural components, fan-gear units and control systems hardware in the newer models.

Lummus is a design engineering and construction firm owned by Combustion Engineering, Inc., with engineering offices throughout the world. The proposal for the Braintree dry tower was engineered by personnel at the Heat Transfer Division office in The Hague, The Netherlands and transmitted by Combustion Engineering's office in Windsor, Connecticut. The Lummus LATEC (Lummusaire Turbine Exhaust Condenser) design has evolved through three stages (designated I, II and III), and over 130 condensers are currently in service or under construction (earliest installation, 1962). The recent LATEC II and III designs (subsequent to 1972) are similar with regard to heat transfer design concepts, the basic difference between them being that the LATEC II configurations have one overhead steam header, while LATEC III configurations have a pair of fan-level headers.

Hudson Products Corporation, a subsidiary of J. Ray McDermott and Company, Inc., is the largest U. S. manufacturer of air-cooled heat exchangers, and, with its licensees in the United Kingdom, France, Italy, Australia, Japan and Brazil have a similar position for process applications in the world. Hudson pioneered the design and manufacture of AUTO-VARIABLE fans and large industrial wet-dry cooling towers, and has had that equipment in extensive service for over 20 years. Hudson designs and furnishes complete cooling systems for direct or indirect steam condensing in natural or mechanical draft. Over 100 Hudson steam condensers since as early as 1940 are in service, including over 25 vacuum steam condensers operating since 1961.

MRM Division is the former McKinzie-Ris Manufacturing Company, now owned by Ecodyne Corporation. MRM has manufactured finned tubing and air-cooled heat exchanger assemblies for the past 40 years, and can document more than 10 vacuum steam condensers in service since 1964.

The Marley Cooling Tower Company, through its Dri-Tower Committee, has studied various design and application problems associated with dry cooling towers since early 1967. This Committee has held the opinion that direct, air-cooled condensing systems for large power plants would not be feasible in the foreseeable future, but that designs adopted from the hydrocarbons and petrochemical industry could be used by utilities for small steam units with only a slight additional concern for operating procedures. Marley, therefore, is concentrating on larger utility applications with their Parallel-Path Wet-Dry Tower.

GENERAL DESCRIPTION OF AIR-COOLED CONDENSER OPERATION

GEA, Lummus and Hudson Products Corporation offer dry-cooled vacuum steam condensers which differ significantly in detail. However, since their fintube bundle and mechanical equipment arrangements embody heat transfer concepts which are representative of the designs offered by the various manufacturers, their units will be described in detail.

GEA Air-Cooled Vacuum Steam Condenser

The GEA patent encompasses the use of elliptical finned tubes and a series connection of parallel ane counterflow elements known as the "condenser-dephlegmator" combination (see Figure 1). The steam duct through which the turbine exhaust steam is transferred to the air-cooled coils runs horizontal to the point of rising to the condenser inlet headers. The condenser tube bundles are installed in A-type frames on the condenser platform. Only the parallel flow bundles are directly welded to the inlet steam header located on top of the bundles. The steam enters these bundles and flows downward parallel with the condensate to the bottom condensate header which runs along the bottom inside the A-type structure. The excess steam is carried through the condensate header and flows upward, countercurrent to the condensate, through the dephlegmator bundles. The noncondensible air is evacuated from the top of the dephlegmator bundles. The dephlegmator bundles are located toward the center of the unit to assure maximum symmetry in the steam distribution. The hot condensate flows by gravity to the hot well tank.

Each fan module encompasses tube bundles on each side of the A-frame. Adjacent modules are separated by partition walls to avoid evacuating air when a fan is "off". Doors are provided in the partition walls to allow free access into the air plenum even while the fans are in operation. The fans are driven by horizontal two-speed motors via worm gear speed reducers supported on the fan bridges.

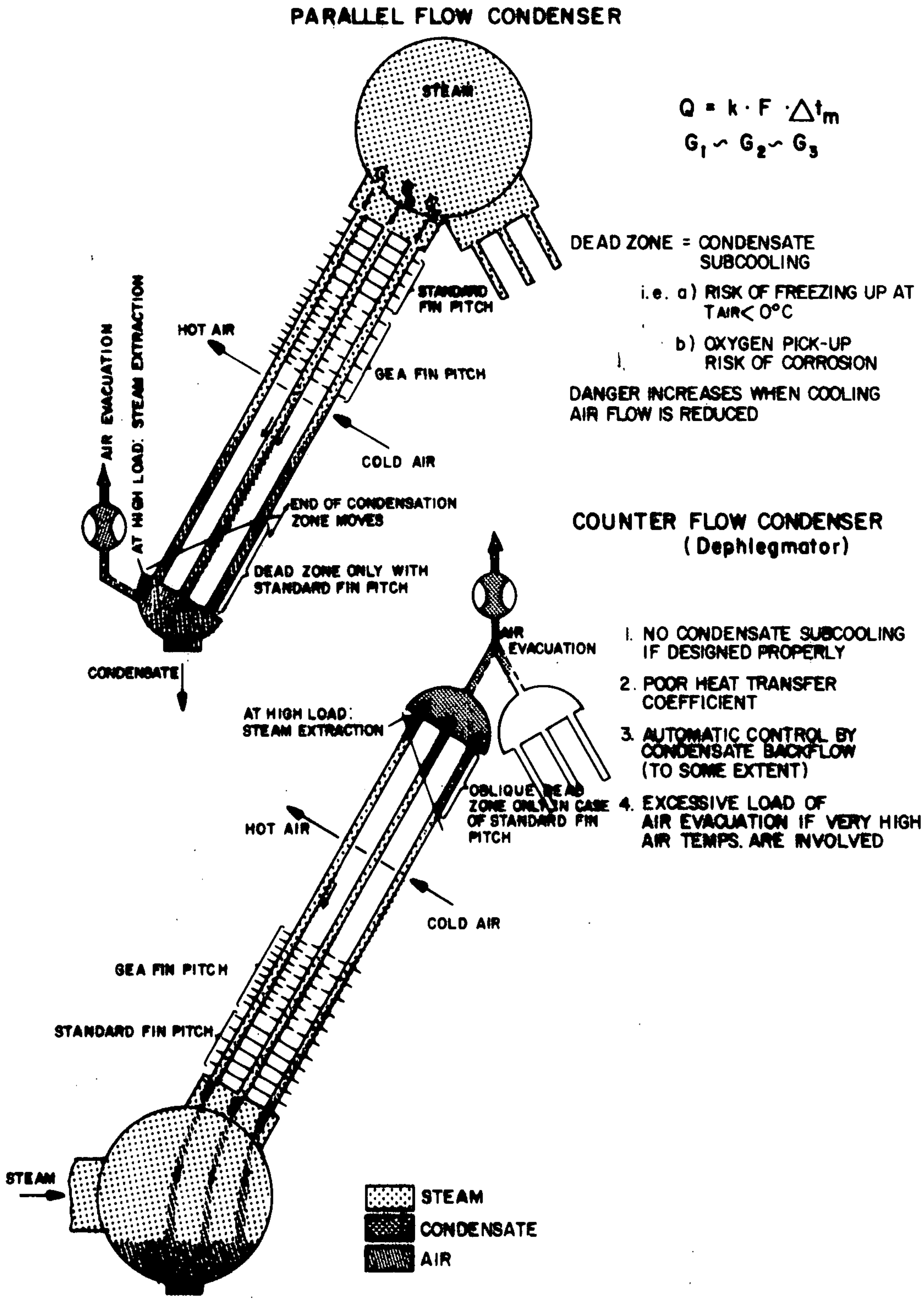

FIGURE I — GEA AIR-COOLED CONDENSER DESIGN DETAILS

A wind wall of the same height as the tube bundles is sometimes used to prevent warm air recirculation, which may be a problem under strong wind conditions. The condenser platform is elevated above ground and supported by a steel structure. The height of this structure is chosen to assure an average air access velocity of not more than 5 meters per second (16.5 fps). This is necessary to achieve low air inlet pressure loss and even air flow distribution.

The holding ejectors for condenser evacuation during normal operation are mounted on a platform on top of the condensate tank. A separate hogging ejector is used for startup operation.

Lummus Air-Cooled Vacuum Steam Condenser

The patented Lummusaire Turbine Exhaust Condenser (LATEC) design illustrated in Figure 2 is based on a modular concept for ease of manufacture, control, maintenance and erection. The basic component of the module is the tube bundle consisting of a number of finned U-tubes. Each tube bundle includes a separate secondary condenser which removes noncondensibles.

The bundles are supported by an "M" or "A" frame structure and are arranged for co-current flow (from the inside to the outside of the tube bundle) of air and steam. Several fintube bundles are combined in one module and are served by one or more axial flow fans which supply air under forced draft. Each fan is driven by an electric motor through a gear box. Each bundle has its own inlet manifold and two outlet condensate manifolds. The inlet manifold is connected to the main steam manifold which feeds steam from the turbine exhaust through the main steam line. The bundle condensate manifolds are connected to the main condensate line going to a loop seal and into the condensate receiver. The noncondensibles are removed from the secondary condenser of each bundle through air take-off lines to the air ejector system.

The bundles are arranged such that the unfinned part of the U-tube, i.e. the return bend, is located just on top of or underneath the steam manifold of the adjacent bundle. This results in a plot space saving of up to 25 percent over side-to-side designs without increased power consumption.

Turbine exhaust steam flows through a minimum length exhaust line which is connected to the distribution steam manifold serving the condenser. The condenser manifold provides steam distribution to the individual bundle manifolds or headers. The steam flows from the header manifold through the inlet legs of two rows of U-tubes. The axial flow fans force atmospheric air across the tube rows. A portion of the steam is condensed in the first two rows of tubes. The mixture of steam and condensate then flows by gravity through the sloped U-bends and the remainder of the steam is condensed in the second two rows. The cold inlet air is heated as it passes through each successive row in co-current flow with the hot fluid.

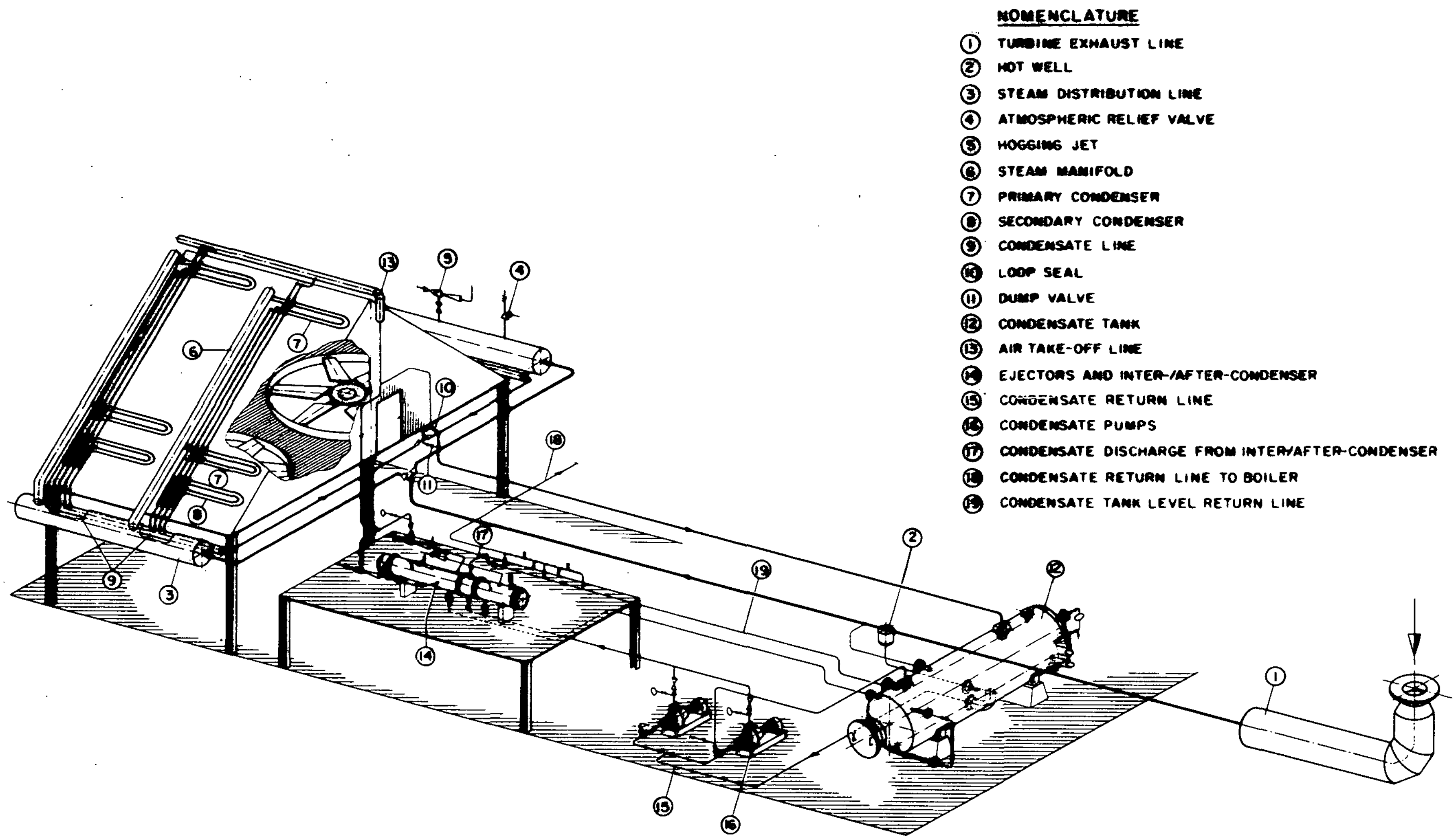

FIGURE 2 – LUMMUS AIR-COOLED CONDENSER DESIGN DETAILS

The condensate from each of the two return legs is drained through the separate condensate manifolds to the condensate line. Each condenser has a loop seal between the main condensate line and the condensate receiver.

In each bundle, the noncondensibles and any uncondensed steam flow into the separate condensate outlet manifolds and are further cooled in the secondary condenser before entering the air ejector system. Thus the maximum amount of steam is condensed before the noncondensibles are evacuated.

Normally, separate forced draft fans provide cooling air for tube bundles on each side of the "A" or "M" frame structure. Each cooling module is separated from adjacent modules by internal partition walls.

Wind walls are an integral part of the "M" frame design and are used, where necessary, with the "A" frame configuration to prevent external warm air recirculation that may occur during strong wind conditions.

Hudson Air-Cooled Vacuum Steam Condenser

Among the design features utilized by Hudson in vacuum steam condensers, a number of which are patented, are:

Steam Side

Restrictive steam flow on a modular or row basis
Special two-pass design
Multiple tube diameter in succeeding tube rows
Vent condensers following main condenser in series
Dephlegmator (for vertical or drastically sloped tube designs) following main condenser in series

Air Side

AUTO-VARIABLE Pitch Fans
- Allows totally modulated automatic control
- Saves power (compared to shutter or step-wise motor speed control)
- Permits reversal of air flow direction for winterized designs

Variable tube finned length in succeeding tube rows
Induced draft designs with internal air recirculation, utilizing AUTO-VARIABLE pitch fans and wind skirts, or AUTO-VARIABLE pitch fans and top mounted shutters
Forced draft designs with external air recirculation, utilizing shutters for air inlet, air exit and air bypass, with or without AUTO-VARIABLE pitch fans

Hudson offers horizontally or vertically oriented bundles, "A" or "V" designs, for ground or structure mounting.

As designers of the first industrial AUTO-VARIABLE fan in 1952, in addition to a standard line of adjustable pitch fans (both in diameters from 6 to 60 feet), Hudson has experience in modulation and direction control of air flow for steam condenser control and in special fan designs for low noise applications.

SECTION V

HIGHLIGHTS OF SITE VISITS

In the course of visits to the 24 dry cooling tower installations listed in Table 1, specific items of interest were investigated. Three main areas of concern for this research project were prevention of external corrosion of fintubes in marine or industrial environments, prevention of coil freezing during cold weather, and noise attenuation. Additional highlights included examples of design development for both the GEA and Lummus condensers, recent analysis of corrosion problems at installations which have been visited previously by R. W. Beck and Associates personnel, and development of a new concept in the structural engineering of natural-draft towers. These visits are described below in chronological order.

ALBATROSS REFINERY (5)*

This installation is located on the northeast edge of Antwerp, Belgium along the canal which connects the city with the North Sea. The GEA unit at this refinery condenses steam from a small turbine driving an electric generator. Figure 3 is a photograph of this unit. The corrosive effects of the salt and industrial pollutants in the atmosphere at this location have taken their toll on various metals. All bare steel is in very poor condition, and some aluminum fintubes in a process cooler have failed. Frequent repainting has kept painted steel in good condition, and galvanizing shows only a slight dulling.

Behind the power plant is a pile of discarded tubes from one of the process coolers in this refinery. These tubes, which were made by wrapping an L-shaped strip of aluminum around a steel tube, are commonly referred to as the "L-fin" tube. They were removed from service because the bottom row of fins became so corroded that cooler performance was inadequate and the construction of the cooler required that the top banks of tubes be cut away in order to remove the bottom row.

The aluminum fins on the tubes taken from the bottom row have accumulated a coating of black, brown and reddish dirt. The edges of the fins have been eaten away by corrosion, while cracks run from the corroded areas toward the tube. Corrosion and cracking are worse on the sides of the fins which were toward the incoming air stream. The fins on tubes from the second row are in much better condition, although some dirt buildup and light corrosion appear on the inlet air sides of these tubes also. Figure 4 shows these corroded fins.

---

* Numbers in parentheses refer to identification numbers in Table 1.

FIGURE 3 — GEA CONDENSER AT ALBATROSS REFINERY
ANTWERP, BELGIUM

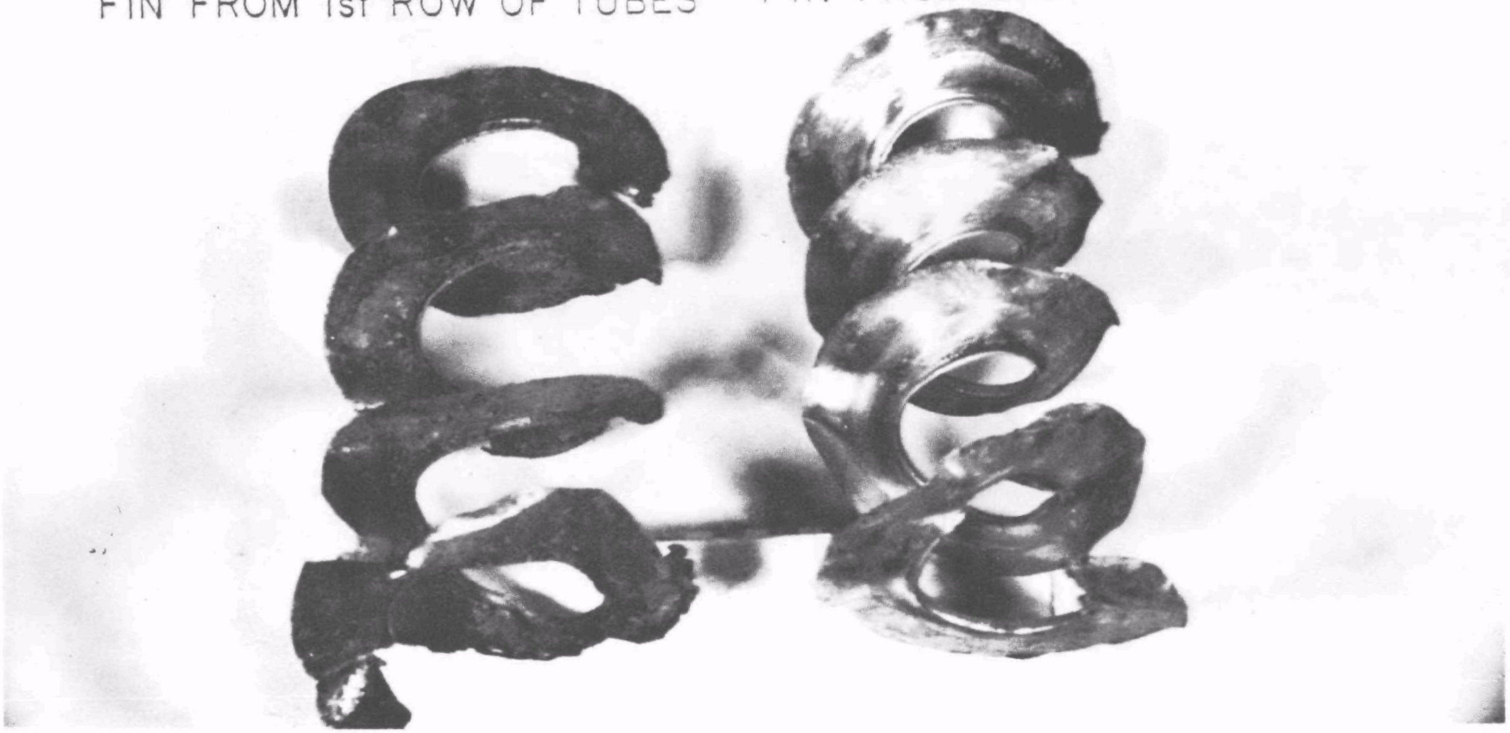

FIGURE 4 — DISCARDED ALUMINUM FINS AT ALBATROSS REFINERY ANTWERP, BELGIUM

Since the fins corroded only where dirt collected on them, some pieces of these fins were analyzed by chemical methods to identify the corrosive agent in the dirt. The analysis report indicated that soluble salts (chlorides and sulfates) compounds in the air plus moisture created an acid condition and, in conjunction with heavy metals, resulted in corrosion.

As fins were peeled from these tubes, it was observed that the steel tube had been rusting underneath the foot of the fin. This rust is present on all tubes, not just those which were located in the bottom bank. This would indicate that moisture in the air had come into contact with the steel tubes, quite possibly after their removal from service.

CONDEA REFINERY (6)

The location of this installation is Brunsbuttelkoog, West Germany, at the mouth of the Elbe River on the west end of the Kiel Canal connecting the North Sea with the Baltic. The GEA unit at this refinery was installed in 1963 and enlarged in 1971 by the addition of some fintube bundles. Thus it allows a comparison between the condition of a relatively new unit with a unit that has been in operation for more than 10 years. Figure 5 is a photo of this condenser. The three bundles of fintubes located on the left side of the unit and separated from the other six bundles are the sections installed in 1971. Note that the unit includes space on the left for the addition of yet another three bundles.

The unit operates today under different criteria than those originally used. When the new sections were added in 1971 to increase the condensing capacity, the overall performance parameters were changed to allow lower turbine backpressure and better plant thermal efficiency. Operating personnel indicated that since the new sections have been added, the increase in heat transfer capability has resulted in a tendency for the unit to begin freezing at -7 C (20 F) under low loads. They cover some of the sections with tarpaulins during severe weather to prevent this freezing.

The atmospheric conditions here that contribute to corrosion of metals consist mainly of salt spray borne inland by winds. Salt collects on the windward side of buildings and equipment where it is allowed to remain until washed away by subsequent rains. Industrial-type pollutants are reputed to be uncommon in this rural area. Bare steel is badly rusted, while painted steel and galvanizing are in good condition. A special alloy of aluminum containing some magnesium has been used as lagging on pipe insulation and is in good condition, with its oxidized surface intact. Aluminum-finned heat exchangers in the refinery give satisfactory service, according to operating personnel.

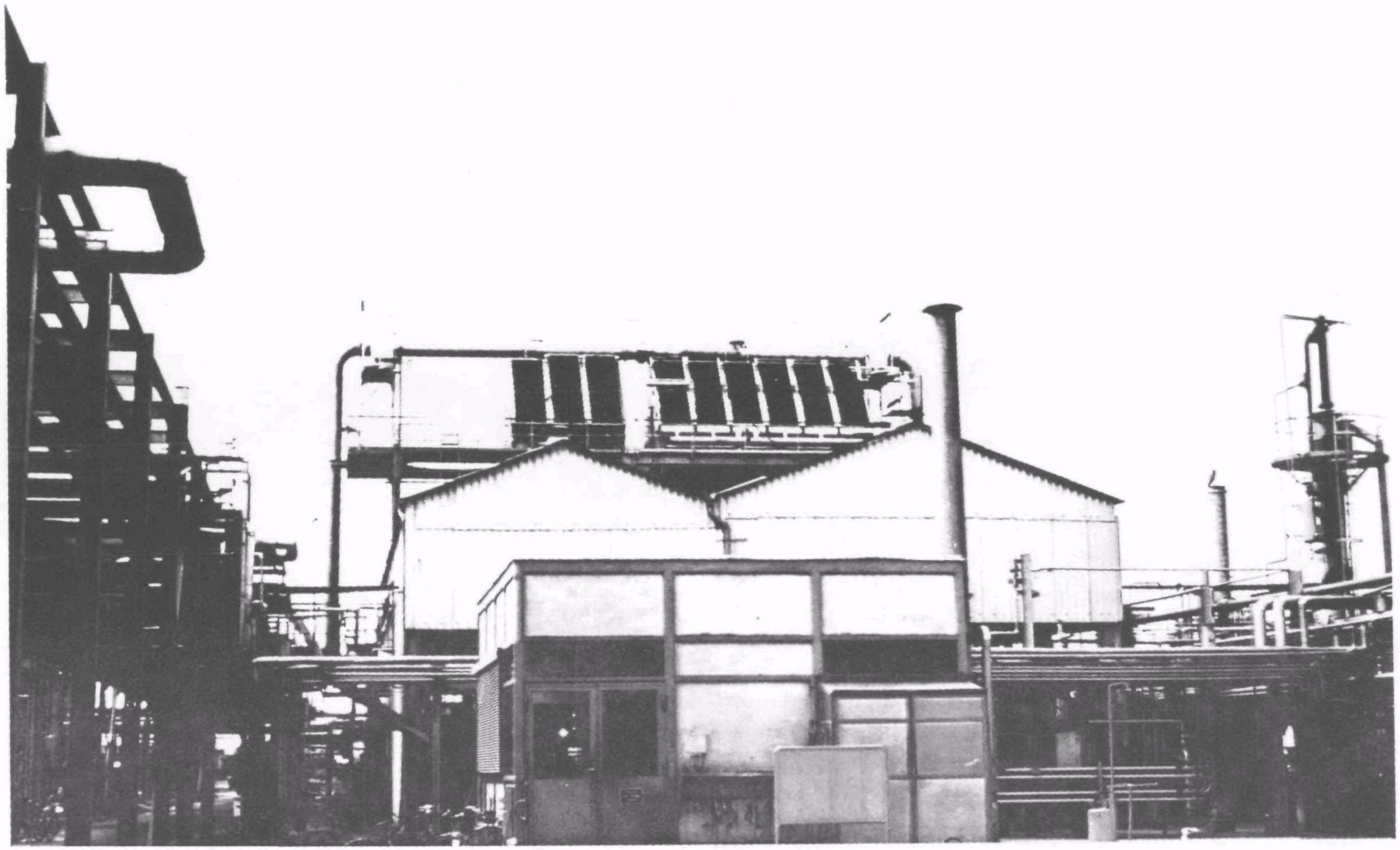

FIGURE 5 — GEA CONDENSER AT CONDEA REFINERY
BRUNSBUTTELKOOG, WEST GERMANY

Figures 6 and 7 compare the appearance of galvanized fintubes on the old and new sections of the GEA condenser. The older fins are darker in color than the new fins, but in quite good condition. Some of the fins from the older section which have been bent and damaged to expose the steel beneath are rusted where the galvanizing has been removed, but have not suffered a significant reduction in heat transfer capabilities.

ZURICH, SWITZERLAND MUNICIPAL INCINERATOR (7)

This GEA unit is connected to the steam turbines which generate power at this incinerator. This unit is located inland in a relatively pollution-free environment. The main reason for visiting this unit is that it was designed for the extremely low noise level of 45 dB(A) at 120 meters (400 feet). Figure 8 is a photo of this condenser.

A number of methods were used to attain the low noise levels for this unit: 1) large diameter fans were employed; 2) motors are slow-speed units connected directly to the fan in order to eliminate a reduction drive gear with its attendant whine; and 3) the air inlet plenum is totally enclosed on the two sides that allow air into the unit by a set of acoustical baffles. Figure 9 is a closeup of these baffles from inside the plenum chamber. The baffles, consisting of a fibrous material sandwiched between plates of perforated metal, are about 15 cm (6 inches) thick and spaced about 0.5 m (1.5 feet) apart.

The eight fans on this unit are approximately 6 m (20 feet) in diameter and are powered by two-speed electric motor drives which operate the fans at either 136 or 68 revolutions per minute. Noise measurements were made at the unit by the research team and are reported in Section VIII.

LINDE AIR SEPARATION PLANT (8)

This unit is located in central West Germany, in a light-industrial area near Nuremburg. The unit was manufactured to a design provided by the Lummus Company and condenses steam from a turbine generator. It is designated a LATEC II type by Lummus. The main difference between this unit and the later LATEC III type is that it has a single upper header (see Figure 10), while the steam header for the LATEC III runs along each side of the bottom of the coils.

This condenser has experienced a single episode of freezing which occurred during the first cold weather period of the season. Operating personnel injected live steam into the condensate line as they thought this would keep the condensate warm and thereby prevent freezing. In fact, this had the effect of setting up a reverse-flow of condensate back up into the finned tubes with subsequent freezing. It is a characteristic of the LATEC bundle design that, if freezing does occur, as in this rather unusual case, it will be confined to the V-bends which are exposed and readily accessible for repairs. Being circular in shape, the finned section of the U-tube does not undergo deformation.

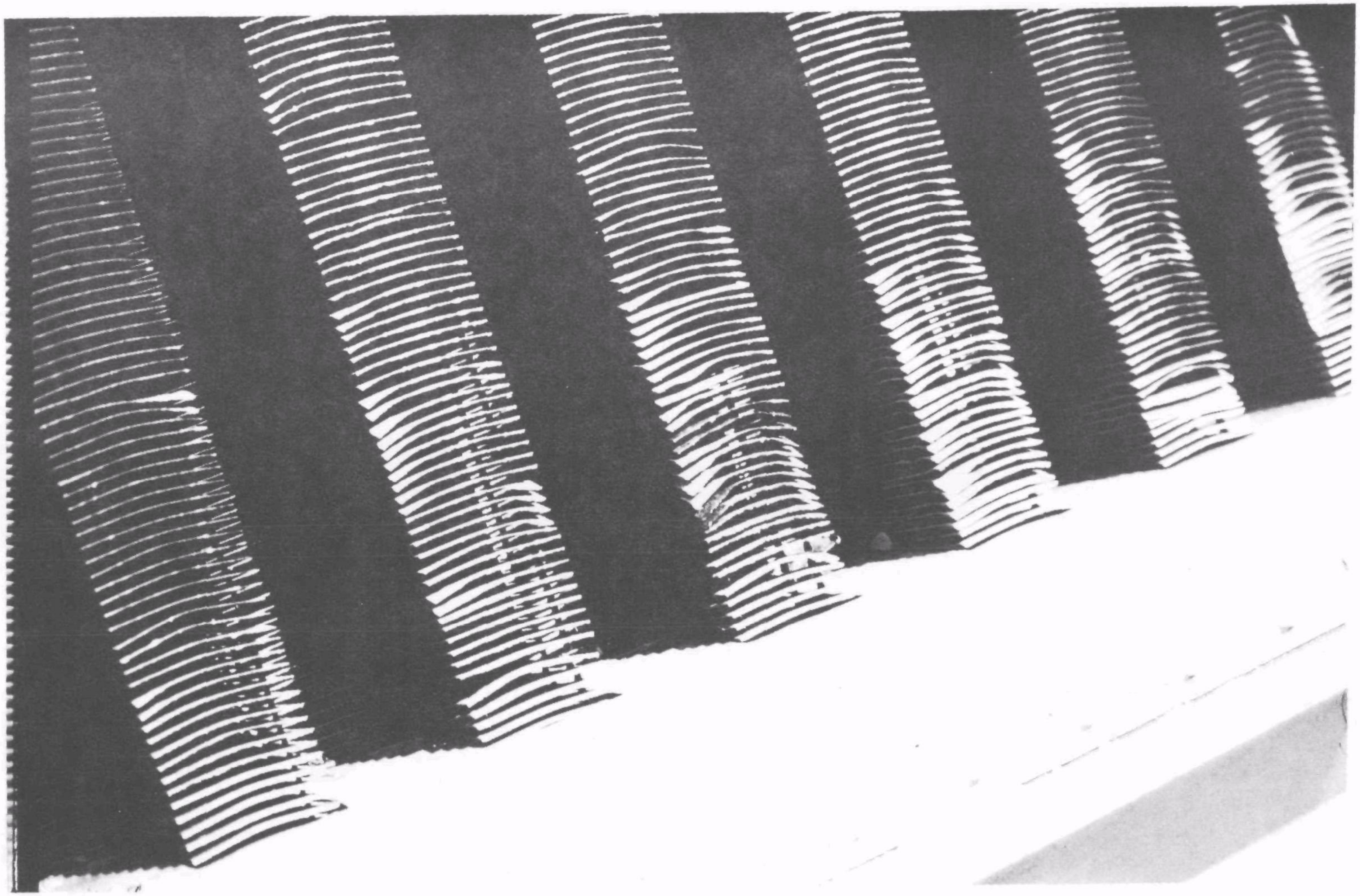

FIGURE 6 — 10 YEAR OLD GALVANIZED FINTUBES AT CONDEA REFINERY
BRUNSBUTTELKOOG, WEST GERMANY

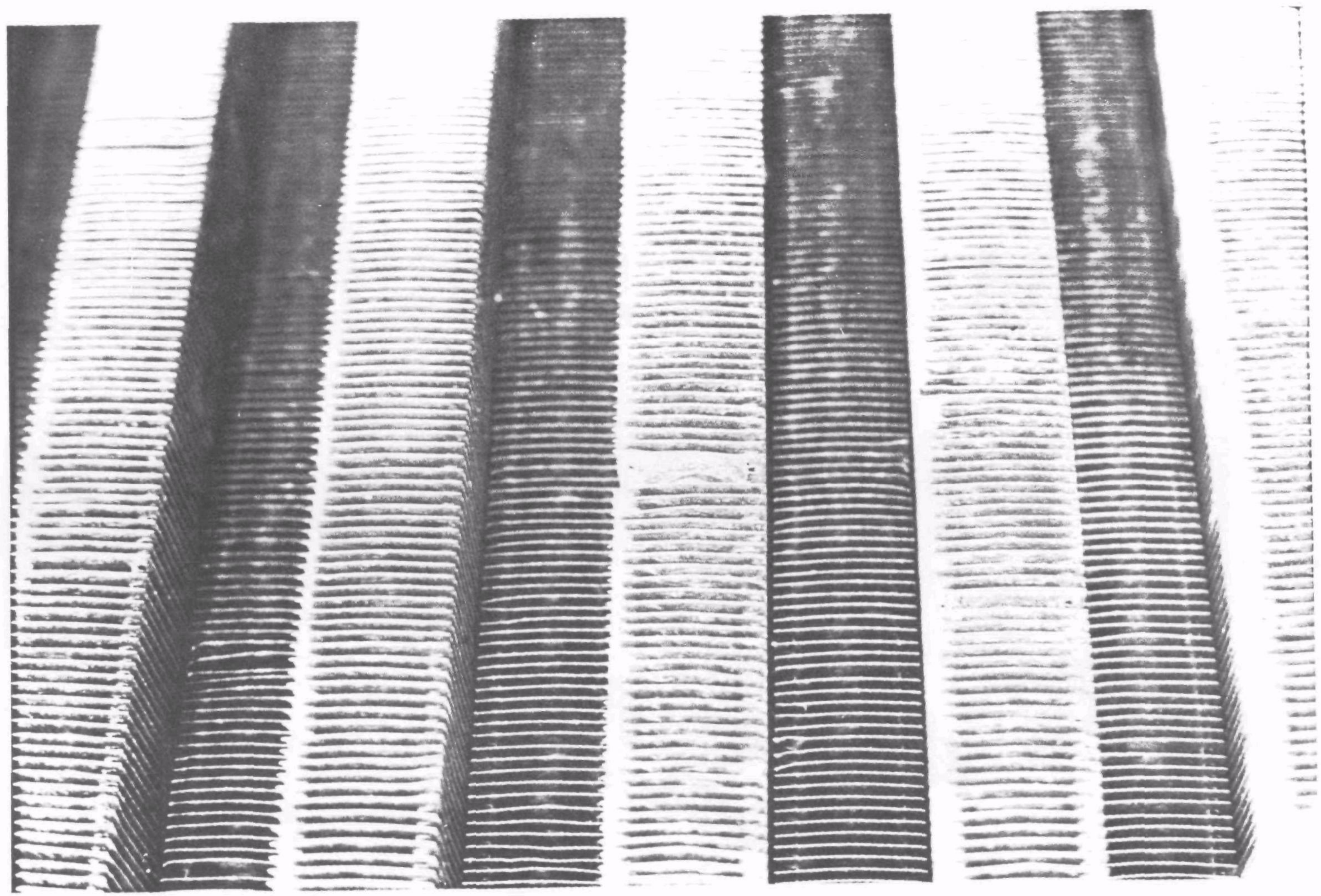

FIGURE 7 — 2 YEAR OLD GALVANIZED FINTUBES AT CONDEA REFINERY BRUNSBUTTELKOOG, WEST GERMANY

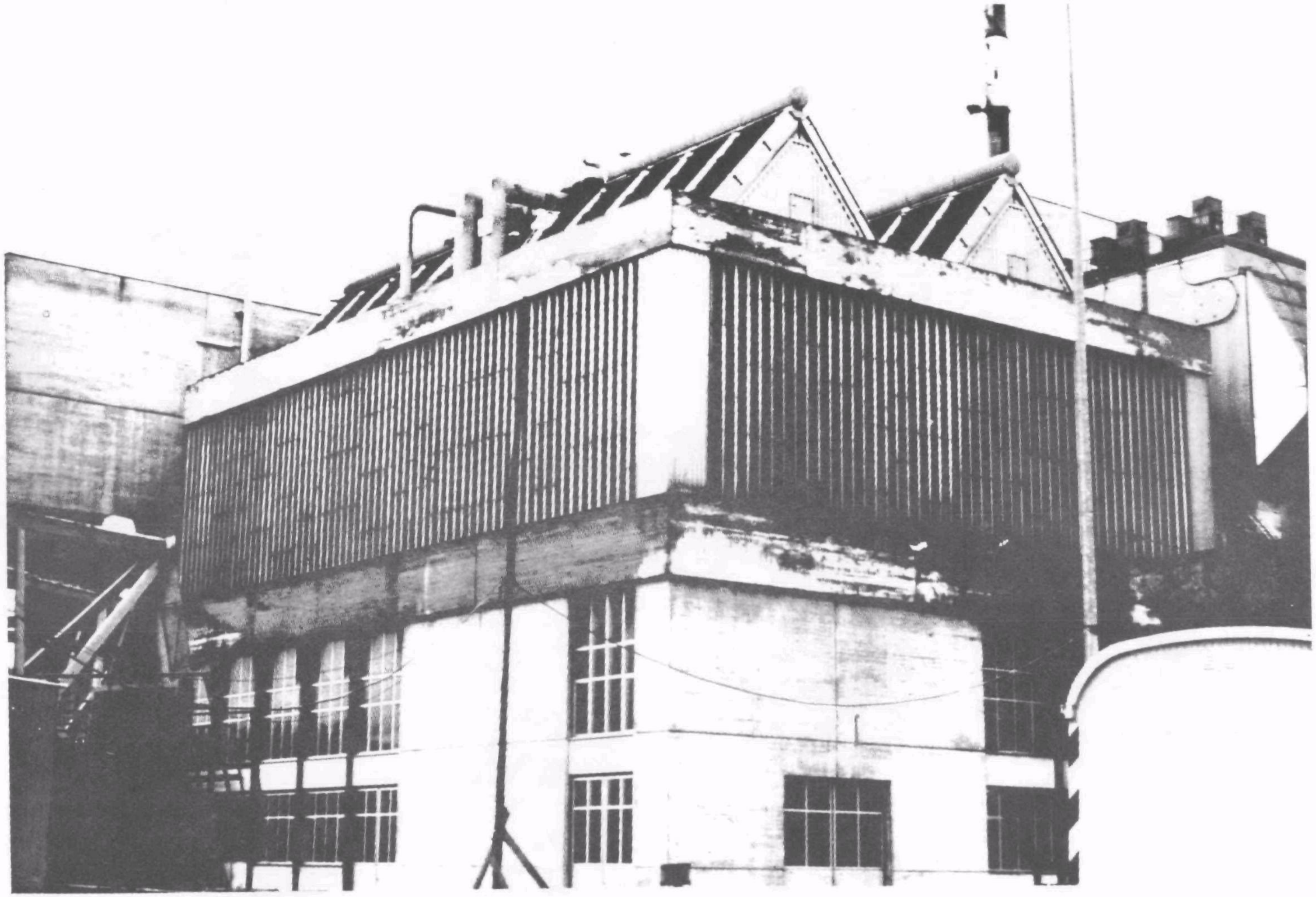

FIGURE 8 — GEA LOW-NOISE CONDENSER AT MUNICIPAL INCINERATOR ZURICH, SWITZERLAND

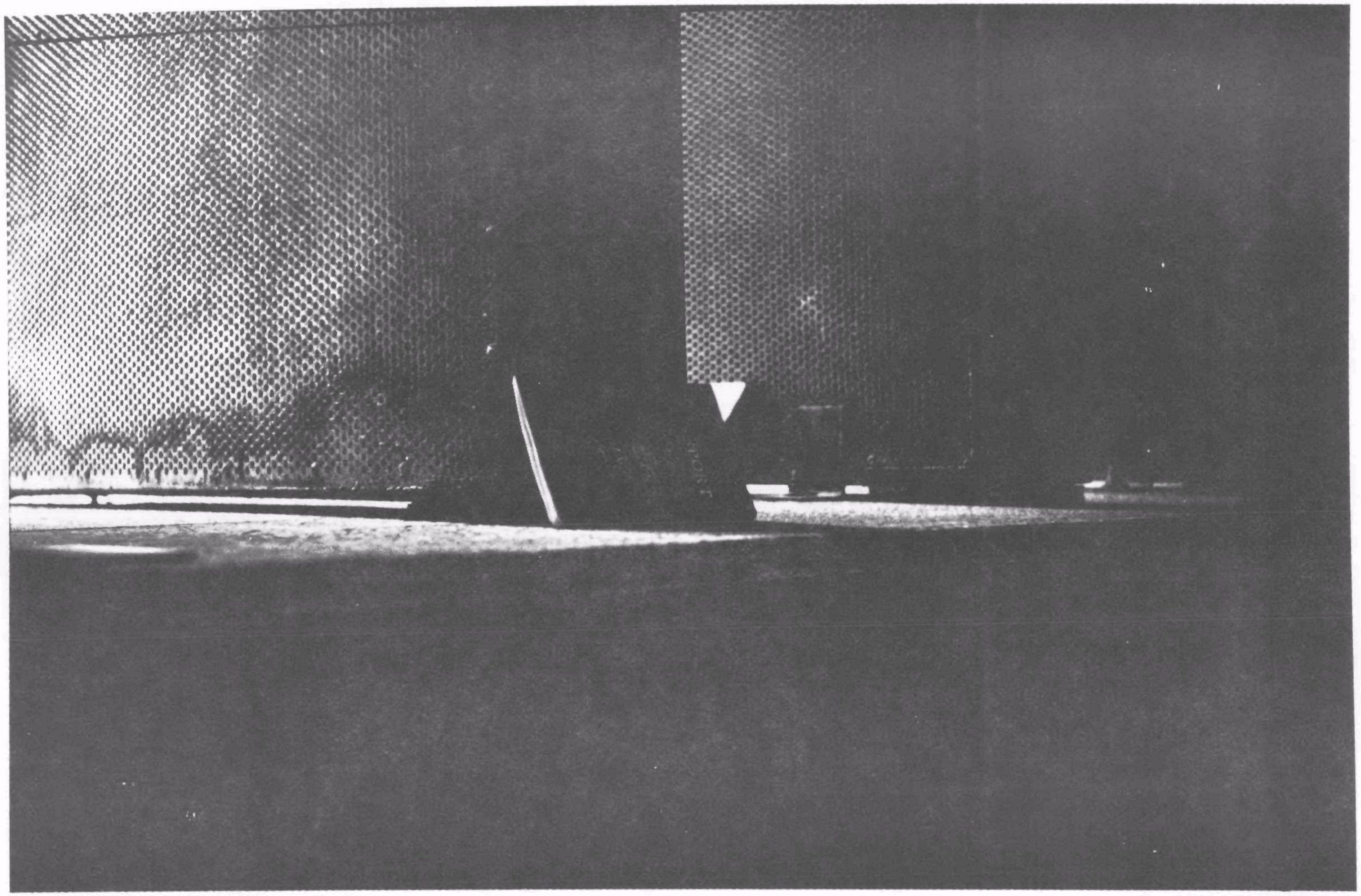

FIGURE 9 — CLOSEUP OF ACOUSTICAL BAFFLES AT MUNICIPAL INCINERATOR ZURICH, SWITZERLAND

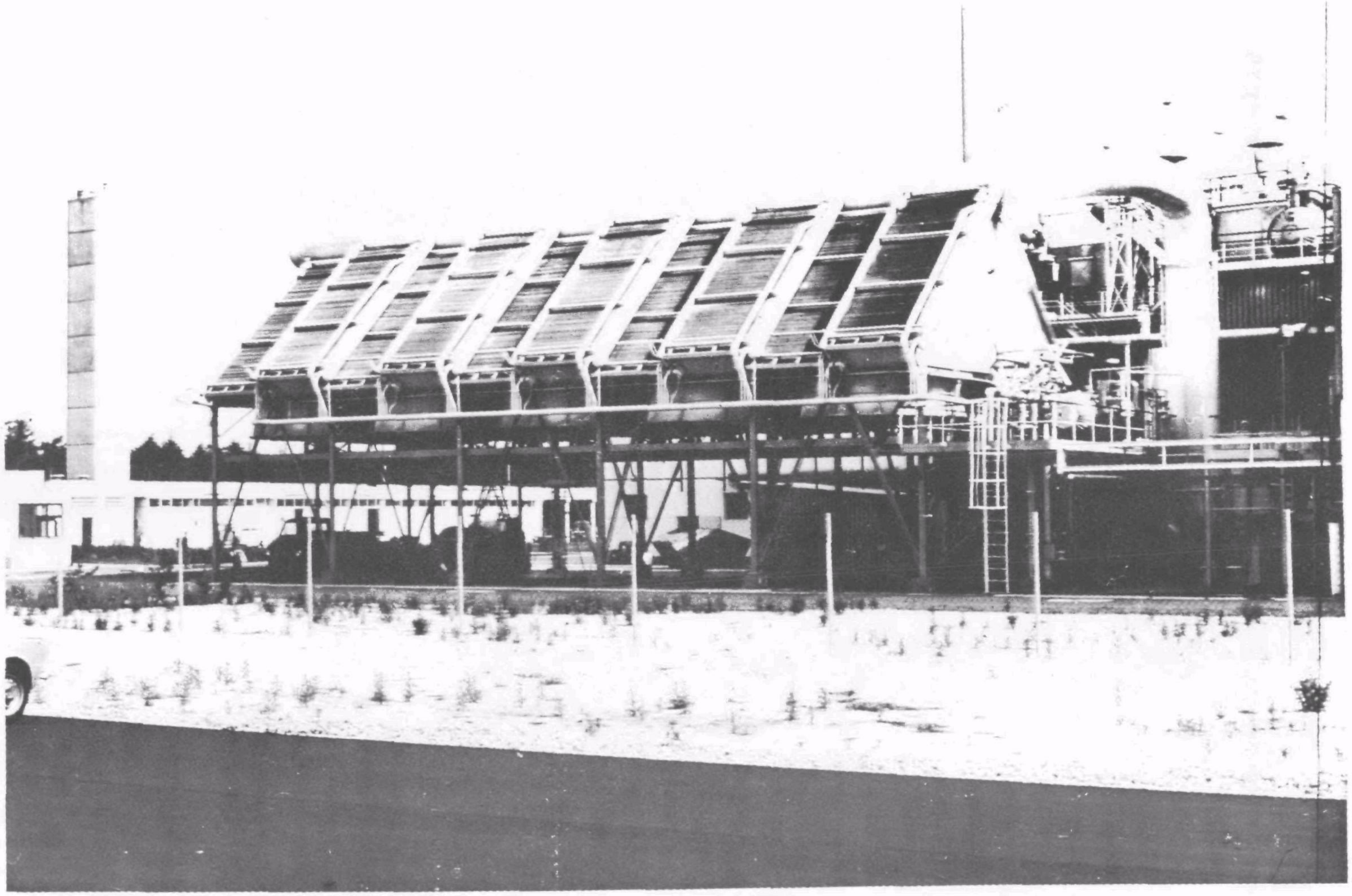

FIGURE 10 — LUMMUS LATEC II CONDENSER AT LINDE PLANT
NUREMBURG, WEST GERMANY

Lummus used an infrared camera at this unit to examine the effect of artificially-induced air leaks during operation; the areas near the air leaks were cooler than the parts of the unit that were operating properly. With this method, operating condensers can be examined to investigate air recirculation and wind effects, steam maldistribution and operation at partial loads.

VOEST-ALPINE STEEL WORKS (14)

This LATEC III unit, located in a mountain valley in the Austrian village of Donawitz, condenses steam from a turbine generator. Its design combines an especially steep angle of the tube bundles with a system of overlapping the header ends of the bundles in order to save ground area and to make the airflow distribution more efficient. These concepts can be seen in Figure 11, and were quite important in the selection of a condenser for this particular application because of space limitation at the site. Details of the secondary condenser, located at the lower end of the fintube bundle and upstream of the air evacuation equipment, can be seen in Figure 12.

NUOVO PIGNONE PLANT (15)

This unit designated as a LATEC I, is located approximately 75 km (45 miles) inland from the Ligurian Sea in a highly-urbanized area of Florence, Italy, and was manufactured by Nuovo Pignone to a design produced by the Lummus Company. The unit is used to condense steam during the testing of turbines and compressors built by Nuovo Pignone at this plant and for this reason has been subject to a cyclic variation of its operational use and working temperature levels. This early LATEC design is easily distinguished from later models by the use of nearly-horizontal fintube bundles as shown in Figure 13. The unit is also of a single-pass steam flow with aluminum G-fins, i.e., embedded into the steel tube, in contrast to the double-pass U-tubes with aluminum L-fins typical of later designs.

Even though traces of chloride ion were found in laboratory analysis of a fin sample from this unit, the cooling coils were in very good condition. The only noticeable corrosion was that of unpainted steel, which has had no effect on its performance.

CHEVRON REFINERY (17)

This unit, located in a rural area approximately 30 km (20 miles) south of Brussels, Belgium, was manufactured to a design provided by the Lummus Company and condenses steam from a turbine pump drive used for pumping refinery products through a product pipeline. Figure 14 is a photo of this unit.

The unit was designed for a sound pressure level of 82 dB(A) at 1 m (3 feet) below the fans with four large diameter slow-speed fans. The fans are single-speed (128 rpm)with automatic variable pitch blades and bell-shaped inlet plenums. Noise measurements were taken at the unit by the research team and are reported in Section VIII.

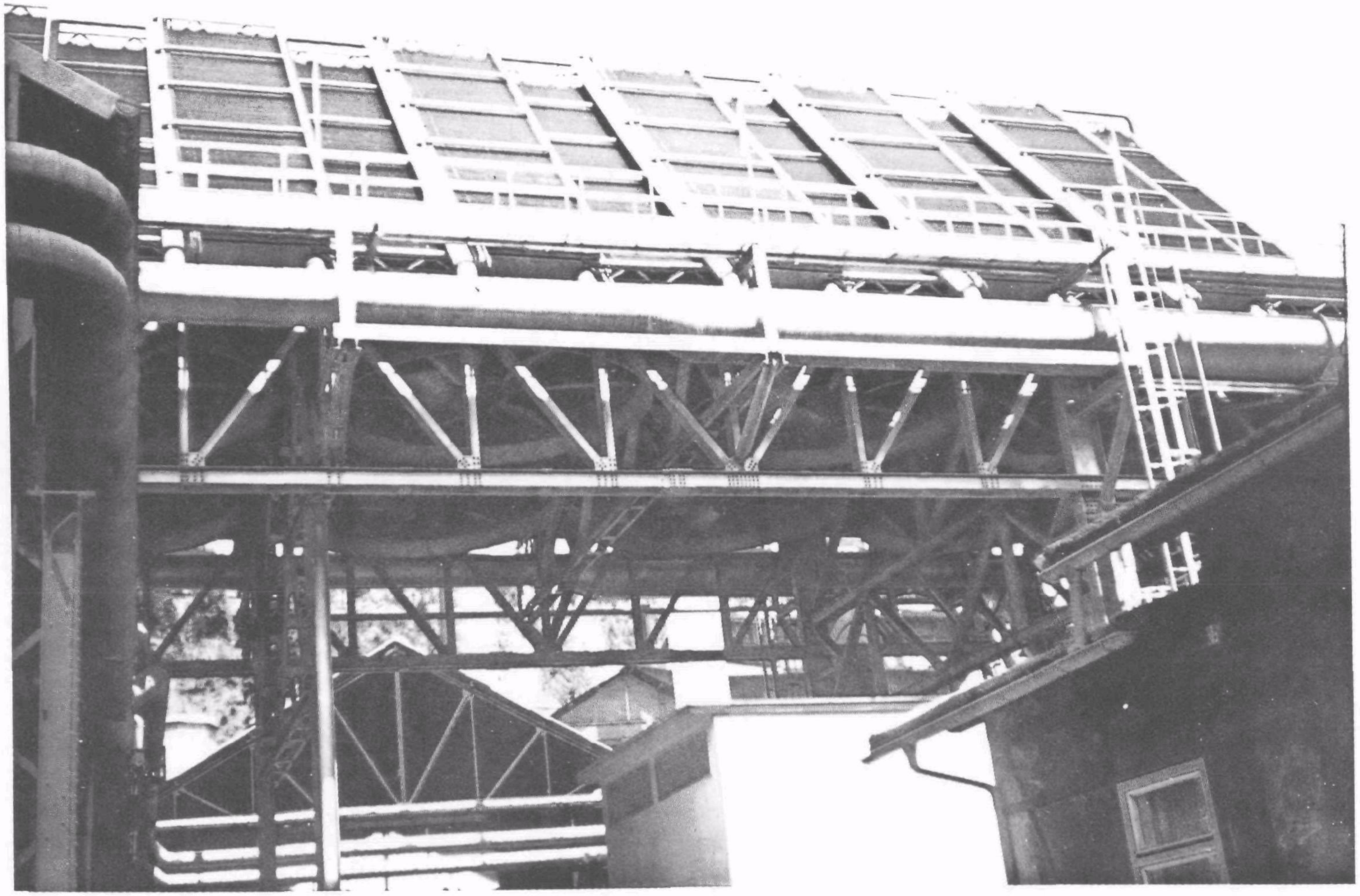

FIGURE 11 — LUMMUS LATEC III CONDENSER AT VOEST-ALPINE STEEL WORKS DONAWITZ, AUSTRIA

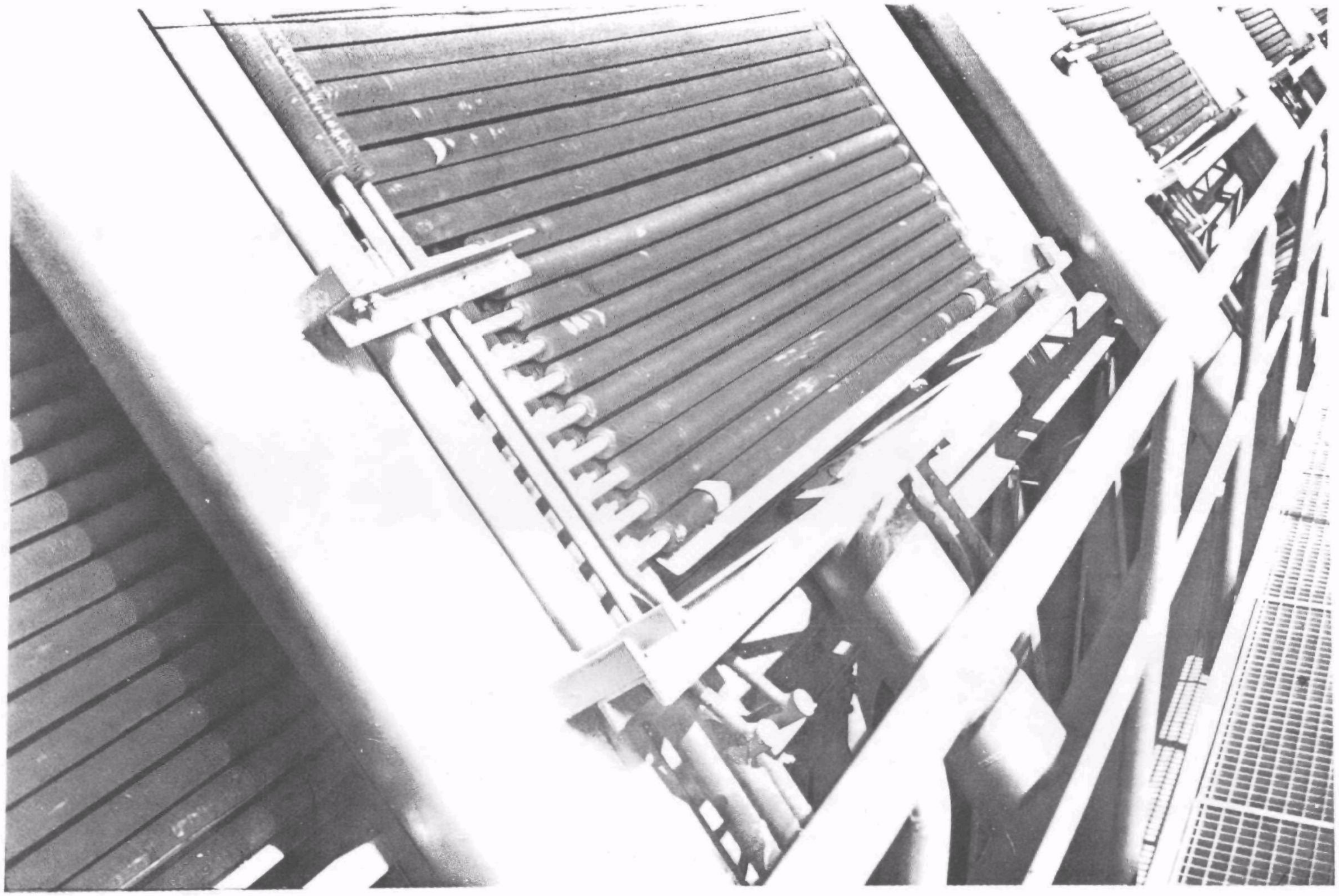

FIGURE 12—LUMMUS SECONDARY CONDENSER DETAIL AT VOEST-ALPINE STEEL WORKS
DONAWITZ, AUSTRIA

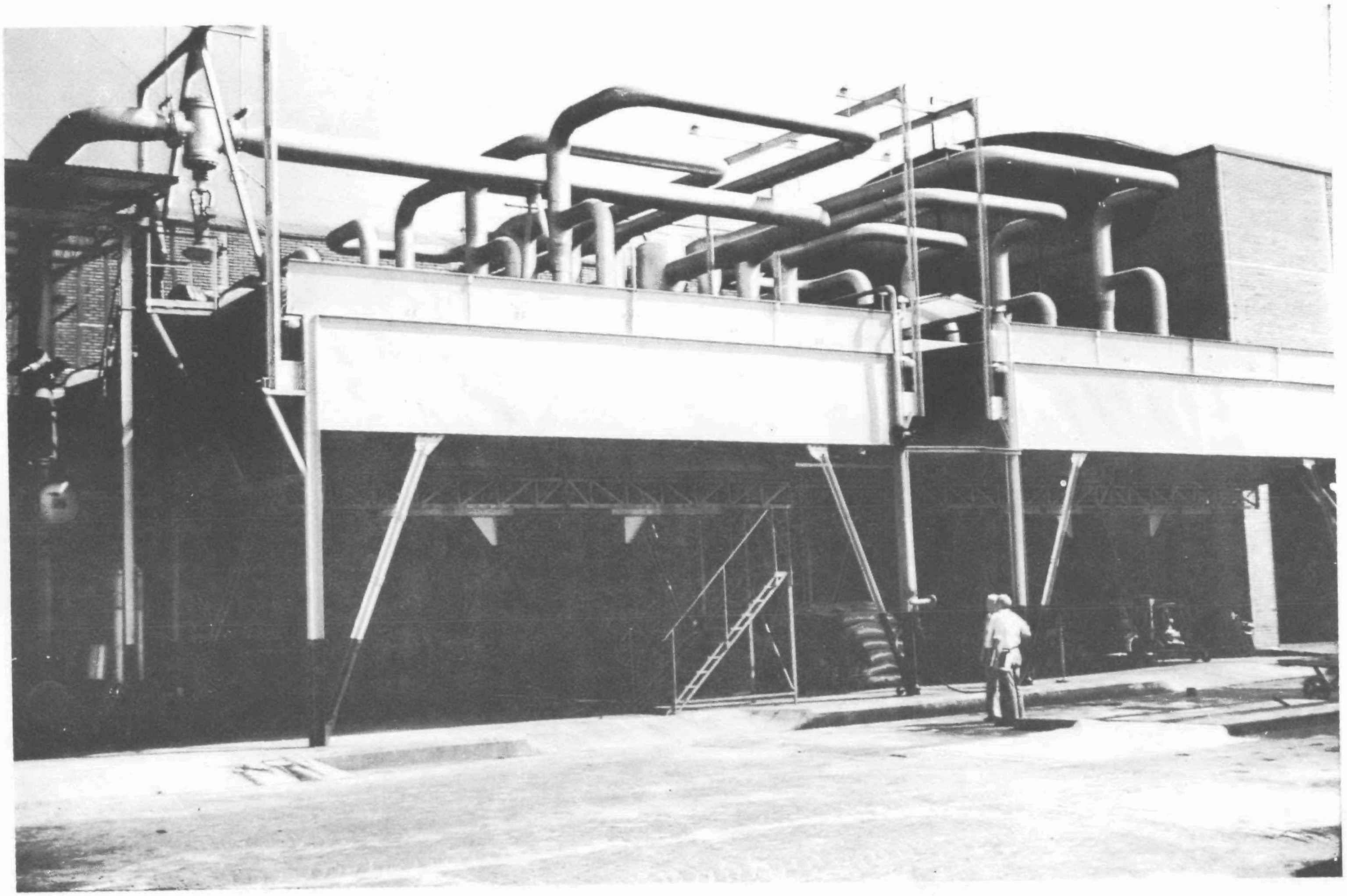

FIGURE 13 – LUMMUS LATEC I CONDENSER AT NUOVO PIGNONE PLANT
FLORENCE, ITALY

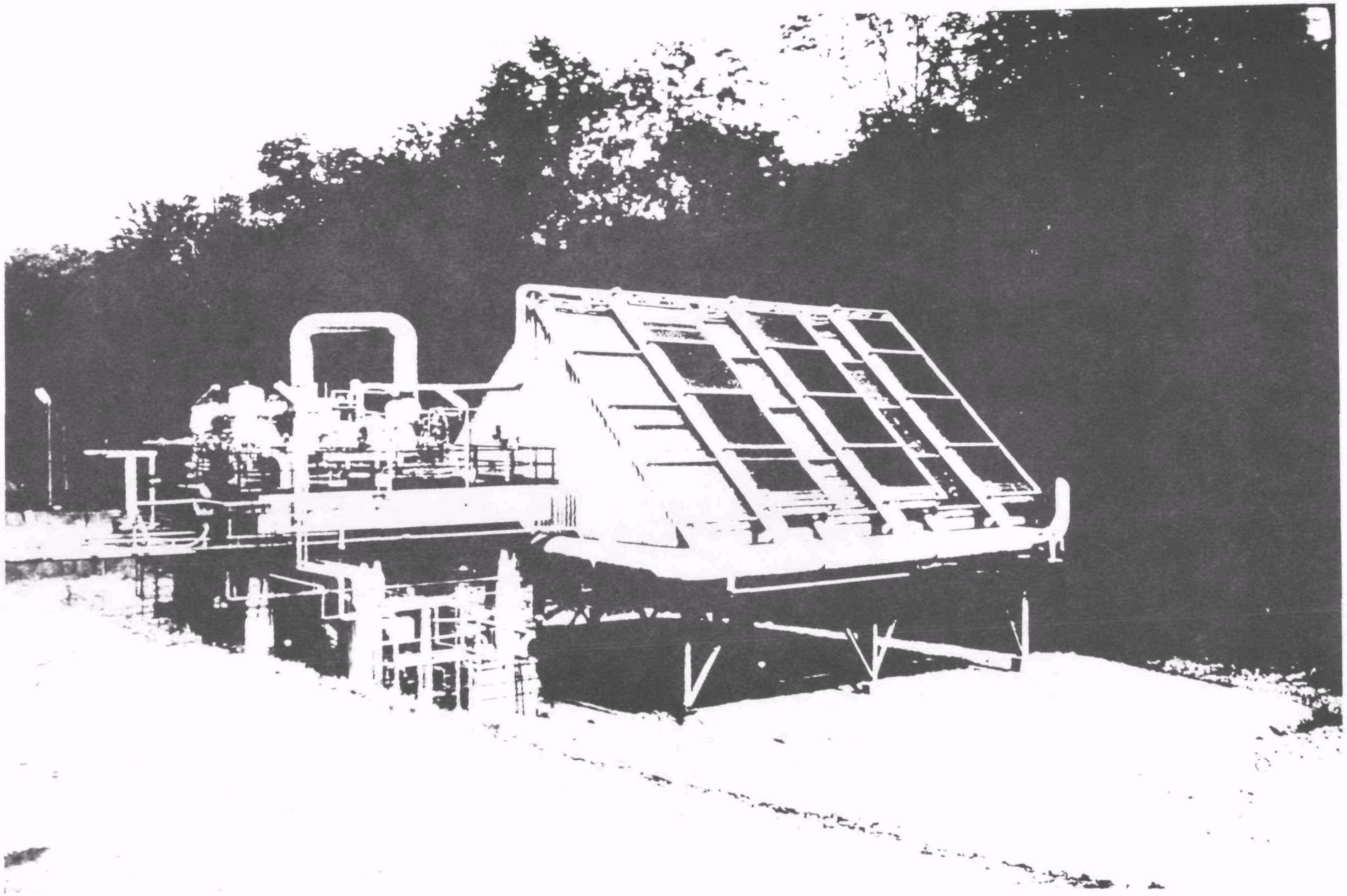

FIGURE 14 — LUMMUS LOW-NOISE CONDENSER AT CHEVRON REFINERY FELUY, BELGIUM

C.E.G.B. RUGELEY STATION "A" (18)

Located approximately 200 km (120 miles) northwest of London in a rural coal-mining village, Rugeley Station has been the site of the Central Electricity Generating Board's research into the feasibility of dry cooling towers for power plant application since late 1961. A description of the indirect dry-type Heller system utilized with a natural-draft tower has been prepared previously.[2] Figure 15 is a photo of the four natural-draft wet towers which serve Station "B" and the shorter, wider-mouth dry tower which serves 120 MW "A" Unit 3. Station "A" is comprised of five 120 MW units, and Station "B" has two 500 MW units.

The principal reason for visiting this generating station was to check on progress made in controlling external fintube corrosion since an earlier visit in late 1969. Corrosion is thought to result from the proximity of the coal mining/storage operation, an ash-sintering plant (for the production of building materials), and the evaporative cross-flow cooling towers. The coal mined at the site is relatively high (0.6%) in chlorine content and probably contributed significantly to the failure of the original aluminum (tube-collar-plate fin) Forgo coils. All of these fintube bundles have been subsequently replaced.

A total of four sets of fintube bundles have been used in the Rugeley dry tower. Only the original bundles were a complete set. The latest three types (still in use), in chronological order, have been: epoxy-coated Forgo elements (see Figure 16), an English Electric Company scallop-edged plate fin design, and epoxy-coated Forgo elements. In conjunction with this test program on various fintube constructions, a new repair technique involving epoxy injection directly into the bundle to repair leaks internally has been used. Maintenance techniques currently involve washing and physical inspection of the bundles on a once-per-month basis. The cycling of warm water in out-of-service bundles to maintain approximately a 2 C (4 F) temperature differential with ambient air is also under consideration. Freezing is not a serious problem, however, due to the winter peak experienced at this plant.

VOLKSWAGEN PLANT (19)

This unit is located in the West German city of Wolfsburg whose primary industry is the Volkswagen plant. The GEA unit condenses steam from four turbine generators of 48 MW capacity each. Figure 17 is a photo of the unit. Two condensers were installed in 1961, another in 1966 and the last in 1972. There are also wet cooling towers which serve the old power plant. Prinicipal reasons for visiting this plant were to compare the different GEA designs for the three vintages of condenser, and to observe the relative condition of galvanized fintubes differing in age by more than 10 years.

Blocks A and B (1961) each have four condenser groups, three of which are parallel flow and one of which is counterflow (dephlegmating).

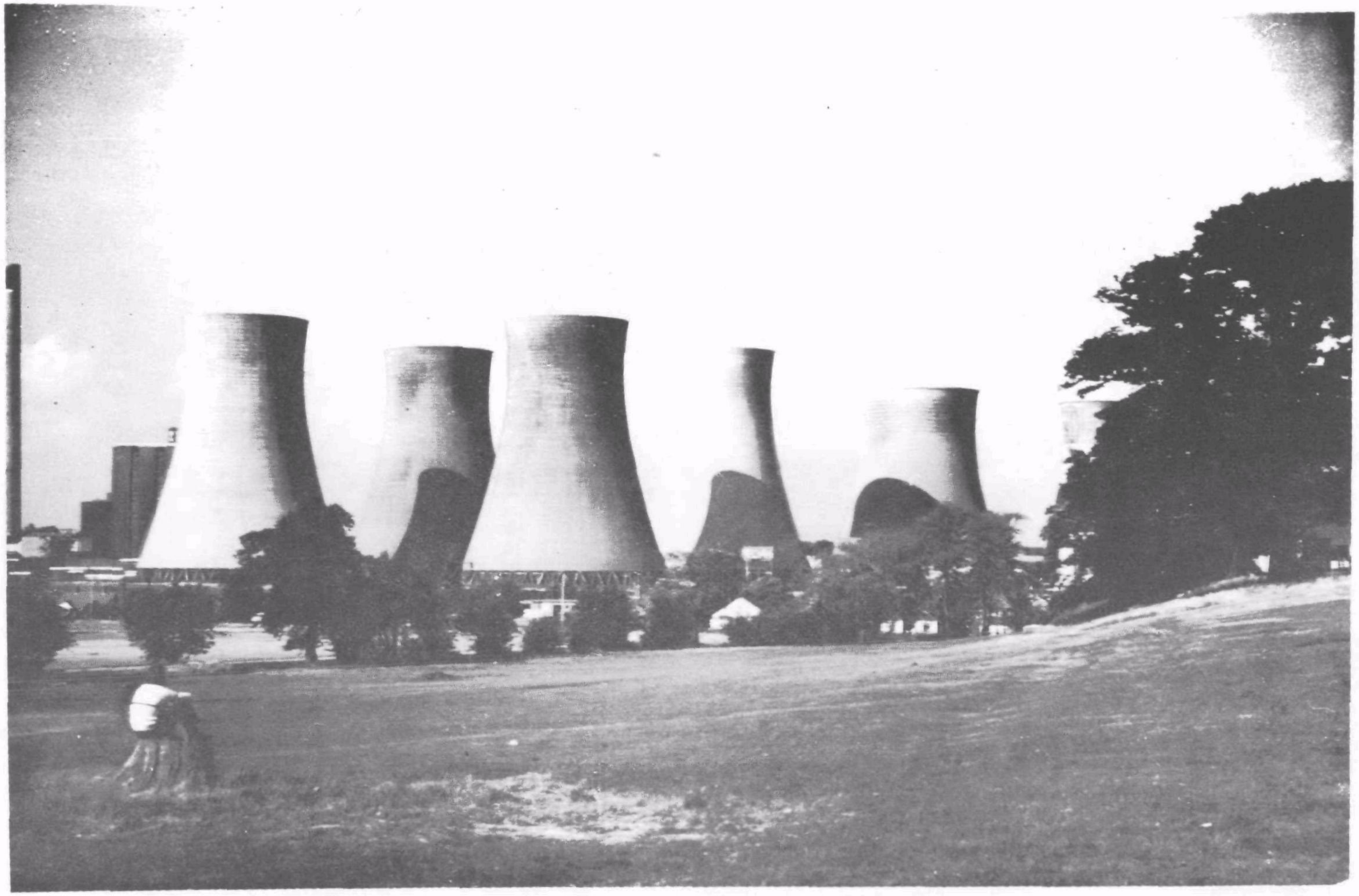

FIGURE 15 — NATURAL-DRAFT COOLING TOWERS AT C.E.G.B. GENERATING STATION RUGELEY, ENGLAND
(DRY TOWER IS SHORTER, WIDER-MOUTH UNIT)

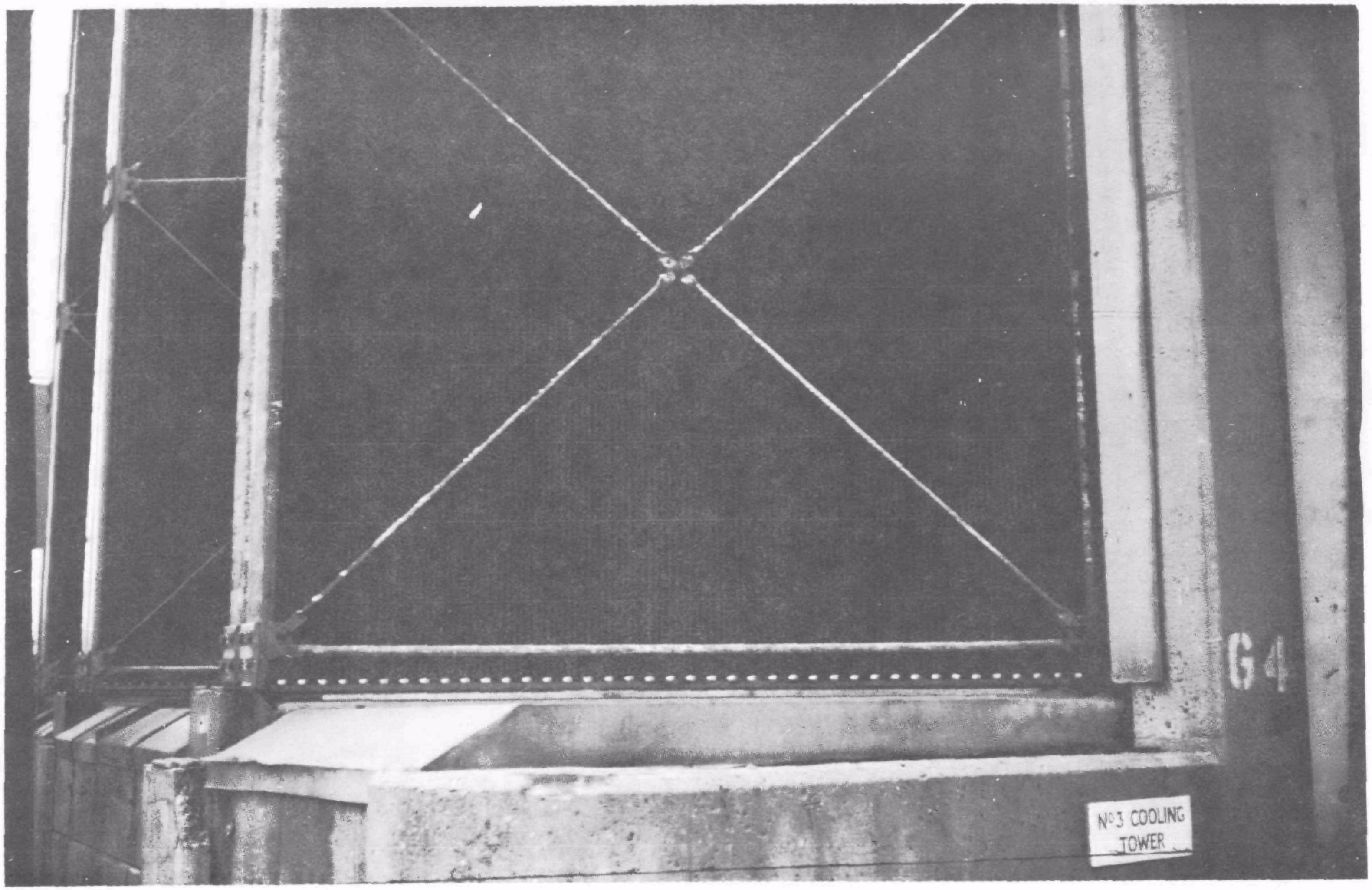

FIGURE 16 — EXAMPLE OF THE OLDEST EPOXY-COATED FINTUBE BUNDLES AT C.E.G.B. PLANT — RUGELEY, ENGLAND

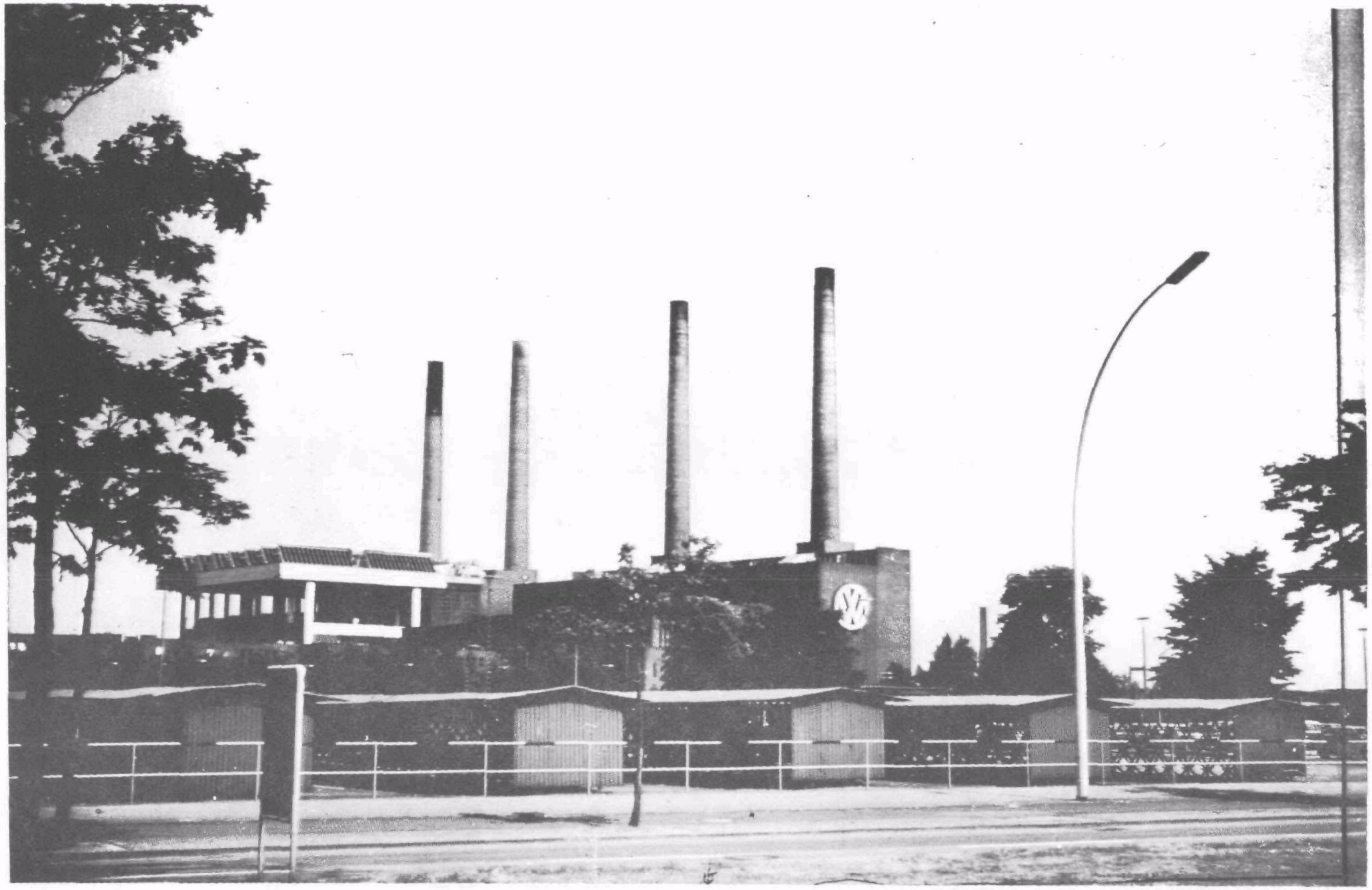

FIGURE 17 — GEA CONDENSER AT VOLKSWAGEN PLANT
WOLFSBURG, WEST GERMANY

The condenser groups are isolable through shutoff devices in the steam and evacuation lines. An aftercondenser upstream of air evacuation equipment is shown in Figure 18. Block C has four groups, each having a counterflow section in the center and two parallel flow sections arranged at the ends. These hookups permit different operating modes.

For ambient temperatures below 0 C, Blocks A and B are started up with only the dephlegmators. With increasing exhaust flows, the three dephlegmator fans are started sequentially at reduced rpm and are finally operated at high speed. The parallel flow groups remain shut off. As the limit of dephlegmator capacity is approached, a parallel flow group is brought on line in order to maintain vacuum. The cooling surface is thereby increased, initially more than the steam flow would require. In order to prevent condensate subcooling and possible icing of the tubes, the added parallel flow group should immediately be heavily loaded with steam. This is done by shutting down the dephlegmator fans as soon as steam is admitted to the parallel flow group and switching the parallel flow unit fans to high speed. The dephlegmator loading, in this case, is only the excess over the capacity of the parallel flow units just placed on the line. A further increase in steam flow is accommodated by loading up the dephlegmators, i.e., re-energizing the fans, and finally, the second and third parallel flow groups are likewise put on line.

Block C is started up a group at a time. A control sequence first energizes the fans of the dephlegmator elements and then those of the parallel flow sections. The other groups are similarly put into operation, depending upon demand. A diagram shows the operator the temperature and load points for fan speed cutback and eventual shutdown.

Condenser response to variations in load and air temperature is achieved by air flow adjustment. It should be noted that there is an economic limit beyond which the cost of added fan power consumption for increased air flow exceeds the fuel cost savings resulting from vacuum improvement.

Control of air flow for units A through C is accomplished by means of two-speed motors. However, these coarse steps require frequent speed changes at light loads, and a different means was, therefore, chosen for Block D. It has three parallel flow groups each of which includes a small counterflow unit, and a startup group having two of three sections that may be connected in the parallel flow or dephlegmator mode. This startup group is equipped with variable pitch fans, permitting better accommodation of load conditions at low temperatures.

As regards the aging of galvanized fintubes, the oldest units have turned a dark dull color, in contrast to the light gray surface of the newest unit. The only noticeable corrosion is where mechanical accidents have removed the galvanizing, allowing oxidation of the underlying steel fintube. This corrosion has not, however, significantly altered the heat transfer capability of the units.

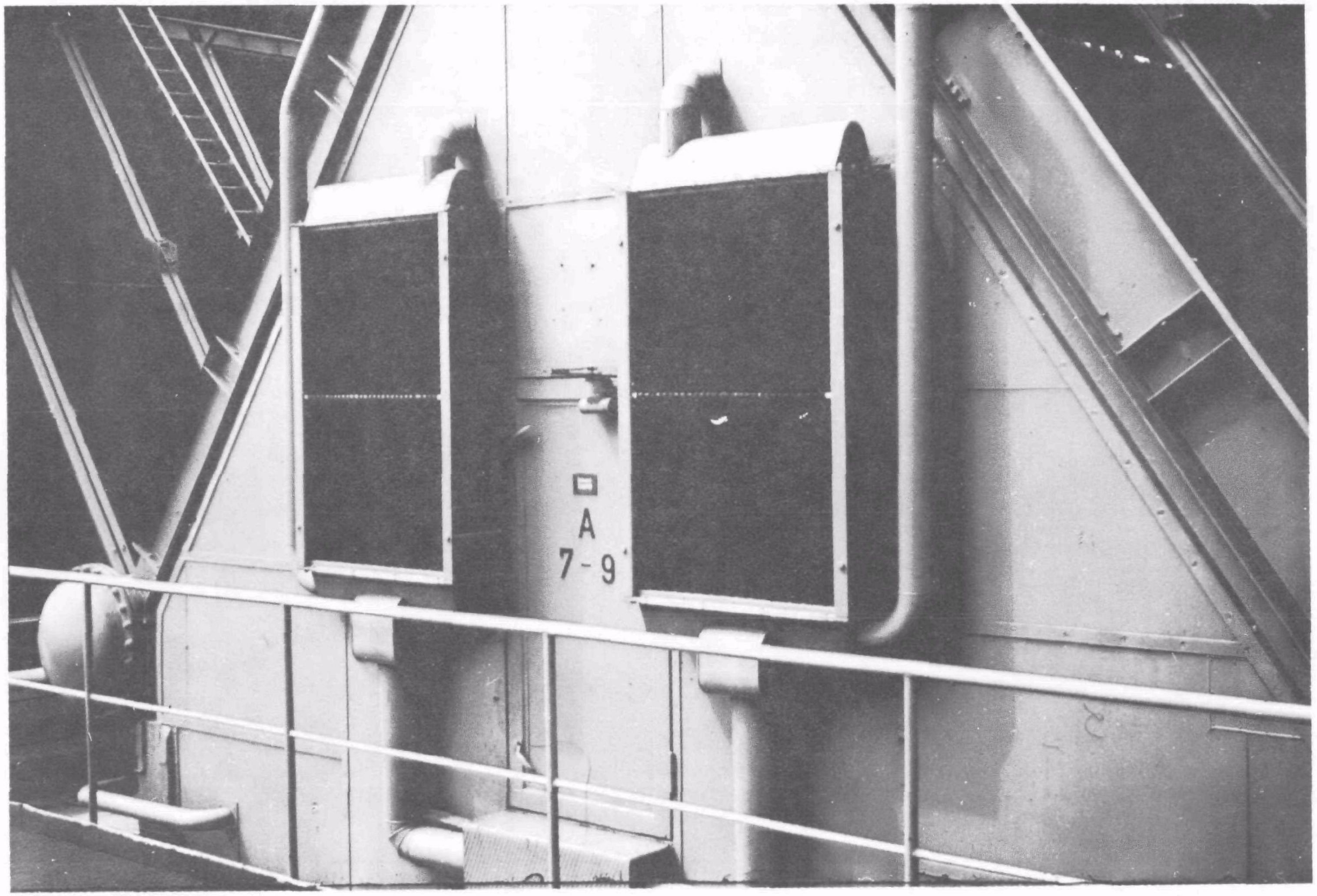

FIGURE 18 — AFTERCONDENSER ON OLDEST GEA CONDENSER (DEPHLEGMATOR) AT VOLKSWAGEN PLANT — WOLFSBURG, WEST GERMANY

PREUSSAG A. G. IBBENBUREN STATION (20)

Located in a rural coal-mining village in north-central West Germany, Ibbenburen Station is the site of a 150 MW indirect, dry-cooled generating unit. A description of the Heller system utilized with a natural-draft tower has been prepared previously.[2] Figure 19 is a photo of this unit. Adjustable louvers on the outside of the air-cooled coils are used for air flow control. The dry cooling equipment for this plant was furnished by GEA. An older plant (vintage 1954), of 100 MW capability, is immediately adjacent and is cooled by two natural-draft wet towers.

The principal reason for visiting this generating station was to investigate minor fintube corrosion thought to have resulted from the proximity of the coal mining/storage operation and the wet towers, subsequent to a late 1969 visit. The fintube bundles have not been replaced since their installation in 1967, and have been cleaned only twice by air-blowing. The aluminum Forgo-type coils have experienced some corrosion on the air inlet side.

Some fintube bundles were removed from service (see Figure 20) to be analyzed for corrosive agents. Both chloride and sulfate ions have been identified. These could have contributed to the localized, rather than area-wide, attack which has occurred.

SCHMEHAUSEN CABLE-NET TOWER (21)

The construction site of a new type of natural-draft tower to serve a 300 MW prototype high-temperature nuclear power plant using a pebble-bed reactor is approximately 230 km (140 miles) north of Frankfurt, West Germany. Figure 21 is a photo of the cable-net tower as it appeared in July, 1975. The structural net, formed from aluminum-coated twin steel cables, will be covered on the inside with corrugated aluminum sheets. The German engineers feel that much larger natural-draft towers are possible with this type of construction than currently deemed feasible for conventional thin-shelled, reinforced concrete cooling towers. Designers and contractors, with financial help from the government, have decided to make the tower large enough to provide cooling for a 500 MW plant.

The tower will have a slip-formed central core mast 180 m (590 feet) high, from which a circular, prestressed hyperboloid cable net is suspended and anchored to a 140 m (460 feet) diameter concrete foundation ring. The cable net will rise to a height of 150 m (480 feet) where it is suspended from a 90 m (300 feet) compression ring. The ring which forms the upper edge of the tower proper is, in turn, suspended from the central mast top by 36 radial cables.

The heart of the cooling system are the heat exchangers inside the tower. These will be laid out as three rings inclined at a 17 degree

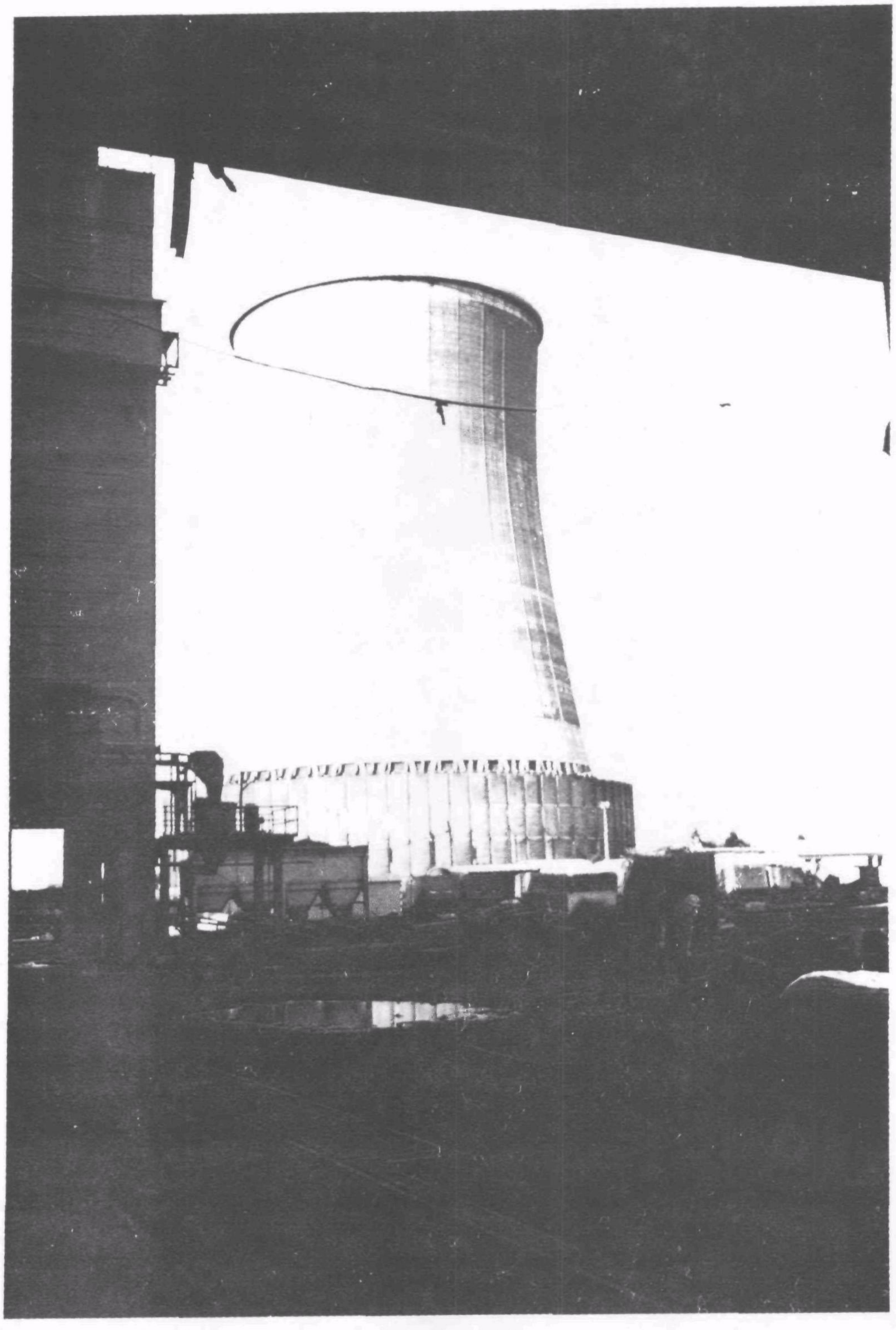

FIGURE 19 — NATURAL-DRAFT DRY TOWER AT PRE USSAG
A.G. GENERATING STATION
IBBENBUREN, WEST GERMANY

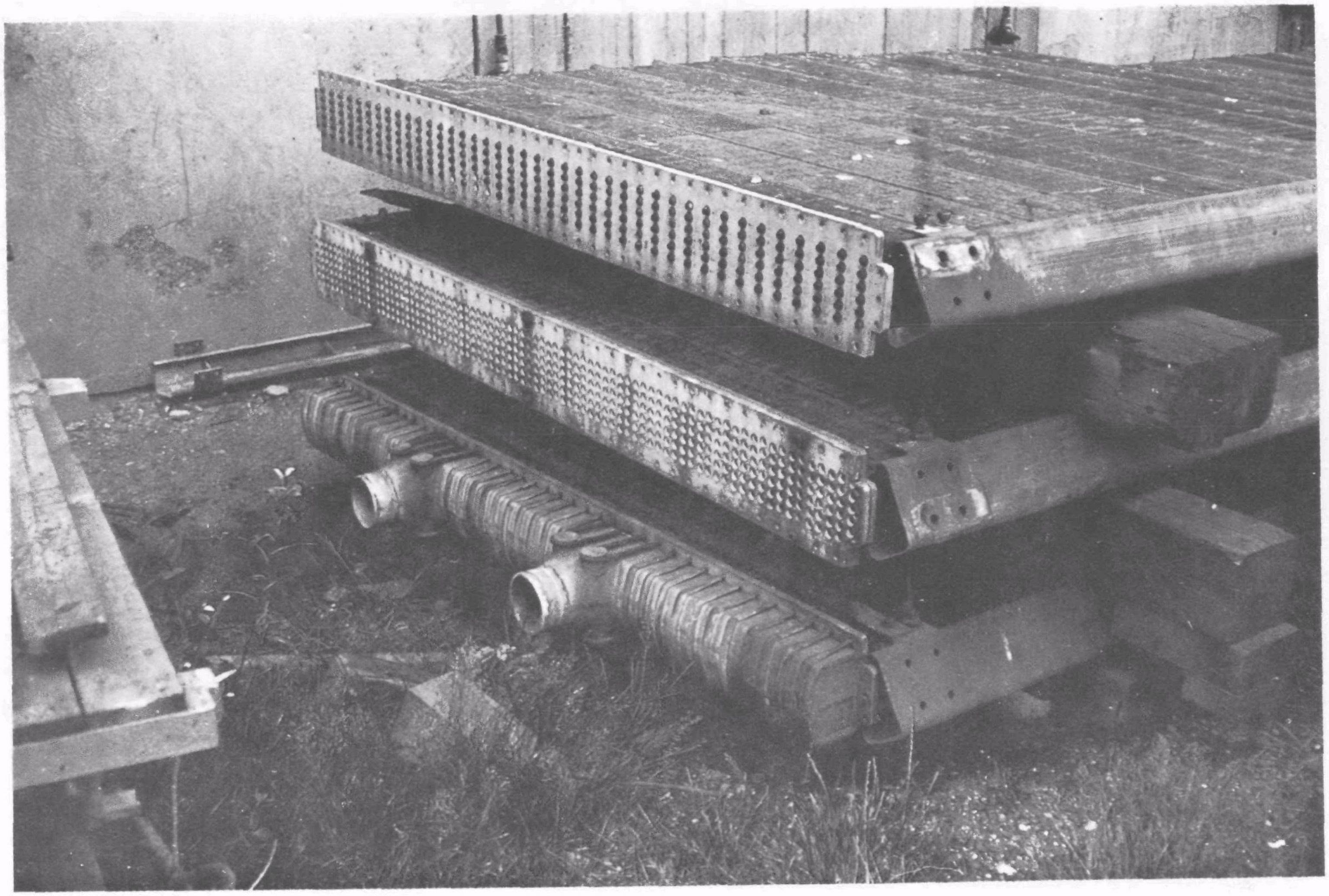

FIGURE 20 — FINTUBE BUNDLES SUBJECTED TO CORROSION ANALYSIS AT PREUSSAG A.G. GENERATING STATION IBBENBUREN, WEST GERMANY

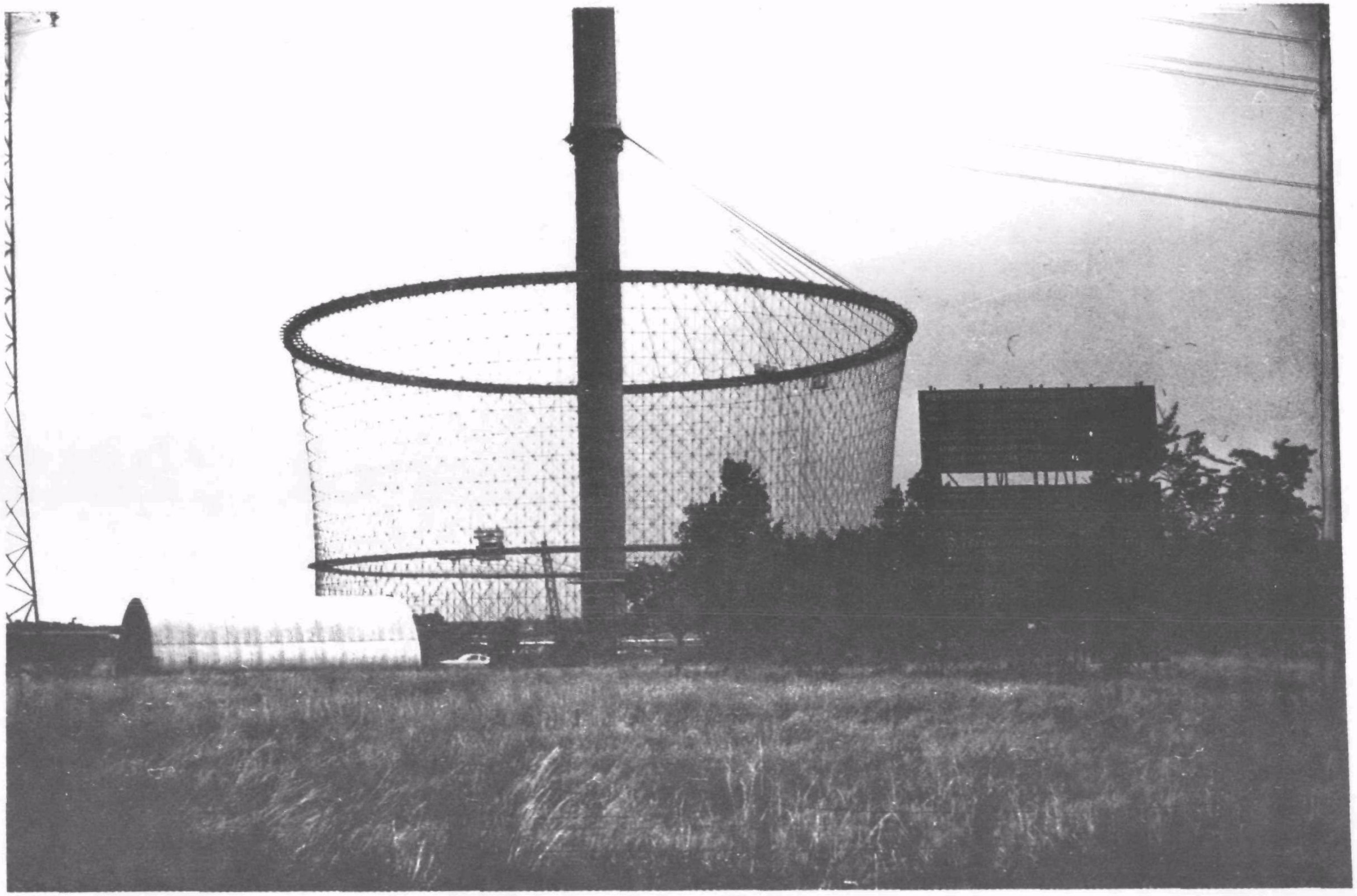

FIGURE 21 — CABLE NET (TO BE FINISHED WITH ALUMINUM SHEETING)
NATURAL-DRAFT DRY TOWER UNDER CONSTRUCTION
SCHMEHAUSEN, WEST GERMANY

angle to the tower's center. Their inclination results from the requirement that equal air flow velocities should prevail in all areas of the heat exchange surface. The individual cooling elements, about 15 m (50 feet) long, consist of two tube walls which are inclined at an angle of 60 degrees to each other in an A-frame manner. Most of the fintube bundles will be supplied by GEA and will consist of steel tubes with oval cross-section and slipped-on steel fins. For the purpose of experimentation, the remainder of the bundles will be supplied by Balcke-Durr, another Bochum firm, and will consist of steel tubes with oval cross-section and wound-on steel ribs. All bundles will be liquid galvanized.

UNION TERMICA S. A. UTRILLAS STATION (22)

This GEA unit is located in a mountainous area of Spain, approximately 240 km (150 miles) east of Madrid. The unit condenses steam from a 160 MW power plant near an underground lignite mine. Figure 22 is a photo of this condenser, which was commissioned in 1970, and is, to date, the world's largest direct, air-cooled system. Operating personnel indicated that the unit has performed its design function and achieved expected performance over an extreme range of ambient temperatures. The unit is back-washed once a year with air and water and was observed to be in excellent condition. Plans are currently underway for development of an additional steam unit at the plant of approximately 300 MW capacity, with another dry tower.

AMMONIA PLANT - NANGIS, FRANCE (23)

The air-cooled heat exchangers were manufactured by Creusot-Loire, under license from Hudson Products Corporation and are of Hudson design. Air-cooled heat exchangers serve as steam condensers for turbines which drive compressors and a 7 MW electrical generator, operating under vacuum conditions. Two-speed fan motors and auto-variable fans provide freeze protection. Operators reported no freezing of the coils. Tubes are of steel with extruded aluminum finss. No fin corrosion has been experienced. In addition to the vacuum steam condensers, there are a number of Hudson air-cooled heat exchangers for ammonia condensing.

PARIS METRO SUBWAY AIR CONDITIONING SYSTEM (24)

This three-unit Hudson air-cooled heat exchanger, manufactured by Creusot-Loire, is located on a rooftop next to the Paris Opera House. Because of this location a low noise level of 65 dB(A) at 1 m (3 feet) with all fans at full speed was specified. The noise level is extremely low and normal conversation can be heard directly below the fans. No corrosion was evident on the extruded aluminum fins.

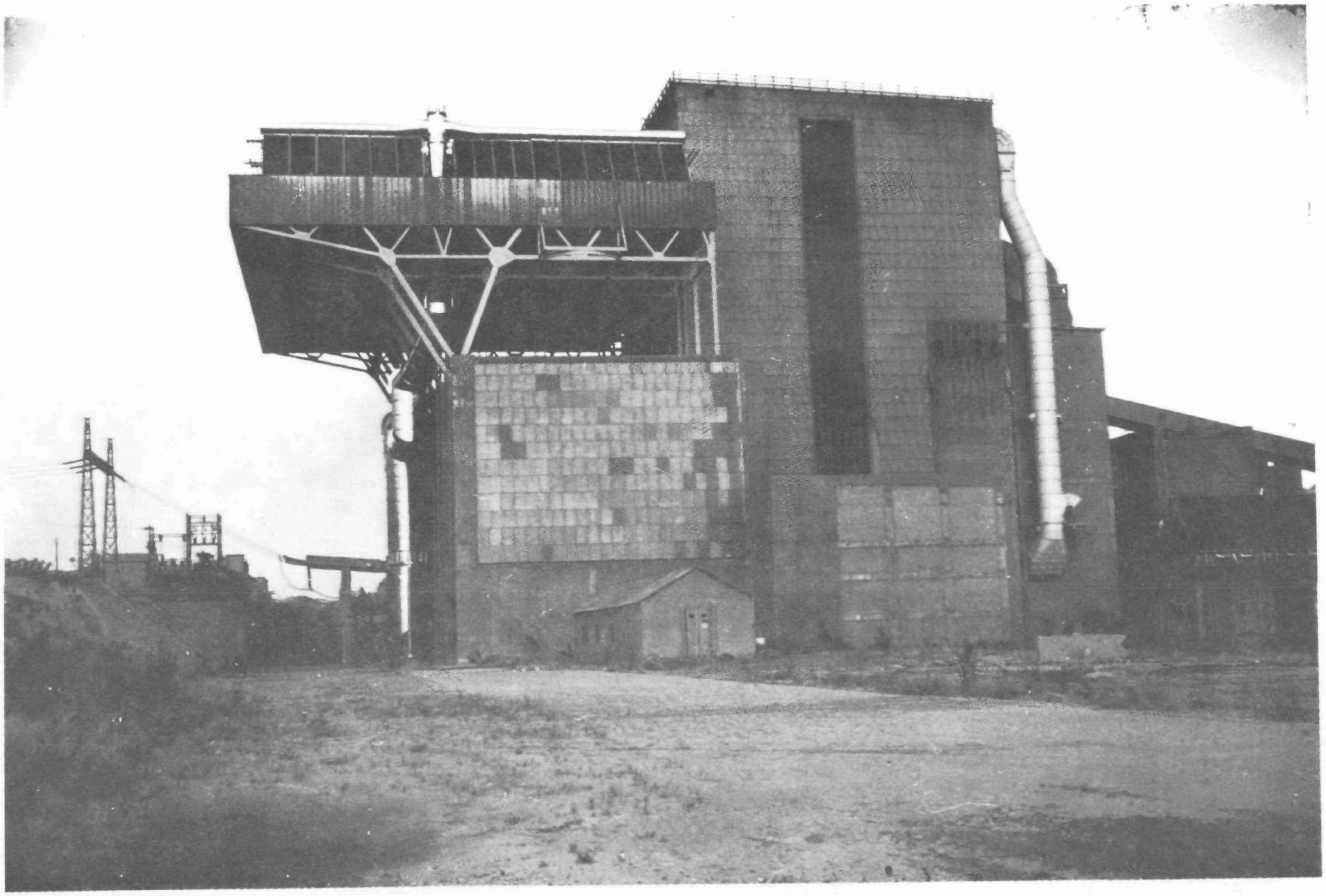

FIGURE 22 — GEA CONDENSER AT UNION TERMICA, S.A. GENERATING STATION UTRILLAS, SPAIN

SECTION VI

PREVENTION OF FINTUBE CORROSION

Two factors are of prime importance in determination of the useful life of fintube bundles in dry cooling towers. These are the construction and manufacture of the fintube itself and the atmospheric environment in which it is used. Figure 23 depicts several basic fintube designs. Illustration (a) is the GEA fintube, consisting of steel plate fins over oval steel tubes with the entire assembly hot-dip galvanized after fabrication. Illustration (b) is the L-fin quite commonly used in LATEC units. This is an L-shaped aluminum fin wrapped on a steel tube under tension. Illustration (c) is the embedded (G-type) fin, made by wrapping aluminum fins into a spiral groove in a steel tube, followed by rolling the tube material against the fin base. These are also used in LATEC units. Illustration (d) is the extruded fin of aluminum over a steel tube. Extruded fin tubes, combined with tube end coatings, provide a complete protective sheath over the steel tube and effectively prevent corrosion of the steel tube and galvanic corrosion of the aluminum fin. Illustration (e) is the overlapped version of the L-fin. Illustration (f) is the "Forgo" fintube consisting of aluminum slotted plate fins over aluminum tubes. Any of these fintube designs can probably give satisfactory service in a seacoast environment, without severe industrial contamination.

Fintubes which can allow the moisture in the air to come into contact with steel tubes may, however, be subject to corrosion. The embedded type of fintubes falls into this category, while careful manufacture of the L-fin type can alleviate this problem.

GEA's experience has been that the service life of their fintube bundles has been adequate for all air-cooled condenser applications -- based on coating with an appropriate zinc compound. The thickness of the zinc coating depends on the anticipated atmospheric environment. GEA feels that a marine atmosphere is less corrosive than either an urban or industrial area. The main corrosive agents that reduce the service life of galvanizing are thought to be sulfur compounds, although sea spray in direct contact with the fintube surface is also known to cause corrosion.

Lummus normally uses the aluminum L-fin tube. Aluminum is considered to be most susceptible to marine and industrial environments although Alclad products offer supplemental protection in the form of a sacrificial cladding. The corrosion experienced by aluminum L-fins at the Albatross refinery (see Section V) is thought to result from the exceptionally severe environment at the site. Much the same experience has been noted with the Forgo type fintubes at Rugeley and to a lesser extent at Ibbenburen. The replacement epoxy-coated fintubes at Rugeley have seen longer service, with a slight increase in heat transfer capability.

Hudson recommends extruded aluminum finned tubes for most steam condensers, but they also offer embedded or plate fin tubing in either aluminum or steel. Their experience is that extruded aluminum fin tubing is adequate except where chemical pollutants in an industrial atmosphere, in combination with a low tube wall temperature permitting liquid water on the fin surface, results in a specific chemical degradation of the aluminum. Hudson considers extruded aluminum fin tubing adequate for power plants, located in relatively benign rural settings, but also for locations, such as Rugeley or Ibbenburren, where corrosion has taken place due to the presence of solid chemical pollutants and moisture at the crevice between the fin and tube.

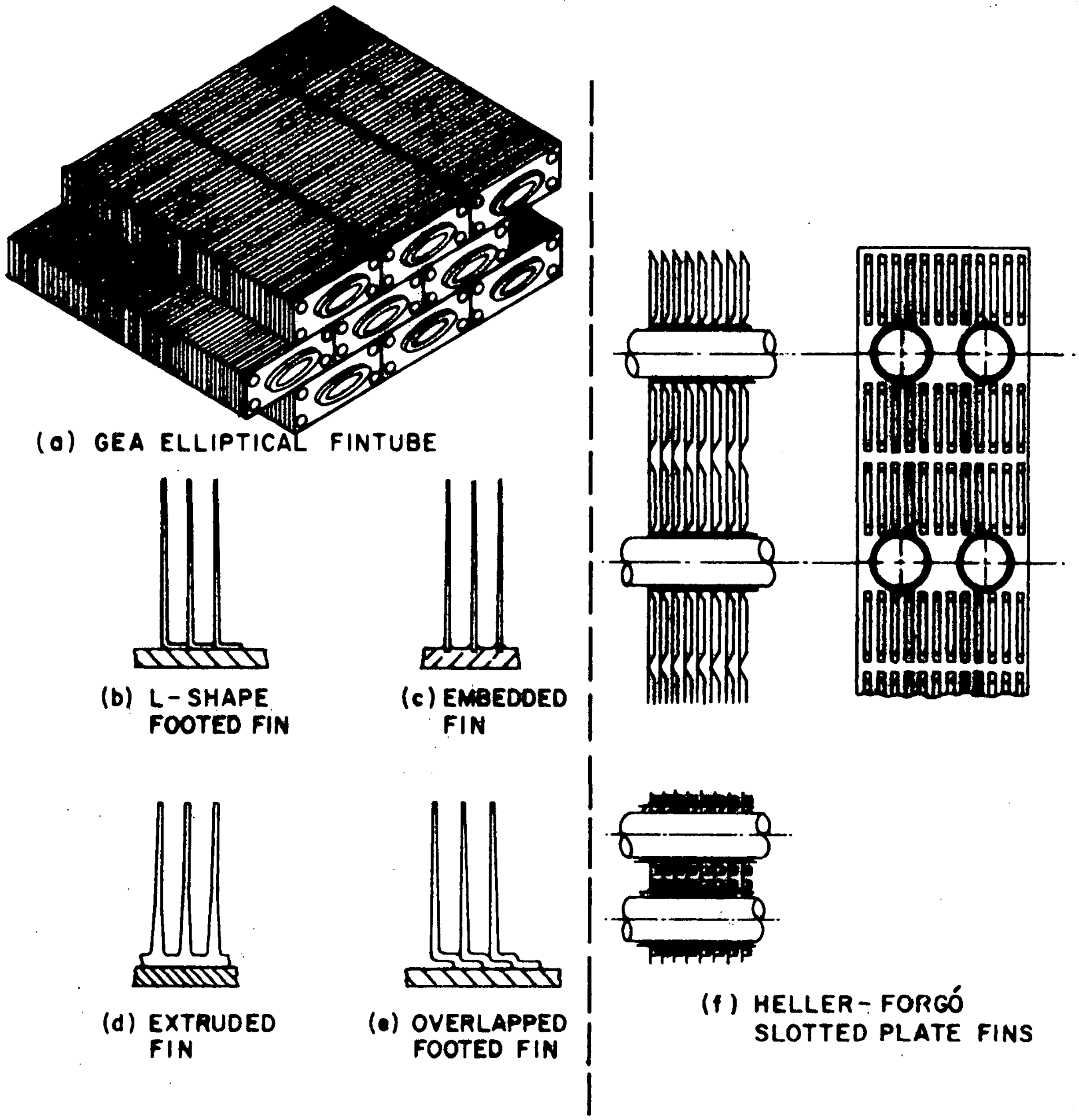

FIGURE 23 - TYPES OF FINTUBE CONSTRUCTION

SECTION VII

PREVENTION OF COIL FREEZING

Many of the direct air-cooled condensation systems which have been investigated have recorded incidents of freezing, e.g., Wyodak, Condea refinery, Linde plant, Wolfsburg, Columbia Gas S. N. G. plant. Most of these incidents have been attributed by the manufacturers to improper operating procedures. All freezing episodes took place at low loads or during startup. None of the units investigated have encountered any difficulty with freezing when operating at design load. The special freeze protection features of the units offered by GEA, Lummus and Hudson Products Corporation are explained below.

GEA SYSTEM (With Reference to Figure 1)

In a multi-row tube bundle the cooling air is heated gradually as it passes over successive rows of tubes. Since the condensation temperature is approximately the same in all tubes, the temperature difference for heat transfer decreases in the direction of air flow. If the heat transfer surface area is the same for each row of tubes, the condensing capacity of subsequent rows likewise decreases. Since all tubes are subject to the same steam pressure drop, the steam flow is virtually the same for all tubes. If the bundle is designed so that all of the steam passing through the last row of tubes is condensed, it follows that the steam passing through the previous rows of tubes which are in contact with colder air will be completely condensed before reaching the end of the tubes. Once condensation is complete in a parallel flow condenser tube, the condensate will be subcooled as it passes through the remaining length of tube or "dead zone."

The subcooled condensate will also pick up oxygen from the non-condensible gas mixture which collects in the "dead zone" of the tubes. This can result in corrosion of the tubes, headers and other internal parts of the condenser. If the ambient air temperature is below 0 C (32 F), the condensate may freeze and rupture the condenser tubes.

A counterflow condenser in which steam and condensate flow in opposite directions avoids this problem since the condensate is always in close contact with steam. However, with the steam flow opposing the condensate, the condensate film will be thicker than for parallel flow. The thicker condensate film will reduce heat transfer and may increase steam pressure drop to such an extent that the condensate may temporarily build up in the tubes with subsequent rapid discharge which can cause freezing.

GEA has found that the most effective solution to the "dead zone" problem is a combination of parallel and counterflow condenser elements. The steam entering the condenser first passes through parallel-flow bundles. These are so designed that, under all operating conditions, excess steam leaves all tubes with more steam coming from the last tube rows than from the first one. This excess steam is transferred by means of a large diameter carry-over pipe to the subsequent counterflow bundles where it is condensed. The noncondensible gases are extracted from the upper end of the counterflow tubes after having been cooled several degrees below the steam saturation temperature.

In the GEA design, large internal cross-section elliptical tubes are mounted in an inclined position to ensure good condensate drainage from all units. An additional feature of the GEA condenser is the use of fintubes with variable fin pitch which decreases from tube row to tube row in the direction of air flow. This means that the heat transfer surface increases from tube row to tube row to compensate for the decrease of the effective temperature difference. A secondary effect of variable fin pitch is that, due to the large fin spacing of the first tube row, cleaning of the fin surface by means of high-pressure water jets is facilitated.

In addition, GEA units are equipped with two-speed fan motor drives which permit a control scheme whereby the heat rejection capability of the air-cooled condenser can be closely matched to load over the entire range of operating conditions. Thus, careful attention to explicit operating instructions should prevent coil freezing.

<u>LUMMUS SYSTEM</u> (With Reference to Figure 2)

LATEC freeze protection is provided by a combination of basic design configuration, cooling air flow control and isolation of effective surface.

The conventional single-pass air-cooled condenser design is prone to freezing problems in cold weather due to subcooling in the lower end of the tubes, recirculation of noncondensible gases from the higher pressure areas of the condenser and subsequent tube blockage. The Lummus HTD double U-tube design features separate condensate headers for each flow path and a loop seal arrangement which prevents the aforementioned recirculation and blockage. This design ensures uniform flow and heat flux distribution over a wide range of ambient temperatures and steam flows. In addition, the U-tube design in conjunction with co-current cooling air flow ensures that the condensate leg is in contact with warm air. The design is such that cooling air reaching the condensate legs is warmer than 0 C (32 F) under all specified operating conditions.

The type and extent of airflow control and/or surface isolation used depends on a number of factors, namely:

Minimum ambient temperature
Minimum steam flow
Wind velocity and direction
Allowable backpressure variation
Size of unit

In areas subject to moderate freezing (down to -18 C), freeze protection and backpressure control can be maintained with either two-speed motors or automatic variable pitch fans. Whether all or only half the fans are so equipped depends on the size of the unit, or the relative size of a step change.

At temperatures below -18 C (0 F), consideration is given to isolating steam valves which remove sections from service or modulating louvers to regulate cooling air flow. For maximum protection under severe wind conditions, preference would be given to the use of louvers. In this case, the (inverted) M-type module which offers a "built in" wind screen would be offered.

From steam distribution considerations, it is preferred to have all condenser sections operating at equal cooling capacity. For units equipped with two-speed motors and louvers, all louvers are operated from a common signal and assume the same position for all sections in operation. With decreasing load, louvers are adjusted to reduce air flow as long as louver position in the air stream is satisfactory from a control standpoint. Below this, motors are switched from full to half speed and the louvers are reopened as required to compensate for the reduced fan draft. Further load or ambient temperature reductions can be accommodated by turning motors off, the number depending on the relative size of the step change.

Isolating steam valves can also be used with or without louvers, but generally with either two-speed motors or auto-variable fans. The specific control system selected is matched to plant requirements. With the exception of simple auto-variable fan pitch control, all systems can be manual, semiautomatic or fully automatic. Here again, the degree of automation is tailored to the specific plant requirements of operator attention and cost of instrumentation.

HUDSON SYSTEM

The major problem in design of vacuum steam condensers is accommodating the fact that all steam contains at least some air. It has become common practice to utilize either a vent condenser or a dephlegmator after and in series with the main condenser to minimize air binding and the potential of condensate freezing. The systems are designed such that excess steam actually "blows" through the main condensers, displacing the final condensation and air removal to the aftercondenser. Ideally, sufficient steam should pass to just provide positive flow in the bottom row. Since the aftercondensers are less efficient as steam condensers and may require more expensive anti-freeze devices, their cost per Btu of heat removal is high. Thus, it is desirable to minimize that portion of the condensing surface which is aftercondenser.

For the more demanding condenser application with respect to freezing, Hudson utilizes an internal means of varying steam flow in proportion to the temperature driving force in each row, thus minimizing the amount of steam that must be blown through the main to prevent freezing, and minimizing the size of the aftercondenser. Manufacturers who do not provide such proportioning must either pay the price for a larger aftercondenser and its reduced capacity in the summer, or must provide a means of manifold valving to reproportion the surface between the mains and the aftercondensers on a seasonal basis.

To deal with these considerations, Hudson combines a number of in-tube and air side features chosen to provide a maximum of condensing capacity in the summer with protective mechanism against freezing in the winter, particularly at low steam loads and at startup and shutdown. Hudson generally recommends automatic and modulating air side systems, minimizing system shock and with less demands on operating personnel to prevent freezeups. Modulated air control is unnecessary in equatorial locations.

SECTION VIII

NOISE ATTENUATION

The relationship of dry tower design parameters to sound pressure levels is complex. Certain basic relationships do exist, however. For example, doubling the number of fans of a given size will cause an increase of 3 dB in the sound pressure level.

Halving fan speed will cause a reduction of 14 dB in sound pressure level. Obviously, halving the rpm will cause a 50 percent decrease in air flow rate if no compensating fan changes are made, such as more blades or wider blades. Therefore, doubling the number of fans and halving the fan speed will provide the same air flow rate with a net decrease in sound of 11 dB.

The use of large slow-speed fans will generally produce lower sound pressure levels than will smaller, higher-speed fans of the same capacity.

Other attenuation techniques include direct coupling of fan and motor drive thus eliminating reduction gear whine, enclosure of the entire dry tower structure, and acoustical baffling of the air inlet plenum.

Two plants visited in the course of this research project were representative of current practice. These plants were the Chevron Refinery at Feluy, Belgium and the municipal incinerator at Zurich, Switzerland. Sound pressure level readings were taken at each of these sites with a General Radio Model 1933 Precision Sound-Level Meter. Recordings were made on a Uher 4200 Report Stereo Tape Recorder, using a General Radio 1562A calibrator to provide analysis information. Tape analysis was performed on a General Radio 1521-B Graphic Level Recorder.

Field data taken at the Zurich Municipal Incinerator at an approximate distance of 220 feet from the geographical center of the unit indicated an average sound pressure level of 61 dB(A). At a distance of 400 feet from the geographical center of the unit, a sound pressure level of 56 dB(A) is forecast. It was noted during field monitoring that steam turbine noise was the major contributor to the noise levels observed.

Field data taken at the Chevron Refinery at Feluy, Belgium at a distance of 50 feet from the unit's geographical center indicated an average sound pressure level of 70 dB(A). At a distance of 400 feet from the geographical center of the unit, a sound pressure level of 52 dB(A) is forecast. It was noted during field monitoring that steam throttling was a major source of the observed noise levels.

SECTION IX

APPLICATION OF A DIRECT, AIR-COOLED CONDENSATION SYSTEM IN A COASTAL ENVIRONMENT

The Braintree, Massachusetts Electric Light Department (BELD) has contracted to build an 85 MW combined cycle (gas turbine-steam turbine) electric generating unit to be known as Norton P. Potter Station, Unit No. 2. The exhaust heat from the 65 MW gas turbine will be utilized in an unfired heat recovery boiler to produce steam for a 20 MW steam turbine. Because of the utilization of gas turbine waste heat, the generating unit will have a high thermal efficiency. The gross heat rate, i.e. the amount of energy consumed to produce a kilowatt-hour (kWh) of electricity, for the unit is expected to be 8,970 Btu/kWh (38 percent thermal efficiency), which is considerably better than most generating alternatives.

During the course of the preliminary design and environmental investigations for Potter No. 2, it became evident that it would be costly and time-consuming to attempt to secure permits for an open-cycle cooling system. The use of water from the Weymouth Fore River Estuary would require permits from the various federal, state and local agencies concerned with environmental quality. A study of alternative methods for cooling the plant showed that an air-cooled vacuum steam condenser would result in an estimated power cost 2 percent higher than the cost of power using an open-cycle system. In addition, due to the relatively high cost of clean water suitable for use in evaporative cooling towers ($0.70 per 1000 gal), the power cost using the air-cooled condenser was estimated to be no higher than using evaporative towers.

BRAINTREE AIR ENVIRONMENT

Prevention of external corrosion of the fintube bundles of a dry tower, and prevention of coil freezing were very real concerns to BELD. Situated on the Weymouth Fore River Estuary, there are definitely soluble chloride salts in the air at the Braintree site. Other contaminant levels, as noted in the Draft Environmental Analysis,[4] (40 g/m^3 of sulfur dioxide -- 24-hour average, 60 g/m^3 of particulate -- 24-hour average, and 80 g/m^3 of nitrogen dioxide -- 24-hour average) are representative of light industrial areas. Subsequent studies have indicated that most of the suspended particulate matter is less than 1 micron in diameter, with negligible amounts of trace metals. The Decennial Census of U. S. Climate[3] indicates a temperature range for Boston of 36 C (97 F) to -22 C (-8 F), with sub-freezing temperatures on the average of 958 hours per year.

NOISE REQUIREMENTS

Currently, the Commonwealth of Massachusetts regulations require that new sources do not increase the broad band noise level in excess of 10 dB(A) above the ambient level. The Commonwealth of Massachusetts also limits production of "puretone conditions" which exceed ambient. A "puretone" is defined as an A-weighted sound level, at any given octave band center frequency that exceeds the levels of adjacent center frequencies by three or more decibels. As defined by the Commonwealth of Massachusetts, the "ambient level" is that "A-weighted noise that exists 90 percent of the time measured during the period in question." In order to determine the ambient levels in the Braintree area, noise analyses were made during 1972 using acoustical instrumentation of A.N.S.I. Type 2 standard.[5] Noise samples were obtained in the daytime and in late evening between 10 p.m. and midnight. For residential areas close to the plant the residual noise levels are around 45 dB(A). This value is within the typical range for urban residential areas.[6]

The noise specification for the dry cooling tower limits sound pressure levels to 51 dB(A) at 400 feet. The manufacturer has guaranteed that he will meet these requirements. Field data from the European low-noise installations indicated somewhat higher levels. For example, the Chevron Refinery at Feluy, Belgium would have a forecast sound pressure level of 52 dB(A) at 400 feet. However, approximately three times more cooling capacity will be required at Braintree than at Feluy. Tripling the plant size might increase noise levels by as much as 5 dB(A) resulting in a noise level approximately equal to the predicted level for the Zurich incinerator. However, the interference of other sound generating components exclusive of the dry cooling towers at both Feluy and Zurich have raised the recorded levels somewhat.

SPECIFICATION OF THE BRAINTREE CONDENSER

The condensing duty of Potter No. 2 is approximately 45 Gcal per hour (180 MM Btu per hour), which is well within the range of operating installations as indicated in Table 1. Table 2 lists design conditions for fifteen direct, air-cooled condensers which were visited in the course of this research project. The two parameters of greatest concern to equipment manufacturers are the turbine backpressure and the initial temperature difference (I.T.D) between condensing steam and ambient air. Turbine heat rate decreases with decreasing backpressure and the amount of fintube surface required for a specified duty varies inversely with I.T.D. The GEA dry tower for Braintree has been selected on the basis of 0.12 atm (3.5 inch Hg) backpressure, or a design I.T.D. of 34 C (62 F). The benefits of unit operating economy offset the initial capital cost penalty of this size tower. The other design data for Potter No. 2 are: steam flow - 86,000 kg per hour (190,000 pounds per hour), exhaust steam temperature - 49 C (121 F) and ambient air temperature - 15 C (59 F).

Table 3 lists the site conditions for the 15 sites referred to above where air-cooled condensers have been successfully applied. Braintree conditions are within the range of conditions shown.

Table 2. DESIGN DATA FOR DIRECT, AIR-COOLED CONDENSATION SYSTEMS

No.*	Steam Flow		Steam Pressure		Steam Temperature		Air Temperature		ITD	
	Kg/Hr	Lb/Hr	Atm.	In. Hg	°C	°F	°C	°F	°C	°F
1	76,000	168,000	.15	4.5	54	130	24	75	30	55
3	20,000	44,000	.17	5.0	57	134	17	62	40	72
5	34,000	76,000	.28	8.4	68	154	27	80	41	74
6	NA		.08	2.4	42	108	15	59	27	49
7	NA		NA		NA		NA		NA	
8	51,000	112,000	.19	5.7	59	139	NA		NA	
9	137,000	302,000**	.25	7.5	66	150	32	90	34	60
11	6,000	12,000	.12	3.6	53	127	32	90	21	37
14	70,000	154,000	.10	3.0	46	115	20	68	26	47
15	31,000	68,000	.15	4.6	55	131	NA		NA	
16	45,000	100,000	.11	3.2	47	117	NA		NA	
17	30,000	65,000	.17	5.1	57	135	NA		NA	
19	440,000	970,000**	.09	2.7	44	111	15	59	29	52
22	520,000	1,150,000	.10	2.9	46	114	15	59	31	55
23	92,000	188,000	.10	2.9	46	114	25	77	20	37

* Numbers refer to installations with like designation in Table 1

** Total of several condensers

GEA has selected a design for the Braintree application embodying twin A-frame units comprised of 60 bundles of galvanized elliptical tubes with plate-type fins. Ten two-speed fans (110 rpm/55 rpm) with 4.9 meter (16 feet) blades will provide air movement. Similar configurations are used at Zurich (7) and Feluy (17) as shown in Table 4. The GEA bid guarantees noise levels from this arrangement will not exceed 52 dB(A) at 400 feet. The bid also lists performance data for each of octave bands 1-8. The levels specified in each band satisfy the Commonwealth of Massachusetts criteria for "puretone" generation. The 52 dB(A) sound pressure level, when combined with a similar sound pressure level generated by the combined-cycle unit, should produce a 55 dB(A) sound pressure level at 400 feet for both units. Since ambient residual sound pressure levels are approximately 45 dB(A), the addition of this total plant would satisfy the Commonwealth of Massachusetts' 10 dB(A) maximum increase criteria at the property line (approximately 700 feet from the units).

EVALUATION OF AIR-COOLED COMBINED CYCLE PLANT PERFORMANCE

Economic analyses were made to determine total bus-bar energy production costs for the Braintree dry-cooled combined cycle plant for various combinations of values of economic and operating parameters. All costs associated with the plant and/or affected by its operation were included in the analyses. These costs include the evaluated capital costs of the combined-cycle unit and the air-cooled condenser, including the supplemental evaporative cooling system for auxiliary cooling; annual makeup water costs for the supplemental system; and annual plant fuel costs.

Total bus-bar costs were based on the gross annual generation of the combined cycle unit minus the annual fan energy requirements for the air-cooled condenser and the supplemental evaporative cooling system. The plant was assumed to operate 7500 hours per year with specified percentages of each operating hour to be at nominal 100-, 80- and 60-percent-load conditions. Full-power operation of the supplemental evaporative cooling system was assumed throughout the operating period.

Fuel rate, gas turbine output and waste heat-generated steam flow at a given nominal load condition are functions of ambient temperature. For given throttle steam flow conditions, steam turbine-generator output varies with exhaust pressure which, for a given air-cooled condenser design and mode of operation, is also a function of ambient temperature. Manufacturers' performance data for the gas turbine, waste heat boiler, steam turbine-generator and air-cooled condenser were used in the analyses.

Although the actual control scheme for the GEA air-cooled condenser provides for 13 different combinations of fan operating conditions, only three combinations were considered in the present analyses; viz.: all fans full-speed, all fans half-speed, or all fans shut off. For a given

Table 3. SITE CONDITIONS FOR DIRECT, AIR-COOLED CONDENSATION SYSTEMS

No. *	Elevation		Minimum Temperature		Maximum Temperature		Average Temperature		Environment
	m	ft	°C	°F	°C	°F	°C	°F	
1	1200	3900	-35	-31	41	106	7	44	rural arid
3	0	0	-16	3	35	95	10	50	seacoast refinery
5	100	300	-18	0	37	98	10	50	seacoast industrial
6	0	0	-19	-3	33	91	8	46	seacoast refinery
7	400	1300	-18	-1	38	101	10	50	urban
8	100	300	-22	-7	38	100	10	50	light industrial
9	200	800	-23	-9	39	103	11	51	rural
11	0	0	-4	24	32	90	21	70	seacoast industrial
14	200	700	-26	-14	37	98	9	49	industrial
15	100	400	-7	20	40	104	16	61	urban
16	100	200	-16	4	40	104	11	51	refinery
17	100	300	-18	0	37	98	10	50	refinery
19	100	200	-24	-11	37	98	9	48	industrial
22	700	2200	-10	14	39	102	13	56	coal mine
23	100	300	-23	-10	40	104	11	51	industrial

* Numbers refer to installations with like designation in Table 1.

Table 4. DESIGN SPECIFICATIONS FOR DIRECT, AIR-COOLED CONDENSATION SYSTEMS

No.*	Number of Fans	Fan Diameter m	Fan Diameter ft	Fan Configuration	Fintube Construction	Number Bundles	Bundle Configuration
1	6	6.4	21	2 x 3	galvanized elliptical tube plate-type fins	48	2 A-frame
3	NA	NA		NA	galvanized elliptical tube plate-type fins	NA	NA
5	3	NA		1 x 3	galvanized elliptical tube plate-type fins	18	A-frame
6	3	NA		1 x 3	galvanized elliptical tube plate-type fins	18	A-frame
7	8	6.1	20	2 x 4	galvanized elliptical tube plate-type fins	44	2 A-frame
8	10	NA		2 x 5	Al L-fins	20	A-frame
9	NA	NA		NA	Al embedded fins	NA	NA
11	4	4.0	13	4 x 1	Al extruded	4	nearly horizontal
14	8	6.1	20	2 x 4	Al spiral-wound fins	24	A-frame
15	12	4.3	14	3 x 4	Al G-fins	36	nearly horizontal
16	24	NA		4 x 6	Al L-fins	NA	2 A-frame
17	4	5.5	18	2 x 2	Al L-fins	12	A-frame
19	48	6.5	21	8 x 6	galvanized elliptical tube plate-type fins	120/96/72	8 A-frames
22	40	3.0	10	8 x 5	galvanized elliptical tube plate-type fins	240	8 A-frames
23	68	3.1	10	34 x 2	Al extruded	68	nearly horizontal

* Numbers refer to installations with like designation in Table 1.

nominal load condition, it was assumed that when the ambient temperature decreased to where the minimum heat rate condition for the steam turbine was reached, fan speed would be reduced to the next lower level provided, however, that such reduction did not result in a backpressure greater than 10 inch Hg.

Annual plant performance was evaluated on an hourly basis, taking into account the annual durations for each five degree F interval over the range of ambient temperatures normally experienced at Braintree. The annual temperature durations, in percent of total hours, were assumed to be applicable also to the 7500 hours per year during which the plant would operate.

A computer program, a listing of which is included in the Appendix, was developed to facilitate the performance and economic analyses. The program provides for input of the following data:

1. Number of annual fixed-charge rates to be considered (maximum of three) and annual fixed-charge rates;

2. Number of unit fuel costs to be considered (maximum of three) and unit fuel costs;

3. Number of unit makeup water costs to be considered (maximum of three) and unit makeup water costs;

4. Percentage of total annual hours of operation during which plant is to operate at nominal 100-, 80- and 60-percent-load conditions, respectively.

All other design, performance, operating and cost data are incorporated in the computer program in DATA statements or in equation form.

VARIABLES AFFECTING BUS-BAR ENERGY PRODUCTION COSTS

Annual Fixed-Charge Rate

The annual fixed-charge rate is applied to the total capital cost in order to determine the annual costs of the following items as defined by the Bureau of Power of the Federal Power Commission:

1. Interest, or cost of money.

2. Depreciation, or amortization.

3. Interim replacements.

4. Insurance, or payments in lieu of insurance.

5. Taxes (federal, state and local), or payments in lieu of taxes.

Annual fixed-charge rates of 12, 15 and 18 percent were considered in the present analyses.

Unit Fuel Costs

Of the costs considered in evaluating the performance of the dry-cooled combined cycle plant, fuel costs represent the major component of the total bus-bar costs determined.

Unit fuel costs of $1.75, $2.00 and $2.25 per million Btu were considered in the analyses.

Makeup Water Costs

For the dry-cooled plant, cooling water makeup requirements are minimal; amounting only to the evaporation, blowdown and drift losses from the supplemental evaporative cooling system used to provide auxiliary cooling. Therefore, makeup water costs represent only a small percentage of total annual costs and, hence, bus-bar energy production costs are not appreciably affected by variations in unit makeup water costs.

For the present analyses, makeup water requirements were assumed to be 2.0 percent of the design circulating water flow for the supplemental evaporative cooling system. Unit makeup water costs of $.70 per 1000 gallons were used.

Load Demand Profile

In general, bus-bar energy production costs for a plant will be a minimum when the plant is base-loaded. Scheduled and unscheduled downtime and daily and seasonal variations in load demand will result in an annual plant load factor considerably less than 100 percent, however.

In the primary analysis, it was assumed that the plant would operate 50 percent of the total operating hours at a nominal 100-percent-load condition, 25 percent of the time at 80-percent-load and 25 percent of the time at 60-percent-load. For purposes of comparison, another analysis was made assuming that the plant would operate 100 percent of the total operating time at a nominal 100-percent-load condition.

Backpressure Control Range

Optimizing the performance of the dry-cooled plant for a given load demand profile is essentially a matter of determining the steam turbine operating backpressure range for which the net annual generation will be a maximum. The increase in gross generation at lower backpressure must be balanced against the potential decrease in auxiliary energy requirements attendant to a reduction in fan speed.

The Braintree air-cooled condenser is designed to control steam turbine backpressure between 2.3 and 3.0 inches Hg absolute by use of a 13-step fan control scheme. With only a 3-step control scheme considered in the present analyses, backpressure was maintained between 2.0 and 10.0 inches Hg absolute.

Operating and Maintenance Costs

Annual operating and maintenance costs for the plant were assumed to be 1.0 percent of the total capital cost.

RESULT OF ANALYSES

Two sets of output from the Air-Cooled Combined Cycle Plant program (ACCCPB) are presented in the Appendix. As discussed above, the program was run for the Braintree plant with GEA air-cooled steam condenser for three fixed-charge rates, three fuel costs and a single cost of makeup water. The total bus-bar energy costs calculated for the specified primary 7500-hour annual load profile ranged from 21.4 mills per kWh to 28.3 mills per kWh. In addition, the savings achievable by running the plant at full-load for the entire 7500-hour schedule were determined to be approximately 1.8 to 2.4 mills per kWh.

REFERENCES

1. Armstrong, C. H. and Schermerhorn, R. S., "Economics of Dry Cooling Towers Applied to Combined-Cycle Plants," ASME Paper No. 73-WA/Pwr-5, November, 1973.

2. R. W. Beck and Associates, "Research on Dry-Type Cooling Towers for Thermal Electric Generation," Parts I and II, for the Water Quality Office of the Environmental Protection Agency, November, 1970.

3. "Decennial Census of U. S. Climate - Summary of Hourly Observations," Boston, U. S. Department of Commerce Weather Bureau, 1963.

4. R. W. Beck and Associates, "Draft Environmental Analysis - Norton P. Potter Station Unit No. 2," for Braintree Electric Light Department, July, 1973.

5. "American National Standard Specification for Sound Level Meters," ANSI S1.4, 1971.

6. "Community Noise," U. S. Environmental Protection Agency NTID 300.3, December, 1971.

APPENDIX

AIR-COOLED COMBINED CYCLE PLANT

PERFORMANCE EVALUATION

EVALUATION OF BRAINTREE COMBINED CYCLE PLANT

WITH GEA AIR-COOLED CONDENSER

ANNUAL PLANT LOAD FACTOR = 72.8 PERCENT

ANNUAL FIXED-CHARGE RATE	UNIT FUEL COSTS	UNIT MAKEUP WATER COSTS	GROSS ANNUAL GENER-ATION	ANNUAL AUXILIARY ENERGY REQUIRED	NET ANNUAL GENER-ATION	ANNUAL MAKEUP WATER REQUIRED	ANNUAL CAPITAL AND O+M COSTS	ANNUAL FUEL COSTS	ANNUAL MAKEUP WATER COSTS	TOTAL ANNUAL COSTS	TOTAL BUSBAR ENERGY COSTS
PERCENT	$/MMBTU	$/1000 GAL	MWH	MWH	MWH	1000 GAL	$	$	$	$	MILLS/KWH
12.0	1.75	.70	564650	2156	562494	14400	2665000	9352189	10080	12027269	21.382
12.0	2.00	.70	564650	2156	562494	14400	2665000	10688216	10080	13363296	23.757
12.0	2.25	.70	564650	2156	562494	14400	2665000	12024243	10080	14699323	26.132
15.0	1.75	.70	564650	2156	562494	14400	3280000	9352189	10080	12642269	22.475
15.0	2.00	.70	564650	2156	562494	14400	3280000	10688216	10080	13978296	24.851
15.0	2.25	.70	564650	2156	562494	14400	3280000	12024243	10080	15314323	27.226
18.0	1.75	.70	564650	2156	562494	14400	3895000	9352189	10080	13257269	23.569
18.0	2.00	.70	564650	2156	562494	14400	3895000	10688216	10080	14593296	25.944
18.0	2.25	.70	564650	2156	562494	14400	3895000	12024243	10080	15929323	28.319

EVALUATION OF BRAINTREE COMBINED CYCLE PLANT

WITH GEA AIR-COOLED CONDENSER

ANNUAL PLANT LOAD FACTOR = 85.6 PERCENT

ANNUAL FIXED-CHARGE RATE	UNIT FUEL COSTS	UNIT MAKEUP WATER COSTS	GROSS ANNUAL GENER-ATION	ANNUAL AUXILIARY ENERGY REQUIRED	NET ANNUAL GENER-ATION	ANNUAL MAKEUP WATER REQUIRED	ANNUAL CAPITAL AND O+M COSTS	ANNUAL FUEL COSTS	ANNUAL MAKEUP WATER COSTS	TOTAL ANNUAL COSTS	TOTAL BUSBAR ENERGY COSTS
PERCENT	$/MMBTU	$/1000 GAL	MWH	MWH	MWH	1000 GAL	$	$	$	$	MILLS/KWH
12.0	1.75	.70	680790	2729	678061	14400	2665000	10613924	10080	13289004	19.599
12.0	2.00	.70	680790	2729	678061	14400	2665000	12130199	10080	14805279	21.835
12.0	2.25	.70	680790	2729	678061	14400	2665000	13646474	10080	16321554	24.071
15.0	1.75	.70	680790	2729	678061	14400	3280000	10613924	10080	13904004	20.506
15.0	2.00	.70	680790	2729	678061	14400	3280000	12130199	10080	15420279	22.742
15.0	2.25	.70	680790	2729	678061	14400	3280000	13646474	10080	16936554	24.978
18.0	1.75	.70	680790	2729	678061	14400	3895000	10613924	10080	14519004	21.413
18.0	2.00	.70	680790	2729	678061	14400	3895000	12130199	10080	16035279	23.649
18.0	2.25	.70	680790	2729	678061	14400	3895000	13646474	10080	17551554	25.885

```
      PROGRAM ACCCPR(INPUT,OUTPUT)
C
      DIMENSION T(22),TDUR(22),PCTLOD(3),OBP(22,3),BP(27),
+        FANBHP(22,3),STGOUT(27,2),AFCR(3),UFC(3),UMWC(3),
+        PCTHRS(3),STGO(2)
C
C AMBIENT TEMPERATURE (F) ARRAY AND ANNUAL DURATION (PERCENT) DATA
C FOR BOSTON
C
      DATA T/97.,92.,87.,82.,77.,72.,67.,62.,57.,52.,47.,42.,37.,
+             32.,27.,22.,17.,12., 7., 2.,-3.,-8./
      DATA TDUR/0.11,0.44,1.45,2.79,4.94,7.71,9.34,9.18,8.93,8.73,
+                8.62,9.48,9.71,7.63,4.92,2.90,1.70,0.86,0.40,0.12,
+                0.03,0.01/
C
C NOMINAL OPERATING LOAD (PERCENT) ARRAY
C
      DATA PCTLOD/100.,80.,60./
C
C STEAM TURBINE OPERATING BACK PRESSURE (IN. HGA) AS A FUNCTION OF
C AMBIENT TEMPERATURE AND NOMINAL LOAD CONDITION
C
      DATA OBP/8.90,7.90,7.00,6.21,5.50,4.85,4.30,3.80,3.35,2.98,
+               2.67,2.40,2.19,2.02,3.67,3.20,2.80,2.48,2.22,2.03,
+               2.00,2.00,
+               6.67,5.85,5.12,4.49,3.94,3.46,3.05,2.69,2.37,2.10,
+               3.85,3.36,2.93,2.55,2.23,2.00,2.00,2.00,2.00,2.00,
+               2.00,2.00,
+               5.00,4.35,3.80,3.30,2.87,2.50,2.17,3.54,3.05,2.65,
+               2.30,2.02,2.00,2.00,2.00,2.00,9.67,8.16,6.89,5.82,
+               4.88,4.08/
C
C BACK PRESSURE (IN. HGA) ARRAY
C
      DATA BP/2.0,2.5,3.0,3.5,4.0,4.5,5.0,5.5,6.0,6.5,7.0,7.5,8.0,
+              8.5,9.0,9.5,10.0,10.5,11.0,11.5,12.0,12.5,13.0,13.5,
+              14.0,14.5,15.0/
C
C FAN BRAKE HORSEPOWER (HP) REQUIREMENT AS A FUNCTION OF AMBIENT
C TEMPERATURE AND NOMINAL LOAD CONDITION
C
      DATA FANBHP/450.,450.,450.,450.,450.,450.,450.,450.,450.,
+                 450.,450.,450.,450.,450., 75., 75., 75., 75.,
+                  75., 75., 75., 75.,
+                 450.,450.,450.,450.,450.,450.,450.,450.,450.,
+                 450., 75., 75., 75., 75., 75., 75., 75., 75.,
+                  75., 75., 75., 75.,
+                 450.,450.,450.,450.,450.,450.,450., 75., 75.,
+                  75., 75., 75., 75., 75., 75., 75.,  0.,  0.,
+                   0.,  0.,  0.,  0./
C
C STEAM TURBINE-GENERATOR OUTPUT (KW) AT 190000 LB/HR AND 170000
C LB/HR THROTTLE STEAM FLOW WITH ENTHALPY OF 1420 BTU/LB AS A
C FUNCTION OF BACK PRESSURE
C
      DATA STGOUT/21111.,21052.,20949.,20800.,20622.,20430.,20230.,
+                 20024.,19816.,19607.,19402.,19202.,19007.,18819.,
+                 18639.,18467.,18304.,18149.,18002.,17862.,17728.,
+                 17600.,17476.,17355.,17236.,17118.,17000.,
```

```
+                       18808.,18734.,18607.,18434.,18230.,18015.,17795.,
+                       17573.,17358.,17157.,16969.,16791.,16623.,16465.,
+                       16316.,16176.,16044.,15920.,15803.,15690.,15580.,
+                       15472.,15367.,15264.,15162.,15061.,14961./
C
C TOTAL CAPITAL COST OF BRAINTRE COMBINED-CYCLE PLANT WITH
C GEA AIR-COOLED CONDENSER AND TOTAL ANNUAL HOURS OF OPERATION
C
      DATA CAPCST/20500000./
      DATA AOPHRS/7500./
C
C CIRCULATING WATER FLOW RATE (GPM); EVAPORATION, BLOWDOWN AND
C DRIFT LOSSES (PERCENT); AND POWER REQUIREMENTS (HP) FOR
C SUPPLEMENTAL EVAPORATIVE SYSTEM FOR AUXILIARY COOLING
C
      DATA GPM/1600./
      DATA EBDL/2.0/
      DATA SEHP/30./
C
C INPUT DATA
C
      PRINT,*ENTER NUMBER OF ANNUAL FIXED-CHARGE RATES TO BE *,
+        *CONSIDERED AND VALUES*
      PRINT,*(PERCENT)*,
      READ,NFCR,(AFCR(I),I=1,NFCR)
C
      PRINT,*ENTER NUMBER OF UNIT FUEL COSTS TO BE CONSIDERED AND*,
+        * VALUES ($/MMBTU)*
      READ,NUFC,(UFC(I),I=1,NUFC)
C
      PRINT,*ENTER NUMBER OF UNIT MAKEUP WATER COSTS TO BE *,
+        *CONSIDERED AND VALUES*
      PRINT,*($/1000 GAL)*,
      READ,NMWC,(UMWC(I),I=1,NMWC)
C
      PRINT,*ENTER PERCENTAGE OF TOTAL ANNUAL HOURS OF OPERATION *,
+        *WHICH ARE TO BE AT *
      PRINT,*100-, 80- AND 60-PCT NOMINAL LOAD CONDITIONS, *,
+        *RESPECTIVELY*
      READ,PCTHRS
C
C ANNUAL PLANT LOAD FACTOR (PERCENT)
C
      SUMPLH=0.
      DO 96 I=1,3
      SUMPLH=SUMPLH+(PCTLOD(I)*PCTHRS(I))
   96 CONTINUE
      APLFAC=(SUMPLH/100.)*(AOPHRS/8760.)
C
C ANNUAL MAKEUP WATER REQUIREMENTS (1000 GAL)
C
      ANNMWR=GPM*60.*AOPHRS*(EBDL/100.)/1000.
C
C ANNUAL PERFORMANCE EVALUATION
C
      GMWH=0.
      FULINP=0.
      FANMWH=0.
C
      DO 97 J=1,3
```

```
C
      IF(PCTHRS(J))97,97,102
C
  102 DO 99 I=1,22
C
C ANNUAL HOURS OF OPERATION AT GIVEN OPERATING CONDITION
C
      OHRS=(TDUR(I)/100.)*(PCTHRS(J)/100.)*AOPHRS
C
C CUMULATIVE FUEL INPUT (MMBTU)
C
      FULINP=FULINP+(150.1+7.711*PCTLOD(J)+(0.344-0.02531*PCTLOD(J)
+        )*T(I))*OHRS
C
C GAS TURBINE GROSS OUTPUT (KW)
C
      GTKW=872.421*PCTLOD(J)+(13.5-2.58527*PCTLOD(J))*T(I)-4186.6
C
C THROTTLE STEAM ENTHALPY (BTU/LB), THROTTLE STEAM FLOW (LB/HR) AND
C STEAM TURBINE-GENERATOR OUTPUT (KW)
C
      TSH=1231.5+1.774*PCTLOD(J)+(0.264-0.00066*PCTLOD(J))*T(I)
C
      STGO(1)=TLU(OBP(I,J),BP,STGOUT(1,1),27)
      IF(PCTLOD(J)-100.)104,103,103
C
  103 TSF=190000.
      STGKW=STGO(1)
C
      IF(T(I)-59.)100,101,101
C
  100 TSF=174745.+250.26*T(I)
      GO TO 105
C
  104 TSF=1860.62*PCTLOD(J)+(158.71+0.0204*PCTLOD(J))*T(I)-13310.
C
  105 STGO(2)=TLU(OBP(I,J),BP,STGOUT(1,2),27)
      DELKW=STGO(1)-STGO(2)
      STGKW=STGO(1)-((190000.-TSF)/20000.)*DELKW
C
  101 STGKWC=STGKW+(TSF*(TSH-1420.)/3413.)
C
C CUMULATIVE GROSS GENERATION (MWH)
C
      GMWH=GMWH+(GTKW+STGKWC)*OHRS/1000.
C
C CUMULATIVE FAN ENERGY (MWH) REQUIREMENTS ASSUMING 90 PERCENT FAN
C MOTOR EFFICIENCY
C
      FANMWH=FANMWH+(FANBHP(I,J)*0.746/0.9)*OHRS/1000.
C
   99 CONTINUE
   97 CONTINUE
C
C ANNUAL AUXILIARY ENERGY (MWH) REQUIREMENTS (FANS PLUS
C SUPPLEMENTAL AUXILIARY COOLING SYSTEM) AND ANNUAL NET GENERATION
C (MWH)
C
      AUXMWH=FANMWH+(SEHP*0.746/0.9)*AOPHRS/1000.
      ANNMWH=GMWH-AUXMWH
```

```
C
C OUTPUT HEADINGS
C
      ITOF=76568
      PRINT 1003,ITOF
 1003 FORMAT(R2)
C
      PRINT 1000,APLFAC
 1000 FORMAT(10/44X,*EVALUATION OF BRAINTREE COMBINED CYCLE PLANT*
+         //51X,*WITH GEA AIR-COOLED CONDENSER*,5/46X,*ANNUAL PLANT*
+         * LOAD FACTOR =*,F6.1,* PERCENT*,3/8X,*ANNUAL*,15X,
+         *UNIT*,5X,*GROSS*,5X,*ANNUAL*,5X,*NET*,6X,*ANNUAL*,4X,
+         *ANNUAL*,14X,*ANNUAL*,14X,* TOTAL  */8X,*FIXED-*,5X,*UNIT*
+         ,5X,*MAKEUP*,4X,*ANNUAL*,3X,*AUXILIARY*,2X,*ANNUAL*,4X,
+         *MAKEUP*,3X,*CAPITAL*,4X,*ANNUAL*,4X,*MAKEUP*,4X,*TOTAL*,
+         5X,*BUSBAR*/8X,*CHARGE*,5X,*FUEL*,6X,*WATER*,4X,*GENER-*,
+         4X,*ENERGY*,4X,*GENER-*,4X,*WATER*,4X,*AND O+M*,5X,*FUEL*,
+         5X,*WATER*,5X,*ANNUAL*,4X,*ENERGY*/9X,*RATE*,6X,*COSTS*,
+         5X,*COSTS*,4X,*ATION*,4X,*REQUIRED*,3X,*ATION*,4X,
+         *REQUIRED*,3X,*COSTS*,5X,*COSTS*,5X,*COSTS*,5X,*COSTS*,5X,
+         *COSTS*//8X,*PERCENT*,3X,*$/MMBTU*,1X,*$/1000 GAL*,3X,
+         *MWH*,7X,*MWH*,7X,*MWH*,5X,*1000 GAL*,5X,*$*,9X,*$*,9X,
+         *$*,9X,*$*,6X,*MILLS/KWH*/6X,12(* -------- *))
C
C ANNUAL AND BUSBAR COST EVALUATION
C
      DO 98 M=1,NFCR
C
C ANNUAL CAPITAL COSTS INCLUDING 1.0 PERCENT FOR OPERATION AND
C MAINTENANCE
C
      ANNCAP=CAPCST*((AFCR(M)+1.0)/100.)
C
      DO 98 N=1,NUFC
C
C ANNUAL PLANT FUEL COST
C
      ANNFUL=FULINP*UFC(N)
C
      DO 98 L=1,NMWC
C
C ANNUAL MAKEUP WATER COSTS
C
      ANNMWC=ANNMWR*UMWC(L)
C
C TOTAL ANNUAL COSTS AND  TOTAL   BUSBAR ENERGY PRODUCTION COSTS
C (MILLS/KWH)
C
      TOTANN=ANNCAP+ANNFUL+ANNMWC
      BUSBAR=TOTANN/ANNMWH
C
C PRINTOUT OF RESULTS
C
      PRINT 1001,AFCR(M),UFC(N),UMWC(L),GMWH,AUXMWH,ANNMWH,ANNMWR,
+         ANNCAP,ANNFUL,ANNMWC,TOTANN,BUSBAR
 1001 FORMAT(/F13.1,F10.2,F9.2,F12.0,F9.0,F11.0,F9.0,2F11.0,F8.0,
+         F12.0,F9.3)
C
   98 CONTINUE
C
```

```
      CALL DATER(IDATE)
      PRINT 1002,IDATE
 1002 FORMAT(//117X,A9)
C
      PRINT 1003,ITOF
      STOP
      END
C
      FUNCTION TLU(X,XT,YT,NT)
C
C THIS IS A FOUR-POINT LAGRANGIAN INTERPOLATION TABLE LOOK-UP
C ROUTINE
C
      DIMENSION XT(NT),YT(NT)
C
C DETERMINE IF INDEPENDENT VARIABLE IS WITHIN RANGE OF TABULATED
C DATA
C
      IF((X-XT(1))*(X-XT(NT)))100,100,101
C
C DETERMINE IF TABULATED VALUES OF INDEPENDENT VARIABLE ARE IN
C ASCENDING OR DESCENDING ORDER
C
  100 IF(XT(1)-XT(2))102,102,103
C
C DETERMINE POSITION OF INDEPENDENT VARIABLE IN ASCENDING ARRAY
C
  102 DO 99 I=1,NT
      IF(X-XT(I))105,104,99
   99 CONTINUE
C
C DETERMINE POSITION OF INDEPENDENT VARIABLE IN DESCENDING ARRAY
C
  103 DO 98 I=1,NT
      IF(X-XT(I))98,104,105
   98 CONTINUE
C
C IF INDEPENDENT VARIABLE IS EQUAL TO TABULATED VALUE, SET FUNCTION
C EQUAL TO CORRESPONDING VALUE OF DEPENDENT VARIABLE
C
  104 TLU=YT(I)
C
      RETURN
C
C IF INDEPENDENT VARIABLE IS BETWEEN FIRST TWO OR LAST TWO
C TABULATED VALUES, ADJUST INDEX TO OBTAIN FOUR POINTS FOR
C INTERPOLATION
C
  105 IF(I-2)106,106,107
  106 I=I+1
      GO TO 108
  107 IF(I-NT)108,109,109
  109 I=I-1
C
C DETERMINE FUNCTION VALUE USING FOUR-POINT LAGRANGIAN
C INTERPOLATION
C
  108 X1=XT(I-2)
      X2=XT(I-1)
      X3=XT(I)
```

```
       X4=XT(I+1)
C
       TLU=(X-X2)*(X-X3)*(X-X4)/((X1-X2)*(X1-X3)*(X1-X4))*YT(I-2)
+         +(X-X1)*(X-X3)*(X-X4)/((X2-X1)*(X2-X3)*(X2-X4))*YT(I-1)
+         +(X-X1)*(X-X2)*(X-X4)/((X3-X1)*(X3-X2)*(X3-X4))*YT(I)
+         +(X-X1)*(X-X2)*(X-X3)/((X4-X1)*(X4-X2)*(X4-X3))*YT(I+1)
C
       RETURN
C
   101 PRINT 1000,X,XT(1),YT(1)
  1000 FORMAT(1H1,39H TABLE LOOK-UP: X NOT IN RANGE OF TABLE//
+         5X,3HX =,F15.5,5X,7HXT(1) =,F15.5,5X,7HYT(1) =,F15.5)
C
       STOP
       END
```

RUN COMPLETE.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-76-178	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Feasibility Study for a Direct, Air-Cooled Condensation System		5. REPORT DATE July 1976
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Michael D. Henderson		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS R.W. Beck and Associates 400 Prudential Plaza Denver, Colorado 80202		10. PROGRAM ELEMENT NO. 1BB392; ROAP 21AZU-034
		11. CONTRACT/GRANT NO. R803207-01
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; Through 12/75
		14. SPONSORING AGENCY CODE EPA-ORD

15. SUPPLEMENTARY NOTES Project officer for this report is J.P. Chasse, EPA Environmental Research Center, Corvallis, OR 97330 (FTS 420-4718).

16. ABSTRACT The report gives results of an investigation of the feasibility of utilizing direct, air-cooled condensation systems in coastal environments. Particular attention was devoted to the prevention of corrosion of external surfaces of fintubes, of coil freezing, and of excessive noise. Manufacturers were contacted to determine the extent of their experience in providing this equipment. Owners and operators of dry towers were visited on-site to determine if the equipment can operate satisfactorily under a wide range of load and atmospheric conditions. Performance was also evaluated for the dry tower associated with an 85-MW combined-cycle unit under construction for the Braintree (Massachusetts) Electric Light Department.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	*Noise (Sound)	Pollution Control	13B	20A
*Air Coolers	*Freezing	*Dry Cooling Tower	13A	07D
*Cooling Systems	*Corrosion	*Vacuum Steam Condenser		
Feasibility			14A	
Thermal Power Plants			10B	
Performance			14D	

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 75
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)