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FLOW DISTRIBUTION CONTROL CHARACTERISTICS IN MARINE GAS TURBINE WASTE-HEAT STEAM GENERATORS

Annual Technical Report
July 1982

Ho-Tien Shu
Simion C. Kuo, Principal Investigator

Prepared for
The Office of Naval Research, Arlington, Virginia
Under Contract No. N00014-80-C-0476, Modification P00002

UNITED TECHNOLOGIES RESEARCH CENTER
East Hartford, Connecticut 06108

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This technical report is concerned with the effect of flow distribution control on the design and performance of marine gas turbine waste-heat steam generators. Major design requirements and critical problems associated with a waste-heat steam generator were reviewed, and an existing two-dimensional heat exchanger model based on the compact heat exchanger design criteria and

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the relaxation approach was modified and updated to estimate the waste-heat steam generator performance at any inlet gas flow distribution. Performance estimates were made of the steam generator using a uniform velocity distribution, and also actual flow distribution data available (at the diffuser inlet) with and without flow distribution controls, all at design and off-design operating conditions of the gas turbine engine. Results of the study indicate that the exit steam temperatures of the baseline waste-heat steam generator with and without flow distribution controls would be 725°F and 450°F, respectively, for a constant design flow rate of 7.9 lb/sec, and for a constant exit temperature of 700°F, the water flow rates would be 8.1 lb/sec and 6.6 lb/sec, respectively. A suggested experimental program to provide information for comparison with the analytical results, and to obtain applicable operational experience is also described in this report.

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FOREWORD

The work described in this Annual Technical Report was performed at the United Technologies Research Center (UTRC) under Contract N00014-80-C-0476, Modification P00002, entitled "Study of Flow Distribution Control Characteristics in Marine Gas Turbine Waste-Heat Recovery Systems", for the Office of Naval Research (ONR). This report summarizes results obtained for the Phase II (second year) study on flow distribution control characteristics in waste-heat steam generators which was preceded by the first-year study on diffusers. Dr. Simion C. Kuo is the Principal Investigator for this contract program, and Dr. Ho-Tien Shu is the major contributor to this phase of the study. The computer program used in analyzing the steam-generator was derived from an existing Fuel Vaporization Model originally developed by Messrs. Chiappetta and Szetela, both of UTRC.

The research contract was signed by ONR on July 23, 1980, and the Scientific Officer is Mr. M. Keith Ellingsworth, Mechanics Division, ONR, Arlington, Virginia. Valuable guidance and comments received from Mr. Ellingsworth are gratefully appreciated.

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SUMMARY

The objective of this study was to investigate the effect of flow distribution control on the design and performance of marine gas turbine waste-heat steam generators. The applicable steam generator design concepts and general design consideration were reviewed and critical problems associated with the design of marine waste-heat steam generators were identified. A once-through counter crossflow heat exchanger was selected as the candidate waste-heat steam generator for recovering the waste heat from the exhaust of a marine gas turbine. A two-dimensional heat exchanger model suitable for the study objective was formulated and computerized. Parametric performance analyses were made of the waste-heat steam generators for four different tube arrangements from which the most desirable design was selected (as baseline waste-heat steam generator) for further investigation. The effect of flow distribution control on the baseline waste-heat boiler performance, under both design and off-design gas turbine operating conditions were analyzed. It was estimated that, at design condition without flow distribution control, the overall heat transfer rate would be approximately 16 percent less than that obtainable based on uniform flow distribution. With appropriate flow distribution control (using one flow guide vane and one flow injection for boundary layer separation control), the boiler efficiency can be expected to improve by approximately 20 percent as compared with that of the uncontrolled case. Based on the results of this analytical study, a suggested experiment program was formulated for ONR consideration.

This study program was conducted by the Thermal Engineering Group at UTRC under Contract N00014-80-C-0476, Modification P00002, from the Office of Naval Research, Mechanics Division, Arlington, Virginia.

RESULTS AND CONCLUSIONS

- The design of a gas turbine waste-heat boiler or hot-water heater depends on the gas turbine model to which it would be mated, its end-use, and space and economic criteria. Units designed for industrial applications have been custom-built to fit different configurations using mostly finned carbon steel tubes.

- For naval propulsion applications, a once-through forced-circulation steam generator design should be selected because of stability, reliability, compactness and lightweight considerations. In order to achieve maximum performance, the gas-side pressure loss for the steam generator should be limited to 200 mm water-gage, and the pinch-point temperature should not be less than 50°F.

- The analytical model developed to predict the waste-heat boiler performance is based on the use of compact heat exchanger design criteria and the relaxation-approach method. The model is capable of estimating the waste-heat boiler performance at any inlet gas flow distribution.

- Results of an extensive parametric performance analysis indicate that among the four candidate tube size and arrangements combinations, a circular finned tube with the following dimensions is the most effective for the baseline waste-heat boiler design: tube length =200 ft; outside diameter =0.774 inch; fin diameter =1.403 inches; fins per inch =9; fin arrangement: staggered with longitudinal pitch =1.75 inches and transverse pitch =1.557 inches.

- At its design condition (corresponding to a 50-percent power output of the gas turbine), the baseline waste-heat steam generator with a uniform gas flow distribution is estimated to be able to generate approximately 28000 pound per hour of superheated steam at 700°F and 300 psia. At this condition, the calculated overall heat transfer rate would be approximately 10000 Btu/sec; the gas-side pressure loss would be 0.55 psia; and the pinch-point temperature would be approximately 75°F.

- When the water flow rate of the baseline waste-heat steam generator is maintained at its design value of 7.9 lb/sec, the steam temperatures with and without flow distribution controls are estimated to be 725°F and 450°F, respectively. When the steam temperature is maintained at its design value of 700°F, the water flow rates with and without flow distribution control would be 8.1 lb/sec and 6.6 lb/sec, respectively.

. To provide adequate technical information so a comparison with the analytical results can be made and to produce operational experience with a gas turbine waste-heat steam generator in naval propulsion applications, an experimental program should be undertaken. A suggested program consisting of nine major tasks would require approximately sixteen months to complete and a level of effort of approximately 3000 man-hours.

INTRODUCTION

As a result of a system feasibility study conducted by NAVSEA in 1977 (Ref. 1) the Rankine Cycle Energy Recovery (RACER) system was selected as a candidate system for future advanced naval propulsion system. The RACER system uses waste heat recovery from the exhaust of the marine gas turbines to provide additional propulsion power for the U.S. Naval combatants. Since then, the development of a reliable, efficient and compact waste heat steam generator has become one of the most important engineering disciplines. Critical technology areas were defined and appropriate programs were initiated to address these and thereby to reduce the risk of system development (Refs. 2 and 3). Results of these critical-technology programs indicate that a self-cleaning boiler is feasible, a low-leakage system can be demonstrated, and IN625 or IN825 would be the candidate material for construction of the waste-heat boiler. Based on the general design objectives outlined by the Navy and on the results of these critical technology programs, contracts for the preliminary design of the RACER system were awarded in 1979 and those for its development, testing and evaluation were awarded in 1981 (Ref. 4).

Although the results of system studies and critical technology programs continue to support the use of RACER system for Naval propulsion applications, some problems related to the general design practices remained to be solved by the design engineers. Because each component of the RASER system must be designed to satisfy specific system performance requirements, and particularly those related to the waste heat steam generators, uncertainties related to heat-transfer and pressure-loss coefficients, as well as to nonuniform flow distributions must be eliminated. Although the degree of nonuniformity and its effect on the waste-heat boiler performance are not completely clear, what is apparent is that the waste heat boiler must be designed with care because of such factors as cost, the space and weight limitations, and performance and reliability requirements. Therefore, an experimental program becomes a necessity. However, for large units like the RACER system, it would be unpractical, if not impossible, to build a full-scale test apparatus to conduct a comprehensive test program. Accordingly, the present analytical study was conducted first to provide some basic understanding of the flow distribution characteristics and the effect this flow has on marine gas turbine waste-heat boiler performance. Based on the analytical results, a desirable and constructive experiment program can be formulated for ONR consideration.

It is well understood that any nonuniform flow distribution will reduce the heat transfer performance and at the same time, increase the pressure loss in a heat transfer device to various degrees, depending on specific design and actual operating condition. Several studies have been made in the past to investigate the effect of flow distribution nonuniformity on the heat exchanger performance (Refs. 5 to 8). Because the actual flow distribution would be different from one design to another, these studies were made based on arbitrarily assumed nouniform flow profiles for the working fluids. Results of these studies indicated that as much as 30 percent reduction in overall heat transfer unit (NTU) could be ascribed to the poor flow distribution in the heat exchanger core. Because the flow distribution profiles assumed in these studies are quite different from that of the marine gas turbine exhaust, and furthermore the heat exchanger core considered are often unsuitable for naval propulsion system applications, these study results can be used for reference purposes only, but not suitable for direct applications. Therefore, an analytical study of waste-heat boiler performance based on actual flow distributions measured in a typical marine gas turbine exhaust was performed and the results obtained are presented in this report.

The overall analytical program has been structured into two phases. Phase I (Ref. 9) emphasizes the understanding of the basic flow-distribution phenomena and its impact on two-dimensional diffuser design and performance. Results of the Phase-I study indicate that flow distribution in marine gas turbine exhaust was highly irregular and nonuniform, and that this flow will remain nonuniform through a two-dimensional diffuser unless proper flow distribution control means are used. This nonuniform flow distribution can be made more uniform by using a specially designed diffuser which incorporates appropriate guide vanes and, if necessary, flow injection at critical locations. The results of Phase-I study were then used in this Phase-II study which emphasizes the effect of nonuniform flow distribution on the waste-heat boiler performance.

This report presents the technical approach and the results of an analytical study of flow distribution control in marine gas turbine waste-heat steam generators. The report consists of three sections and one appendix. In Section I, the applicable steam generator design concepts and general design considerations are reviewed; the design data used by many manufacturers of waste-heat boiler are evaluated; the critical-problem areas associated with design of marine waste heat steam generators are discussed; and a candidate waste heat steam generator configuration was selected. Section II discusses the analytical model formulation and presents the results of parametric performance analysis, including those for both design and off-design operations of candidate waste heat steam generators. Based on the results of this analytical study, a proposed experiment program plan and schedule was prepared; this is presented in Section III. The detailed descriptions of the computer program developed for the analytical model are presented in Appendix A.

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SECTION I

SELECTION OF CANDIDATE STEAM GENERATOR CONFIGURATIONS

Gas turbine waste heat recovery systems have been designed and used with success for generating either hot water or steam or both for various applications (Refs. 1.1 to 1.4). In addition, results of technical and economic feasibility studies have shown that the combined gas and steam turbine power system is attractive for use in marine propulsion applications (Refs. 1.5 and 1.6). The use of small-scale heat exchanger units for recovering waste heat from service gas turbine generators of U.S. DD963 ships has also been reported in Refs. 1.7 and 1.8. Furthermore, the research and development efforts leading to an efficient, lightweight, and reliable waste heat recovery system for U.S. Navy surface combatant propulsion application is underway (Refs. 1.9 and 1.0). Accordingly, the objective of this task was to select a candidate waste heat steam generator configuration which could be integrated with the candidate gas turbine and diffusers investigated in the Phase-I study. In order to achieve this objective, the applicable steam generator design concepts and general design considerations were reviewed; the design data, which include the system operating conditions (flow rate, temperature, and pressure), the boiler, its efficiency, and the tube material, used by manufacturer of waste-heat boiler or hot-water heaters were evaluated; and the critical problem areas associated with design of marine waste heat boilers were investigated. Based on this information, a candidate waste heat steam generator configuration was selected.

I.1 Design Concepts and Considerations of Marine Gas Turbine Waste-Heat Boilers

In the process of specifying a marine gas turbine waste heat boiler, a designer must determine: (1) the total amount of heat that can be recovered economically; and (2) the type of equipment that is best suited to the available space and the quality of the steam. Based on the results obtained, the designer proceeds to investigate other basic design considerations the most important of which are summarized in Table I.1. These considerations are based on general design practices of industrial gas turbine waste heat boiler designs, or on the general constraints and requirements of naval ship operations.

I.1.1 Design-Point Performance Considerations

Capacity sizing: in practice, the design of marine gas turbine waste heat boiler is conducted on one of two approaches. The first is to design the system for a ship which would operate at full load for long periods of time (such as commercial marine and naval auxiliary ships); the other is to design the system for efficient operation at cruise, but still taking into consideration the need to operate for intermittent periods at full-power (such as the naval combat ships). The method of integrating the waste heat steam generator with the marine gas turbine will depend on both the ship type (maximum installed power and duty cycle) and the gas turbine engine selected. If two gas turbines were needed to power one propeller, it would be desirable to have the exhaust systems of these two turbines directed through a single waste-heat boiler for the steam turbine, thereby reducing weight of the waste-heat recovery system. In this case, the maximum heat which could be recovered will depend on the performance characteristics of the gas turbines and their operating profiles. The off-design performance of the steam cycle will depend on whether it is designed for cruise- or full-power operation.

Flow Parameters: Because the ratio of gas to liquid (water) flow rates in the waste-heat boiler or hot water heater are inherently high, externally extended (finned) tubes are more desirable than bare tubes. Many studies (Ref. 1.2, 1.7, 1.11 and 1.12) indicate that when the gas flows across the finned side of the tubes, the heat transfer will be maximized, and therefore, the designers of most gas turbine recovery systems have adopted this cross flow pattern. To handle the relatively large amount of gas flow at low pressure and high temperature and to satisfy the low-pressure-drop requirement, the flow area on the gas side must be adequate. When external finned tubes are considered, gas-side pressure drop through the heat recovery system may impose significant penalties on the operation of the gas turbine. In industrial waste heat boilers, the pressure drop is normally limited to approximately 15 inches of water (0.6 psia). Therefore, the tube size and tube arrangement must be carefully selected. To increase the flow area and heat transfer area, the use of a suitable diffuser to connect the waste heat boiler with the gas turbine exhaust box becomes necessary. The candidate diffuser identified during Phase-I study will serve this purpose.

Pinch Point: It is difficult to assess practical limits on the degree of heat recovery without considering the cost of the equipment, and one of the most important parameter in sizing the waste heat boiler is the pinch point temperature. Figure I.1 shows the profile of the turbine exhaust gas and the water/steam temperature for a typical unfired waste-heat steam generator. The pinch point generally occurs where the liquid reaches its saturated state. The selection of the pinch-point temperature not only effects the liquid-side flow condition (flow rate and pressure), but also the boiler size. As indicated in Ref. 1.11, waste-heat boilers with pinch-point less than 50°F are normally not considered to be economical.

Temperature Differential: Unlike that in a conventional oil or coal fired boiler, the temperature differential between the two working fluids in a gas turbine waste-heat boiler is low. Accommodating this low temperature differential requires a special design in terms of tube arrangement and material selection. Finned tubes with high thermal conductivity can be considered as long as the sum of the material cost and manufacturing cost do not exceed the economic limit.

I.1.2 Tube Design Considerations

After the flow conditions, tube material, tube size, and the tube arrangement have been selected and defined, the waste-heat steam generator performance can be estimated; the selection of the tube size and tube arrangement has a significant effect on boiler performance and size. Use of small diameter tubes yields a high heat transfer coefficient on both sides of the working fluids and results in small boiler. The advantage can be taken of using small tubes only when working with organic fluids or extremely high quality water so hardness or fouling problems are eliminated. However, from a practical standpoint, the tube size selected should be sufficiently large to accommodate a pneumatic tube reamer. This precaution is taken so that if untreated water is used for an emergency condition, or if the cooling water (river water or sea water) leaks into the condensate, the tubes can be cleaned mechanically if chemical cleaning is impossible or if the tubes become plugged to the point where chemicals cannot be introduced. Therefore, from a practical viewpoint, tubes smaller than 3/4 inch in diameter should not be considered.

Heat exchanger tubes should be arranged in such a manner that thermal stress concentration can be avoided; both U-shape and coil arrangements are good candidates in this respect. However these arrangements are not generally regarded as being compact and their accessibility for maintenance and replacement of parts is generally poor. A modular design, similar to the evaporator of the automobile air conditioning unit (with finned straight tubes used as the heat transfer core and with the ends of the tubes welded to a U-shape tube joints which are located outside of the tube sheet as shown in Fig. II.7), may be a better choice for marine gas turbine waste heat applications.

The baffles needed to act as tube support plates and flow guide vanes must be located so that the maximum tube length between support plates, or between a tube sheet and a supporting plate, does not exceed 36 inches. Holes for tubes in baffles, baffles clearances, and tie rod standards must be designed in accordance with the latest standards of the ASME boiler design code (Ref. 1.16).

The selection of tube material affects not only on the heat transfer performance and the initial cost, but also the boiler reliability and its operation. For landbased waste-heat recovery systems, carbon steel or low alloy are commonly used. However, for naval ship propulsion system applications, high-temperature stainless steel (such as 304 or 316) or Incoloy 800 may be used to cope with the possible dry-running conditions.

I.1.3 Performance Degradation C .siderations

In designing heat transfer equipment, the possible performance deterioration due to flow leakage, nonuniform flow distribution, and fouling must be considered. Leakage is one of the most exasperating problems in heat exchanger fabrication and maintenance, for it not only effects the heat exchanger performance, but also requires flow make-up and clean-up equipment. Therefore, use of all-welded tubes may be considered to ease the leakage problem. Nonuniform flow distribution has some effects on heat exchanger performance (Refs. 1.14 and 1.15). In Ref. 1.15 it is indicated that poor flow distribution through the cores of a typical counterflow exchanger can cause degradation in excess of 30 percent in the operating effectiveness as compared with the values predicted for the ideal case of uniform flow distribution. Therefore, applicable flow distribution control, wherever is necessary, must be incorporated into the design of a waste heat boiler to avoid any unnecessary performance degradations.

Fouling has also been a problem common to all waste heat recovery equipment. In order to design a marine waste heat boiler capable of sustaining its design capability over a desired period of operation with minimum maintenance and repair, the designer must give serious consideration to the selection of materials. The material specified must be able to offer maximum resistance to corrosion, and to the fouling characteristics of the fluids being handled.

As an added design burden, consideration must be given to the varying degrees of inclination encountered in sea service. In naval practice, all heat transfer equipment must be designed to perform satisfactorily under conditions of 5 degrees trim, 10 degrees pitch, 15 degrees list, and 45 degrees roll.

1.1.4 System Layout Considerations

The physical arrangement of the gas turbine exhaust relative to the location of the heat recovery unit has considerable effect on turbine maintenance as well as the cost of the overall installed recovery system. For industrial applications, the horizontal side-discharge gas turbine exhaust (Fig. I.2) is preferred. This arrangement provides good access for turbine maintenance, has less structural support for the waste heat recovery components, and provides adequate space for bypass stack and/or supplementary firing. This arrangement also offers the opportunity to use natural circulation (through vertical tube arrangement) for reliable flow circulation and uniform heat distribution, both of which are of particular importance if supplementary firing were required. Because of space and weight constraints in ship propulsion system applications, a vertical top-discharge gas turbine exhaust (Fig. I.3) is more desirable (Refs. 1.9, 1.10, and 1.12). The advantages of this arrangement are primarily for saving in cost and space as well as good exhaust gas distribution across the boiler heating surface provided that diffuser is properly designed. Generally speaking, this arrangement does not create any special gas turbine maintenance problems because the engine is housed in its own enclosure and can be removed through the intake for major services. For easy installation, maintenance and replacement, the heat exchanger tube elements are arranged horizontally. However, this arrangement would require forced circulation of liquid to satisfy such operational requirements as ease of control and dry-running. In addition to having the characteristic of good stability and reliability, the forced circulation design is known to be more compact and lighter in weight in comparison with the natural circulation (vertical) design.

The physical location for the auxiliary components, such as the pump, the automatic (pneumatic) control devices, the feed water treatment system, and the pipings must be carefully selected so that accessibility for their maintenance and parts replacement is adequate. If the space limitation were such that an integral waste-heat boiler system would cause problems in accessibility, dispersed arrangement of some secondary auxiliary component must be considered.

I.1.5 Structural Rigidity Considerations

Due to the rough sea service condition, all components of the waste-heat boiler must be provided with adequate foundation supports. Additional allowances must be made in the design of the heat recovery equipment supports to provide for expansion, contraction and high-impact shock. Furthermore, all design features must conform to the ASME Boiler and Pressure Vessel Code (Ref. 1.16). The design data commonly used by manufacturers of industrial waste-heat boiler and waste-heat economizer (hot water heater) and the critical problem associated with marine gas turbine waste heat boiler design are discussed in the section which follows.

I.2 Waste Heat Boiler Design Data and Critical Problems

A comprehensive survey was performed to identify the state of the art of waste heat boiler design (including the gas and liquid flow conditions, the unit capacity, the efficiency, and the materials used) and the critical technology problem areas. The data obtained from this survey are shown in Table I.2, and the critical technology problem areas are summarized in Table I.3.

It was discovered that there are more than one hundred waste-heat-boiler/economizer manufacturers worldwide and those shown in Table I.2 represent only a few of this total. The design approaches used by these firms have been varied depending on the heat sources, amount of heat which can be recovered economically, the end-use of the recovered heat, and space and economic concerns. The left column of Table I.2 shows that most manufacturers can provide custom-built units (shown with an affixed "*" mark) to meet a specific design requirement. Therefore, the design data obtained vary over a wide range. For example, on the fourth line SA Babcock Belgium NV can provide both waste heat boiler and waste heat economizer (hot water heater) for gas flow rates ranging from 27 to 333 cu. meter/sec, gas temperatures from 400 to 700°C, and gas-side pressure losses from 20 to 60 mm W.G. The liquid flow rate, liquid temperature, and unit capacity would then vary according to the design requirements. The unit capacities and heat recoverying efficiencies of these designs vary from 10 to 200 MW and 60 to 75 percent, respectively. The design data for other manufacturers are similar in nature, but different in level of absolute values.

Among the design data presented, the gas-side pressure loss information is probably the most useful to this present study. It was found that (from column No. 4 of Table I.2) a pressure loss between 100 to 200 mm W.G. would be a practical value for marine gas turbine waste heat boiler design. Other information, such as tube materials (shown on the far right column of the same table) and the boiler design configuration (not shown in the table), offer further insight into boiler design. For industrial applications, finned carbon steel tubes are the most commonly used although stainless steel tubes are also used in some designs. The boiler configurations are mostly once-through designs.

The critical technology problem areas of waste-heat boilers are listed in Table I.3. These critical problem areas are generally related to material selection, mechanical design, or operational requirements. From available information, it appears that problems with materials are the most common and serious of these observed in the steam generator equipment. The commonly encountered material problems are related to corrosion damage in the boiler tubes including those of denting, pitting, cracking, and erosion. These problems results from the attack of concentrated aggressive chemical impurities on the tube materials. Laboratory tests made on samples removed from dented steam generator tubes indicate that denting is an acid chloride reaction (Ref. 1.17). Tube wall thinning has also been observed in the region near the tube sheet when phosphates have been used in water treatment. Examination of tubes removed from a once-through steam generator has also revealed that stress corrosion cracking may result from sulfuric acid attack. In view of these severe material problems, Navy initiated a material study program in FY79 at DTNSRDC/Anapolis to determine the best material for use in boiler tubes. The results of the study indicate that Incloy 800 can resist to oxygen and chloride stress corrosion as well as that from sulfurous and sulfonic acid attack.

The cause of the problem of tube fretting and wear can be traced to vibration. The tube vibration can be induced not only by fluid flow perpendicular to the tube but also that parallel to the tubes. Because the movement between the rubbing surfaces is oscillatory and usually small in amplitude, the rubbing process taking place is termed "fretting". It is well known that the fretted region is highly susceptible to fatigue cracks. The immediate consequence of the fatigue cracks is the leakage of working fluid and/or cooling water. The leakage in the boiler affects system performance, increases feedwater makeup requirements, and demands more frequent cleaning (including deoxygenation) operations. Minimizing the flow-induced vibration is a critical task. One common approach has been to use an all-tubular boiler with no connections other than the water inlet and steam outlet manifolds to reduce the leakage. However, use of flow distribution control to achieve a more uniform flow distribution is even more essential, and in the long run may prove to be the most beneficial solution.

The results of Phase-I study indicate that the flow distribution within the exit diffuser of the gas turbine exhaust is highly nonuniform in the absence of flow distribution controls. This nonuniform flow distribution not only could reduce the heat transfer performance (Refs. 1.14 and 1.15), but also could create thermal and mechanical stress concentrations, local hot spots, and dryout problems (Ref. 1.18). Therefore, before the accurate performance can be predicted, both analytical and experimental programs must be conducted to investigate the actual flow distribution pattern inside the waste heat boiler predicted.

Problems related to transient operation of the marine waste-heat boiler must also be addressed. Because of the self-cleaning requirement, the waste-heat boiler may have to be operated under dry condition for a period of 15 to 30 minutes at elevated temperatures, as recommended by the manufacturer. Additionally, the boiler has to be operated under odd-design condition every so often to meet the duty-cycle requirements. These transient and off-design operation and the routine start-up and shut-down procedures will undoubtedly have profound effect on the boiler reliability and life expectancy. However, available information indicate that the allowable thermal distortion for the steam turbine would limit the rate of load change to not more than approximately 2% per minute. Even at this seemingly slow rate of load change, care still must be exercised to control the boiler and its auxiliary system so that the pressure, temperature, and water inventory distributions in the system create no severe conditions throughout the starting period.

I.3 Selection of Candidate Steam Generator Configuration

Based on the results of Tasks I.1 and I.2 obtained in this study, and the need to simplify the maintenance, increase the reliability, and reduce the size and weight of the system, a once-through cross-counterflow type boiler was selected as the steam generator configuration for this analysis. The criteria used in this selection are consistent with those reported in Refs. I.9 and I.10, and therefore, the results obtained from this study should have direct relevance to the U.S. Navy RACER Program. A sketch of the conceptual steam generator configuration is shown in Fig. I.4 and a summary of its characteristics is presented in Table I.4.

Since the objective of this study was to investigate the effect of gas flow distribution control on waste-heat boiler performance, the liquid flow has been assumed to be uniform. As shown in Fig. I.4, the feedwater would be supplied through a water manifold and distributed evenly among the top two rows of the boiler tubes; the superheated steam (or hot water) would be discharged from the bottom row tubes and then collected in a steam manifold. The gas flow would enter the boiler from its bottom. The flow distribution and flow conditions have been based on the results of the Phase-I study.

In the section which follows, an analytical model of flow distribution control formulated for the candidate steam generator is presented, and results obtained from its analysis are discussed.

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TABLE I.1

CENERAL DESIGN CONSIDERATIONS FOR MARINE GAS TURBINE WASTE HEAT STEAM GENERATORS

- Design -Point Performance Considerations: to handle the large amount of gas flow at low pressure and high temperature; to satisfy the gas-side low pressure drop requirement; to cope with low temperature differential between the two working fluids.
- Tube Design Considerations: tube size, material, and arrangement.
- Performance Degradation Consideration: flow leakage, nonuniform flow distribution, and fouling, sea-service condition.
- Economic Considerations: material, sizing, and effectiveness.
- Operational Requirement Considerations: thermal load, duty cycle, dry running, emergency operation, and control devices.
- System Layout Considerations: accessibility for maintenance and repair, reliability, space and weight limitations.
- Structural Rigidity Consideration: shock and vibration, structural expansion and contraction.

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TABLE I.2 REPRESENTATIVE MANUFACTURERS OF WASTE-HEAT STEAM GENERATOR/
HOT-WATER HEATER AND DESIGN DATA

* - Custom-Built
+ = up to

WHB = Waste Heat Boiler (Steam Generator)
WHE = Waste Heat Economizer (Hot Water Heater)
AR = As Requested

Manufacturer	Gas			Hot Water or Steam			Capacity	Efficiency	Tube Material
	ṁ m^3/s	T °C	ΔP mm W.G.	ṁ m^3/s	T oc	P bar	(MW)		
GA-CTC (WHB, WHE)*	+ 200	600	AR	AR	AR	50	50-100	VARIED	Finned or Plain C.S.
BCO IND. INC (WHB)*	+ 50	370	65	100	225	AR	+ 14.5	65	Finned or Plain C.S.
ARMSTRONG CO. (WHR)*	AR	1100	1.13	AR	AR	700	AR	VARIED	CS, SS. Monel
A BABCOCK BELGIUM NV (WHB, WHE)*	27⟷333	400⟷700	20⟷60	AR	AR	10-60	10-200	60-75	MS, AS
ELTRAN & COOPER LTD (WHB)*	+ 10	200-500	10⟷25	5⟷500	AR	+ 40	+ 30	30	Finned or Plain C.S.
EVERLEY CHEMICAL ENG. LTD (WHB)*	+ 22	200-1200	10-500	0.1	AR	+ 35	+ 30	75	C.S., S.S.
ONO (WHB. WHE)*	+ 10	500-1000	50-150	AR	AR	10-20	-	50-80	NA
BRONSWERK HEAT TRANSFER BV (WHP)*	+ 28	300-1000	20-300	8⟷300	AR	+ 100	+ 300	20-50	Metal
. CASINGHINT & FIGLIO (WHB, WHE)*	AR	300-1000	10-200	AR	AR	7-170	-	-	Steel
OALTECH (WHB)*	+ 45	480-540	+ 350	40	AR	-	+ 5.5	-	C.S., S.S.
ONSECO (WHB)*	+ 42	+ 540	+ 200	6.8	AR	7.0	+ 5.4	65	-
URWEN & NEWBERY LTD (WHB)*	AR	50-800	25-40	AR	AR	AR	AR	70	Cor-ten, C.S., S.S.
CLIPSE LOOKOUT CO. (WHB)*	+ 42	≈ 500	-	AR	AR	-	+ 5.3	VARIED	C.S., S.S.
UEL FURNACES LTD. (WHB)*	+ 3	200-900	2.5-500	AR	AR	-	+ 0.2	VARIED	Cast Iron
RAHAM MANUFACTURING LTD (WHE)*	+ 36	300-750	25-50	0.13	AR	10	+ 4	VARIED	C.S., S.S.
. GREEN & SON LTD (WHB, WHE)*	AR	500-600	AR	AR	AR	10	AR	VARIED	MS, AS
AMWORTHY ENGINEERING CO. LTD (WHB, WHE)*	+ 55	+ 650	AR	AR	AR	35	-	-	Steel Finned
ARRIS THERMAL TRANSFER PRODUCTS INC (WHB, WHE)*	+ 30	+ 450	72	AR	AR	35	+ 3	67	Finned or Plain C.S.
AWTHORN LESLIE ENG. LTD. (WHB)*	20-54	280-450	140	0.03-0.1	AR	6.5	+ 6.0	68	Finned C.S.
URAKAWA IRON WORKS LTD (WHB, WHE)*	+ 144	150-950	10-145	0.07-6.5	AR	9.5	+ 1.4	-	Finned STB
ITACHI SHIPBUILDING & ENG. CO. LTD. (WHB)*	175-322	450-700	100-115	0.013-0.018	AR	14-40	-	-	Finned or plain C.S.
ORTHERN ENGINEERING INDUSTRIES (WHB)*	50-833	540-1000	20-254	0.02-0.04	AR	+ 110	20-100	80-92	Plain MS or low chrome steel
-DOT INTERNATIONAL CORP (WHB)*	-	260-650	25-76	0.4-2.2	AR	10.3	+ 6.5	82	Finned Steel
OTT INDUSTRIES INC (WHB)*	+ 506	160-350	3.7-11	AR	AR	-	+ 15	40-60	Steel
TRUTHERS WELLS CORP (WHB,WHE)*	+ 167	400-1200	200-800	20-150	AR	50-150	+ 200	85-92	

TABLE I.3

CRITICAL PROBLEM AREAS OF GAS TURBINE WASTE HEAT BOILERS

- Material Problems: Tube denting, pitting, cracking, erosion-corrosion
- Vibration Problems: Tube fretting and wear, high-cycle fatigue, stress corrosion
- Leakage Problems: Performance degradation and feed-water makeup and cleanup including deoxygenation
- Flow Maldistribution Problems: Effective flow distribution control, soot formation prevention and self-cleaning methods
- Transient Behavior Problems: dry cleaning operation, and duty cycle operation of gas turbine, regular or emergency shut-down and start-up.

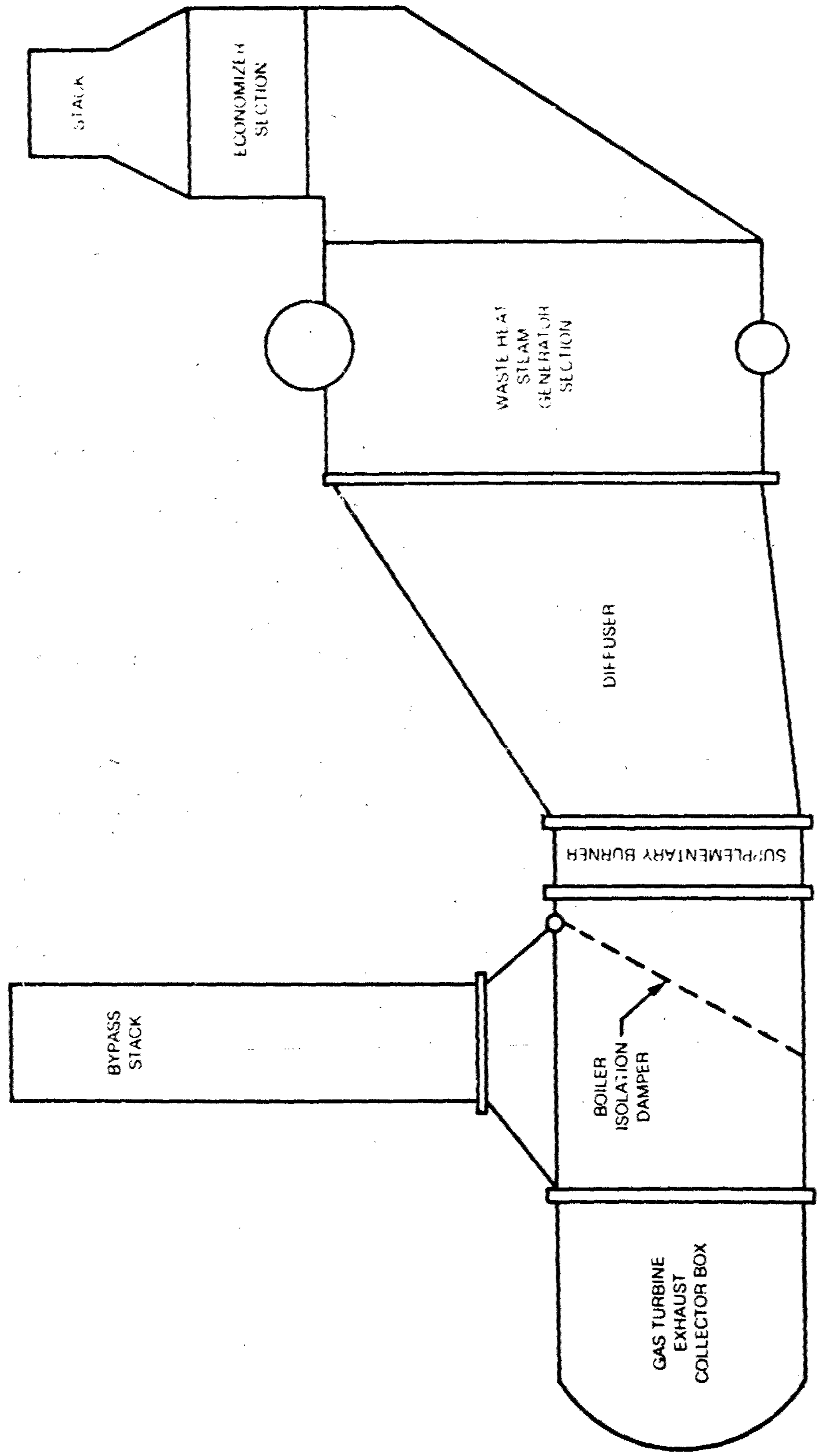
TABLE I.4

CANDIDATE STEAM GENERATOR CONFIGURATION

- Gas Flow: one-pass flowing upward without supplementary firing
- Water Flow: once-through forced circulation, counter cross to gas stream
- Tubes and Tube Arrangement: all-welded finned tubes made of corrosion resistant material (IN 800); placed horizontally along the gas turbine centerline direction
- Boiler Geometry: rectangular corss-section of 10 ft by 7 ft (compatible with the diffuser obtained from Phase-I study), height be less than 8 ft (compatible with the ship)
- Self-cleaning on the gas side and scaling prevention on the water side
- Heat Recovery Capacity: between 12,000 to 20,000 kw

FIG. I.1

LAYOUT OF TYPICAL INDUSTRIAL COMBINED-CYCLE GAS TURBINE SYSTEM



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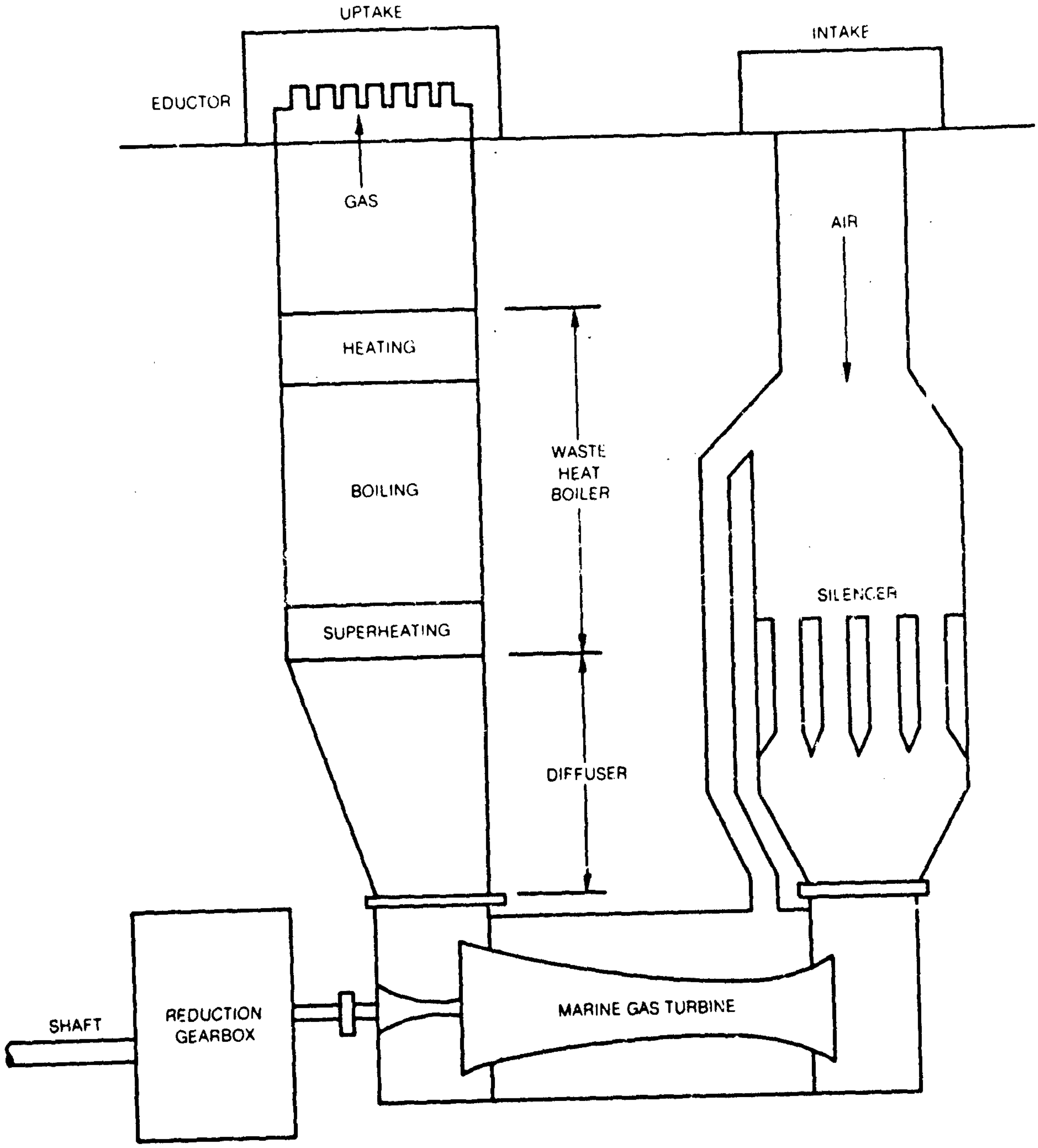
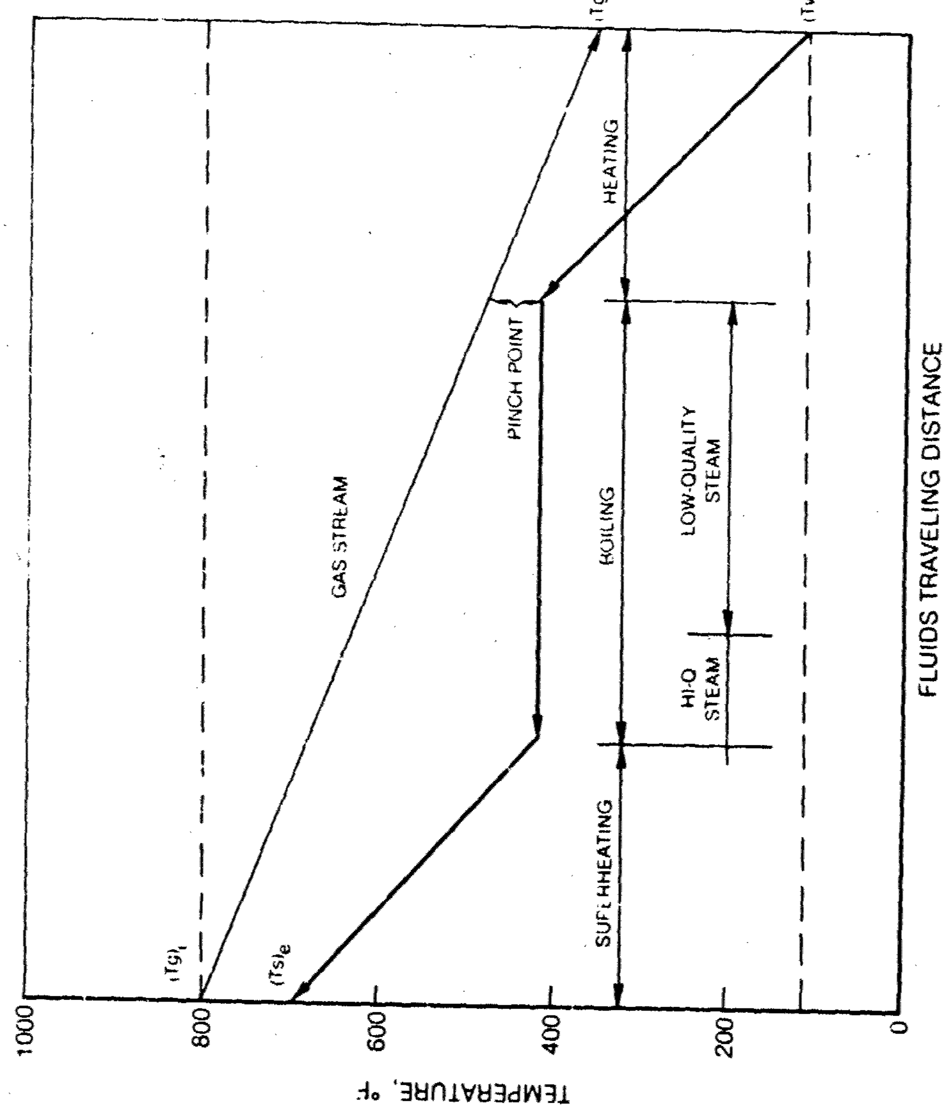
POTENTIAL LAYOUT OF COMBINED-CYCLE GAS TURBINES MARINE PROPULSION SYSTEM



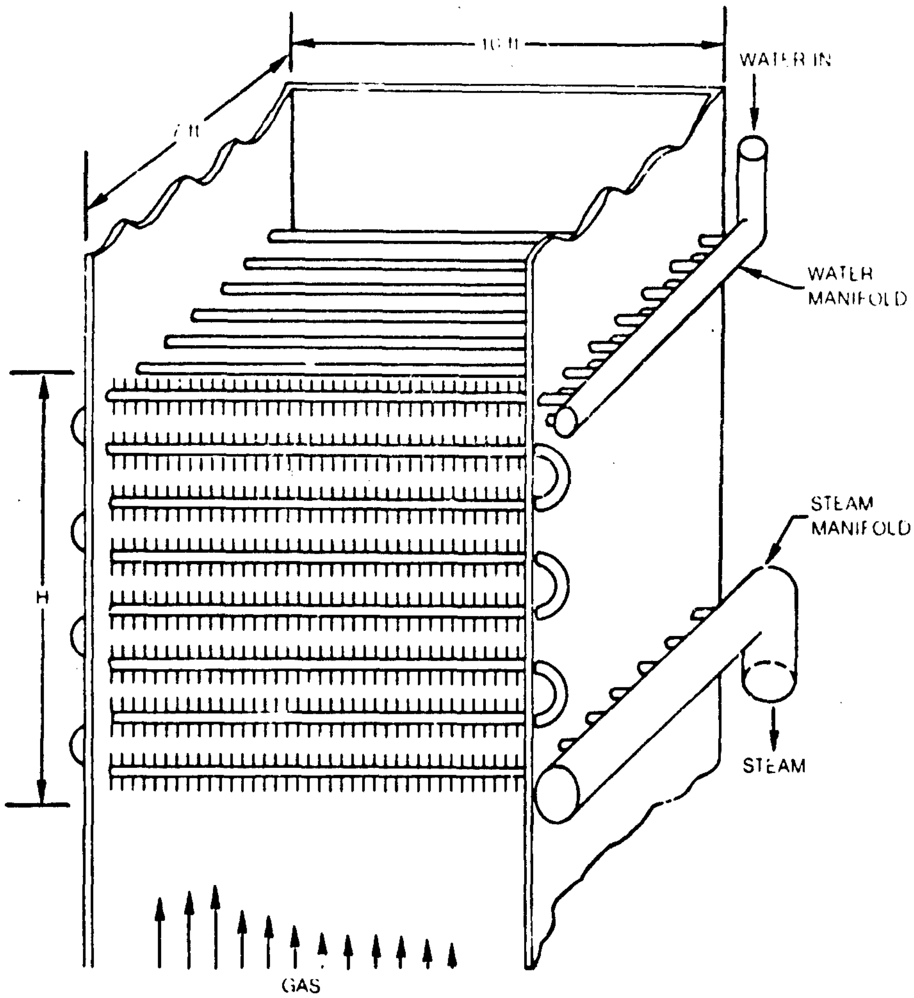
82-6-46-3



TYPICAL TEMPERATURE PROFILE OF GAS COOLING AND STEAM GENERATION PROCESSES

82 6-46-1

LAYOUT OF MARINE GAS TURBINE WASTE-HEAT STEAM GENERATOR: ONCE-THROUGH, COUNTER-CROSS FLOW HEAT EXCHANGER



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SECTION II

PERFORMANCE ANALYSIS OF FLOW DISTRIBUTION CONTROL ON WASTE-HEAT STEAM GENERATOR

This section describes the formulation of an analytical model and the analyses of flow distribution control on marine gas turbine waste-heat boiler (or steam generator) performance. The analytical model formulated is based on compact heat exchanger design concept (Ref. 2.1) and the relaxation-approach method (Ref. 2.2). The configuration of the candidate waste-heat boiler is a once-through, counter crossflow heat exchanger selected in Section I.3. The performance characteristics of this candidate waste-heat boiler at its design and off-design conditions were analyzed for three different flow inlet conditions obtained from Phase-I study (Ref. 2.3). The three flow inlet conditions are: (1) a uniform flow distribution; (2) a nonuniform flow distribution (based on actual flow distribution of a typical marine gas turbine exhaust) without flow distribution control; and (3) a nonuniform flow distribution with flow distribution control.

II.1 Formulation of Analytical Model

The analytical model used in this study is modified version of the distillate fuel vaporization model originally developed by Chiappetta and Szetela (Ref. 2.2). Although the basic assumptions and the method of approach for the fuel vaporization model are adequately described in Ref. 2.2, additional assumptions as well as working formulas pertaining to this present study are presented below to allow a better understanding of the results of this study.

The procedure used in formulating the working model for this present study consists of the following five steps: (1) establishing a nodal system to represent the overall waste heat boiler; (2) compiling all heat transfer and pressure loss working formulas and empirical constants; (3) developing a computer program for computing the thermal and physical properties of water substance for the applicable flow conditions; (4) establishing a numerical computation procedure for computational analysis of the waste-heat boiler; and (5) developing a computer program based on results obtained from steps (1) through (4) to facilitate the computational analysis of flow distribution control in marine gas turbine waste-heat boilers. A detailed discussion of each step follows.

II.1.1 Establishment of Heat Exchanger Nodal System

As cited in Ref. 2.2, in order to use a nodal system for easy computation of crossflow heat exchanger performance, several assumptions must be made. Two basic assumptions made are: (1) the heat exchanger must be rectangular and of uniform thickness; and (2) the working fluid on the shell side must be a gas although the working fluid on the tube side can be either a gas or a liquid. Based on these two assumptions, the overall waste heat boiler can be subdivided into several nodes as shown in Fig. III.1. Each node represents a rectangular parallelpiped of same length, ℓ , but of a different width, Δx_i and height, Δy_i. The overall waste-heat boiler then can be described by a two-dimensional nodal array in i, and j, where i=1,2,3... i_{max}, and j=1,2,3... j_{max}. Nodes are connected to form several groups which represent the flow paths and flow direction. For example, Fig. II.1 shows a 5 by 10 array. Assuming that the gaseous flow for this 5 by 10 array is divided into five paths and is flowing upwards, then the first gas path can be represented by (1,1), (1,2), (1,3),...(1,10), and the second gas path can be represented by (2,1), (2,2), (2,3),...(2,10), etc. If the water were flowing in a single path counter cross to the gas stream, then the nodal connection for the water path can be represented by (5,10), (4,10), (3,10), ...(1,10), (1,9), (2,9)...(5,1). The flow conditions, including the mass flow rate, the temperature, and the pressure, are specified at the inlet of each flow path to provide a starting point for numerical computation.

It should be noted that each node is treated as a miniature heat exchanger. Because of the nodal arrangement, the exit flow condition of each node will automatically become the inlet flow condition of the subsequent node. In order to preserve the mass flow rate for each gas path, a plate-fin-type heat exchanger or a baffle plate tube supporting structure must be specified in the construction of the flow path for the waste heat boiler if experimental and analytical results are to be compared.

The heat transfer coefficient for the "miniature" heat exchanger is computed based on the averaged local flow conditions. Since the number of nodes in each path and the number of paths for each fluid are arbitrarily selected, proper arrangement of the nodal connection can be made to simulate any two-dimensional heat exchanger geometry.

II.1.2 Heat Transfer and Pressure Loss Working Formula

The heat transfer coefficient (convective film coefficient) and the pressure loss characteristics are functions of the surface geometry, fluid properties, and flow conditions. It is not the objective of the present study to develop these functional relationships, but rather to compile the existing working formulas from the open literature and to use them for computing the heat transfer and pressure loss characteristics of the waste-heat boiler being studied. The formula and/or test data which were used in the present analytical model are summarized in the following sections.

II.1.2.1 Gas-Side Working Formulas

The heat transfer and pressure loss characteristics for the gas-side (shell-side) working fluid are based on the data presented in Ref. 2.1. The friction coefficient (f) and the Stanton number ($St=h/C_p \rho U$) were expressed in terms of Reynolds number for various surface geometry in Chapter IX of Ref. 2.1. When extended surfaces were considered, the fin-effect formulas presented in Chapter II of the same reference were also used.

II.1.2.2 Liquid-Side Working Formula

Because the working fluid (water) on the liquid side may experience phase changes from a liquid to a vapor and possibly to a superheated vapor, it was necessary to define different formulas for heat transfer and pressure loss in each phase. In addition, the working fluid might be in laminar flow, turbulent flow, or supercritical flow, appropriate working formulas had to be used.

For liquid-phase flow, the heat transfer coefficient can be computed using one of the following formulas:

laminar flow: $$N_u = C_1 \left(\frac{Re_b\ Pr_b}{L/D}\right)^{C_2} \left(\frac{\mu_b}{\mu_w}\right)^{C_3} \quad (1a)$$

turbulent flow: $$N_u = C_1 (Re_b)^{C_2} (Pr_b)^{C_3} \quad (1b)$$

supercritical flow: $$N_u = C_1 (Re_w)^{C_2} (Pr_w)^{C_3} \left(\frac{\rho_w}{\rho_b}\right)^{C_4} \quad (1c)$$

where C_1, C_2, C_3 and C_4 are empirical constants presented in Table II.1. The Reynolds number (Re), Prandtl number (Pr), viscosity (μ) and flow density (ρ)

are computed based on either the bulk temperature or the wall temperature as designated by the subscripts of b or w, respectively. The pressure drop, Δp, can be calculated using the following relationship from Ref. 2.1:

$$\Delta p = \frac{G^2}{2g_c} \rho_{in} \left[(K_c + 1 - \sigma^2) + 2\left(\frac{\rho_{in}}{\rho_{out}} - 1\right) + f \frac{A_{ht}}{A_{cf}} \frac{\rho_{in}}{\rho_{av}} - (1 - \sigma^2 - K_e) \frac{\rho_{in}}{\rho_{out}} \right] \quad (2)$$

where K_c and K_e are entrance and exit coefficients, σ is the ratio of free-flow area to frontal area, and A_{ht} and A_{cf} are the heat transfer area and core flow area, respectively.

For boiling-phase flow, the heat transfer coefficients were calculated using the correlations developed by Chen (Ref. 2.4), who assumed that the overall boiling heat transfer coefficient consists of two additive basic mechanisms: an ordinary macro-convective mechanism and a micro-convective mechanism associated with bubble nucleation and growth. He defined these two convective heat transfer coefficients as:

$$h_{mac} = 0.023 \, (Re_\ell)^{0.8} \, (Pr_\ell)^{0.8} \left(\frac{K_\ell}{D}\right) F \quad (3a)$$

$$h_{mic} = 0.00122 \left(\frac{K_\ell^{0.79} \, Cp_\ell^{0.45} \, \rho_\ell^{0.49} \, g_c^{0.25}}{\sigma^{0.5} \, \mu_\ell^{0.29} \, \lambda^{0.24} \, \rho_v^{0.24}}\right) (\Delta T)^{0.24} \, (\Delta p)^{0.75} \, S \quad (3b)$$

where F and S are called the effective two-phase Reynolds number function and the bubble growth suppression function, respectively. Both F and S are determined from empirical correlations of heat transfer data and the momentum-analogy analysis and are presented in graphic form in Ref. 2.4. The terms, σ and λ in Eq. (3b) are the vapor-liquid surface tension and latent heat of vaporization, respectively. The difference between the wall temperature and the saturation temperatures, ΔT, and Δp is the difference in vapor pressure corresponding to this ΔT. The subscripts ℓ and v refer to liquid and vapor, respectively.

If the two-phase boiling process were isothermal, the pressure loss can be estimated using the model developed by Lockhart and Martinelli (Ref. 2.5). In this model, the overall pressure loss consists of three additive components: a gravitational loss (ΔP_G), a momentum loss (ΔP_M), and a frictional loss (ΔP_F), which are defined as:

$$\Delta P_G = \left[(1-\alpha)\ \rho_\ell + \alpha\rho_v\ \frac{\sin\theta}{g_c}\right] \tag{4a}$$

$$\Delta P_M = \frac{\rho_\ell U^2}{{g_c}^2}\ \Delta\ \left[\left(\frac{1-\alpha}{1-\alpha}\right)\ \frac{1}{\rho_\ell} + \frac{\chi^2}{\alpha\rho_v}\right] \tag{4b}$$

$$\Delta P_F = \left|1 + Y^{2/N}\right|^N\ \left(\frac{\Delta p}{\Delta X_i}\right)\ s_v \tag{4c}$$

where α and Y are defined as:

$$\alpha = \left[1 + \frac{1-X}{X}\ \left(\frac{\rho_v}{\rho_\ell}\right)^{3/2}\right]^{-1} \tag{5a}$$

$$Y = \frac{{Re_v}^m\ C_\ell\ \rho_v}{{Re_\ell}^n\ C_v\ \rho_\ell}\ \left(\frac{1-X}{X}\right)^2 \tag{5b}$$

where m, n, C_ℓ, C_v, N are constants presented in Table II.1. The term, χ, is the steam quality, and $\Delta\chi_i$ is the nodal width defined in Section II.1.1.

For the supercritical flow, the analytical and experimental results presented in Chapters V and VI of Ref. 2.1 were used to calculate the heat transfer and the pressure losses . In this procedure, the friction coefficient and Stanton number were expressed in terms of the Reynolds number in graphical form, which were tabulated as input data to the computer program which is discussed in Appendix A.

In order to increase the flow depth to satisfy specific design requirements, each flow path may be reversed alternately to form several passes. The pressure drop associated with the turns were calculated using the averaged dynamic head evaluated at the nodes before and after the turn.

II.1.3 Thermodynamic and Transport Properties of Water Substance

Because the original analytical model (Ref. 2.2) was developed for distillate fuel, vaporization application, the development of a computer program which could estimate the thermodynamic and transport properties of water at any flow condition became an essential part of the analytical model for the present study. In this model the thermodynamic and physical properties needed are the temperature, pressure, specific volume, enthalpy, specific heat, viscosity, and thermal conductivity. The numerical values for the thermodynamic properties (the first six items) can be obtained from a fundamental equation, called the Helmholtz free energy equation, which is described in Ref. 2.6. The advantage of using this fundamental equation is that all thermodynamic properties can be obtained from its derivatives. Because differentiation, unlike integration, produces no undetermined functions or constants, the information yield is complete and unambiguous.

To calculate the thermal-conductivity and the viscosity, two well-known relationships contained in Refs. 2.7 and 2.8 were used. These two working relationships, along with the derivatives of the Helmholtz free energy equations, were then incorporated into computer programs for use in this program.

II.1.4 Numérical Computation Procedure

The numerical computation procedure used in this study is the same as that presented in Ref. 2.2. To provide a better understanding of this analytical model, a brief discussion of its computational procedure is given as follows.

As mentioned in Section II.1.1 that each subdivision (called node) will be treated as a miniature heat exchanger. The performance of each miniature heat exchanger will be calculated based on the averaged temperature for each fluid and for the walls in each node during the previous iteration (to be described below). Since the heat transfer areas on the shell-side and tube-side for a finned-tube bundle are not equal, the overall heat transfer coefficient is conventionally referenced to the shell-side. The steady-state heat transfer rate for the K^{th} node can be expressed as:

$$Q_K = (U)_K \, (A_g)_K \left[(\bar{T}_g)_K - (\bar{T}_\ell)_K \right] \qquad (6)$$

where the subscripts g and ℓ denote the gas and liquid sides, respectively. The term, U, represents the overall heat transfer coefficient determined from the film coefficient of the working fluids on both sides of the tubes and the thermal conductivity of the tube material.

The averaged fluid temperatures of the gas and liquid (T_g and T_ℓ) are functions of the heat transfer rate between these fluids. For example the averaged gas temperature is

$$(T_g)_K = 1/2 \left[(T_g)_{in_K} + (T_g)_{out_K}\right] \tag{7}$$

and

$$(T_g)_{out_K} = \left[(T_g Cp_g)_{in_K} - \frac{\dot{Q}_K}{(M_g)_K}\right] \Big/ (Cp_g)_{out_K} \tag{8}$$

By definition, the inlet temperature for this node is the outlet temperature of the previous node (or the gas supply temperature if this is the initial node for the path containing this node). Similarly, for the liquid side:

$$(T_\ell)_K = 1/2 \left[(T_\ell)_{in_K} + (T_\ell)_{out_K}\right] \tag{9}$$

and

$$(T_\ell)_{out_K} = \left[(T_\ell Cp_\ell)_{in_K} - \frac{\dot{Q}_K}{(M_\ell)_K}\right] \Big/ (Cp_\ell)_{out_K} \tag{10}$$

Substituting Eqs. (7) through (10) into Eq. (6), one obtains

$$\dot{Q} = \left[(T_g)_m\ (1+\beta_g) - T_\ell)_m\ (1+\beta_\ell)\right] \Big/ \left[\frac{2}{UA_g} + \frac{1}{M_g (Cp_g)_{out}} + \frac{1}{M_\ell (Cp_\ell)_{out}}\right] \tag{11}$$

where $\beta = (Cp)_{in}/(Cp)_{out}$, and the subscript K has been omitted in Eq. (11) to facilitate typing.

The temperature distributions in gas, liquid and the tube walls of the waste heat boiler were calculated using a relaxation method. This method is described as follows: The averaged temperature of each fluid and of the walls at each node estimated during the previous iteration was used to calculate the thermal properties and the heat transfer coefficients for each fluid. At the completion of each iteration, the outlet temperatures at the last node in each path on each side of the working fluid were compared with those calculated during the previous iteration. If all outlet temperatures were within a specified tolerance, the iteration was then terminated. Otherwise, the new averaged fluid temperatures, together with the new wall temperatures, were used as bases for the next iteration. It should be mentioned that, for the steady-state operation, the inlet condition were used as the initial guesses of the average temperature distribution for each path. This simple iteration algorithm was shown to be quite stable for most cases analyzed by the authors. Typically convergence occurs within fifteen iterations with a convergent tolerance of 5 degree F.

II.1.5 Development of Computer Program

In order to minimize the computer program development effort, the existing fuel vaporization heat exchanger program was updated to satisfy the study objective. This modification was made with permission and assistance from Messrs. Chiappetta and Szetela. The modification included allowance for: (1) isothermal vaporization; (2) variable nodal size, (3) use of water as the working fluid; and (4) inclusion of overall size and cost estimates. Description of this computer program, which includes the program capability and input/out format, is given in Appendix A.

II.2 Design and Off-Design Flow Condition

The shell-side flow distribution and flow condition at the inlet to the waste heat boiler are obtained from the Phase-I study (Ref. 2.3). In Figs. II.2 and II.3, two typical diffuser flow distributions are shown for a gas turbine operating at 50% power with and without flow distribution control. The flow distribution and flow conditions at the exit of the diffuser were calculated for each of the several sections which extend the entire width of the flow paths, as shown in Fig. II.1. The resulting flow conditions are tabulated in Figs. II.4 and II.5 for gas turbine operated at 100- and 50-percent power, respectively. Three different sets of flow distribution data are presented for each operating condition, namely, a uniform flow distribution, an actual flow distribution without control, and an actual flow distribution with control. For the first two data sets, the flow was divided into five paths equally spaced while for the third data set, the flow was divided into six paths because a pressure difference exists between the two sides of the flow guide vane. The averaged flow distribution data were used as input conditions to the parametric performance analyses which are discussed as follows.

II.3 Parametric Performance Analyses

Parametric performance analyses of the waste heat steam generator were made using the computer program discussed in Section II.1.5. The parameters, which were varied, included: (1) the tube arrangement, (2) the effective tube length, and (3) the water flow rate. The uniform gas flow distribution data presented in Figs. II.4 and II.5 were used as a reference for comparison with the results of the nonuniform flow cases. The range of the parameters used were based on the following rationales.

As noted in Section I.3, the candidate steam generator selected was a once-through, counter crossflow design. For this design, optimal heat transfer surface geometry and the tube arrangement still had to be determined in order to define its most efficient performance. Four different tube design configurations, depicted in Fig. II.6, were obtained from Ref. 2.1. Each configuration is comprised of circular finned tubes with tube diameter equal either to 1.024 inch or to 0.774 inch. For each tube diameter, two different longitudinal and transverse pitches and fin geometries were considered. The effect of the tube designs on the performance of the candidate waste-heat boiler were then investigated.

The next parameter determined was the effective tube length which is related to the following factors: (1) ease of installation and removal in the ship (i.e. maximum height of each heat transfer module should be less than 8 ft); (2) acceptable thermal gradient within each node (assumed to be equal to or less than 25°F for numerical stability); and (3) design and manufacture of boiler tubes according to the ASME Boiler Codes. With those concerns in mind, the maximum nodal width (Δx_i) would be approximately 24 inches, and the maximum nodal height, (Δy_i) would be approximately 4 inches. The best tube arrangement which would meet these constraints is shown in Fig. II.7. Based on this tube arrangement, the maximum effective tube length was estimated to be approximately 200 ft.

The maximum water flow was calculated from an energy balance. From the Phase-I study, it was determined that the flow rates of the gas turbine engine exhaust were approximately 160 lb/sec and 100 lb/sec for full-load and half-load operation, and that the corresponding temperatures were 856°F and 796°F, respectively. If the gas exit temperature from the waste heat boiler were kept above 300F to avoid sulfuric-acid condensation (or corrosion) problems, the maximum amount of heat that could be recovered would be approximately 21 MW and 12 MW for engines operated at 100-percent and 50-percent power, respectively. Assuming that the feed water enters the waste heat boiler at 115.7°F (corresponding to a condenser pressure of 3 inch Hg.) and 300 psia, and leaves the boiler as a superheated steam, the maximum water flow rates for a gas turbine operated at 100-percent and 50-percent power would be approximately 18 lb/sec and 11 lb/sec, respectively. In parametric performance analyses, the water flow rates were varied in increment of 0.5 lb/sec per step to investigate the effect of this factor on the performance of the waste-heat boiler.

After the values of all parameters were defined, the parametric performance analyses were conducted. The results of these analyses (which are presented in terms of steam temperature, gas exit temperature, gas side pressure loss, and overall heat transfer rate as function of water flow rate) for all four tube-design configurations and for gas turbine operated at full power are shown in Figs. II.8 through II.11. The water-side pressure loss is not shown because the pumping power required for pressurizing the water has essentially no effect on the cycle efficiency. Results shown in Figs. II.8 through II.11 indicate that the arrangements of tube design indeed have a significant effect on the performance of the waste-heat boiler. Generally speaking, Configuration 1 would perform better than Configurations 3, 2, and 4 in that order if boiler efficiency were the only concern.

Figure II.8 shows that, for a given tube design configuration, the water flow rate can be regulated to yield a wide range of steam temperatures desired. However if the water flow rate were greater than 15.6 lb/sec for Configuration No. 3 (Fig. II.6) a wet steam would be produced. If the water flow rate were too low, the boiler would operate below its attainable efficiency (see Fig. II.11). The experience gained at UTRC from studies of waste-heat recovery systems indicates that a 700-degree Fahrenheit steam at approximately 300 psia would be a practical design for a Rankine-cycle power conversion system application. Therefore, this steam condition was selected as reference in the final selection of a baseline design of waste heat boiler for naval applications.

In order to examine the sulfuric-acid condensation problem on the cold end of the waste heat boiler, the gas exit temperatures were plotted as a function of the water flow rate for all four tube design configurations; these data are shown in Fig. II-9. The constant temperature lines (shown in dash-line) were obtained from Fig. II.8. It is seen that for an effective tube length of 200 ft, the gas exit temperature would be between 370°F and 480°F, or well above the sulfuric corrosion formation temperature of 300°F. Another implication of these data is that it is possible to improve the waste-heat boiler performance by increasing the overall heat transfer area if there is no space limitation and if the gas-side pressure loss can be tolerated.

The effects of tube design configuration and water flow rate on the gas-side pressure loss and on the overall heat transfer rate are shown in Figs. II.10 and II.11, respectively. It can be seen from these figures that the pressure loss varied between 0.7 psia and 2.0 psia for the parameter ranges considered. These pressure loss values were used in identifying the correction factor for gas turbine output power which will be discussed later (Section II.5).

II.4 Off-Design Performance Analysis

In order to compare the performance characteristics of a given waste heat boiler design at different operating conditions, the uniform flow distribution data presented in Fig. II.5 for gas turbines operated at 50-percent power were also considered. The results of this parametric performance analysis were compared with those obtained previously based on the design-point conditions. In Figs. II.12 through II.15, these comparisons are shown in terms of steam temperature, overall heat transfer rate, gas exit temperature, and gas-side pressure loss, respectively. The solid lines are results for gas turbine operated at 100-percent power and the dotted lines are for 50-percent power cases. The relationships of performance to tube design configuration is presented in detail in the following Section (II.5).

Figure II.12 shows that if these candidate waste-heat boilers (Configurations 1 through 4) were integrated with a given gas turbine which was operated at half-load, the water flow rate must be reduced significantly in order to generate the same quality steam (i.e. with the same steam temperature). For example, if the steam temperature required is 700°F, the water flow rate would have to be between 6.8 and 8.4 lb/sec for gas turbine operated at half power, and between 11.0 and 14.5 lb/sec for gas turbine operated at full power. The overall heat transfer characteristics which correspond to these operating conditions are shown in Fig. II.13. There, it can be seen that the maximum heat transfer rate attainable by these candidate boilers would range between 9600 and 11500 Btu/sec at half power and between 15400 and 19400 Btu/sec at full power of the gas turbine engine considered (LM 2500 or similar model).

The gas exit temperature and the gas-side pressure loss characteristics for the waste-heat boilers are shown in Figs. II.14 and II.15. It is seen that the lowest gas temperature shown in Fig. II.14 still exceeds 300°F, which implies that the sulfuric corrosion would not occur. Figure II.15 shows that when these candidates waste-heat boilers were integrated with gas turbine at 50-percent power, the gas turbine back pressure would be between 0.3 and 0.8 psia, indicating that those tube design configurations are technically acceptable from the turbomachinery performance view point.

II.5 Baseline Waste Heat Boiler

The background information which was used to select a baseline design configuration for waste-heat boiler in marine propulsion applications are presented in Figs. II.16 through II.19. Figure II.16 summarizes the performance characteristics of four candidate tube design configurations at steam temperature of 700°F for a gas turbine operated at 100-percent power. Similar performance data for a gas turbine operated at 50-percent power are presented in Fig. II.17.

Based on the heat transfer rate shown on the far right frame of Figs. II.16 and II.17, Configuration No. 1 would yield better performance than Configuration No. 3, No. 2 and No. 4 in that order. However, the gas-side pressure losses for these boiler configurations also decreases in the same order. Unfortunately the higher the gas-side pressure loss, the higher is the back pressure to the gas turbine, and according to the correction factor for exhaust pressure loss shown in Fig. II.18 the greater will be the loss in turbine power output.

It is known that a most desirable waste-heat boiler design should be one which can provide the greatest net gain in power output when coupled with a Rankine cycle power conversion system. In order to evaluate the net gain in power output, the cycle efficiency of the Rankine cycle power conversion system must be identified. From the results of a waste-heat recovery system study conducted at UTRC (Ref. 2.9), it was determined that, for steam condition of 700°F and 3000 psia and a condenser pressure of 3 inch Hg, the cycle efficiency of a typical steam Rankine system is approximately 22 percent. Therefore, the net gain in overall power system is equal to the difference between the Rankine cycle power output and the loss in gas turbine output power due to the increased back pressure. The results of this comparison is shown in Fig. II.19.

The left frame of Fig. II.19 shows the net-gain power for a gas turbine operated at 100-percent power. It was found that Configurations No. 2 and No. 4 would provide almost equal value of net-gain power and this gain is substantially higher than that estimated for the other two configurations. In contrast, the right frame of the same figure shows that at a 50-percent (gas turbine) power condition, Configuration No. 3 is the most desirable selection. Because improvement in the propulsion system efficiency at cruise conditions is of primary concerns in naval ship operation, Configuration No. 3 was selected as baseline design configuration for the marine gas turbine waste-heat steam generator application. The design conditions of the baseline waste-heat boiler can now be defined as those which correspond to gas turbines operated at 50-percent power, and off-design conditions are defined as those where gas turbines operate at any power level other than the 50-percent point.

The temperature distribution inside the baseline waste heat boiler operated at its design condition (as defined immediately above) is shown in Fig. II.20, and the overall heat transfer coefficients (defined as UA in Equation 6) are shown in Fig. II.21. These results were obtained from performance calculations using the miniature heat exchanger approach and the nodal system. Similar information for off-design condition (corresponding to gas turbine 100-percent power) are shown in Figs. II.22 and II.23. From the temperature distribution maps (Figs. II.20 and II.22), it was determined that this waste-heat boiler can be divided into three distinctive regions; a liquid-phase heating region, a boiling-phase region, and a superheated-vapor region. In liquid-phase region, which occupies about one-third of the upper portion of the boiler, the feedwater is heated from 115°F to its saturation temperature (which is 417°F for steam pressure of 300 psia). In the boiling-phase region, which is shown by a shaded boundary and occupies approximately 60 percent of the boiler volume, the feedwater would go through an isothermal boiling process. After boiling, the saturated steam would be superheated in the last 10 percent of the boiler whereupon it would be discharged at 700°F.

From these two temperature distribution maps in Figs. II.20 and II.21, it was determined that the temperature gradient between any two nodes is less than 20°F and relatively uniform under the two steady-state operations. Therefore, the thermal stress concentration should not be a problem. However, based on the performance and design requirements, the water velocity was calculated to be approximately 0.5 to 1.2 ft/sec and the gas velocity was approximately between 80 to 130 ft/sec. The transient response of heat transfer characteristics and thermal stress concentration could become severe under the dry-running or changing load operations and this should be investigated before the final design is undertaken.

The product of the overall heat transfer coefficient (U) and the gas side heat transfer areas (Ag) for all nodes (miniature heat exchangers) are shown in Figs. II.21 and II.23 for baseline waste heat boiler operated at design (gas turbine 50-percent power) and off-design (gas turbine 100-percent power) condition, respectively. These values were computed using the averaged temperatures shown in Figs. II.20 and II.22. From these results, it was determined that the value of UA varied between 1720 and 2585 Btu/hr-F for the design condition and between 2100 and 3000 Btu/hr-F for the off-design operation. It is believed that those values are mainly determined by the gas-side film coefficient rather than by the water-side film coefficient, and are generally within the range of current design practices.

II.6 Effect of Flow Distribution Control on Baseline Waste-Heat Boiler

The actual flow distribution data with and without flow distribution control (see Figs. II.4 and II.5) were used as input to the analytical model for analyzing the effect of flow distribution-control on the performance of the baseline waste heat boiler. The results of this analysis are presented in Figs. II.24 to II.31.

The effects of flow distribution control on steam temperature of the baseline waste heat boiler operated at design (gas turbine 50-percent power) and off-design (gas turbine 100-percent power) conditions are shown in Figs. II 24 and II.25, respectively. It should be noticed that only those water flow rates which can provide superheated steam were considered. The steam temperatures attainable for the uniform flow distribution, actual flow distribution with and without flow distribution controls cases are shown in solid, dashed, and semi-broken lines, respectively. These results show that if the baseline waste heat boiler were designed for uniform flow distribution and for generated steam 700°F, and if it were operated with actual flow distribution without flow distribution, the steam temperature would decrease to approximately 450°F. However, the steam temperature could be maintained at 700°F if the water flow rate were reduced from .9 lb/sec to 6.6 lb/sec. If this occurred, the overall heat transfer rate would be reduced from 10167 to 8540 Btu/sec. On the other hand, from Fig. II.24, it can be seen that if flow distribution control were employed and if the water flow rate were maintained at its design condition (7.9 lb/sec), the steam temperature would increase by approximately 25°F. Alternately, if the steam temperature were to be maintained at the design condition (700°F), the water flow would increase to 8.1 lb/sec. The factors attributing to this improvement in boiler efficiency are believed to be partly attributable to more uniform flow distribution and partly to increased gas flow rate in boundary layer separation control (see Fig. II.3).

The heat transfer performance characteristics of the baseline waste heat boiler operated at design and off-design condition for cases with and without flow distribution controls are shown in Fig. II.26. Again the solid lines represent the results of the assumed uniform flow condition, and the dash lines and semi-broken lines are for cases with and without flow distribution controls. The asterisk represents the conditions where the 700°F steam would be generated. One can readily see that significant improvement in boiler efficiency would be expected if flow distribution controls were employed. The percentage of the boiler efficiency improvement is shown in Fig. II.27 for the baseline waste-heat boiler operated at its design condition.

In Fig. II.27 which illustrates the effect of flow distribution control on the performance of a waste-heat boiler, the overall heat transfer rate for the assumed uniform flow distribution was used as reference. The overall heat transfer rates for constant water (or steam) flow rate and for constant steam temperature were obtained from Fig. II.26. In Fig. II.27 it can be seen that, without flow distribution control (blank bars), if the water flow rate were held constant at 7.9 lb/sec, the overall heat transfer rate would be reduced by approximately 10 percent which, in turn, would lower the steam temperature by approximately 250°F. On the other hand, if the water flow rate were regulated so as to maintain a constant steam temperature of 700°F, the overall heat transfer rate would be reduced by approximately 16 percent. Although this loss is greater than that for the constant flow rate case, a constant-steam-temperature operation would probably be more suitable for Rankine cycle power conversion system applications. Similarly, the shaded bars shown in the same figure are for the results with flow distribution control. It was found that approximately a 20 percent improvement in boiler efficiency would be expected for the baseline waste heat boiler if flow distribution control were considered.

The predicted temperature distribution for the baseline waste-heat boiler operating at design conditions and based on the actual velocity data with and without flow distribution controls are shown in Figs. II.28 and II.29, respectively; the corresponding overall heat transfer coefficients for these two flow cases are shown in Figs. II.30 and II.31. From Figs. II.28 and II.29, it is seen that the gas temperature near the exit becomes highly nonuniform, and that this nonuniformity is more apparent in the absence of flow distribution controls. This temperature distribution nonuniformity is certain to cause uneven thermal expansion in the heat-exchanger tubes, which in turn may result in thermal stress concentration problems. It is also seen that due to the no-flow condition occurring in the far-right column (uncontrol case), the gas temperatures and the liquid temperature may be in equilibrium (see Fig. II.28), indicating a region of "no-heat-transfer" within the waste-heat boiler (see Fig. II.30). The performance degradation of the waste-heat boiler can then be expected when no proper flow distribution control methods are implemented.

The effects of gas inlet temperature on the baseline waste heat boiler performance were also investigated and the results obtained are shown in Fig. II.32. From these results, it can be seen that change in gas inlet temperature would have more profound effect on the baseline waste heat boiler performance under constant steam temperature operation than under constant steam flow rate operation.

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TABLE II.1

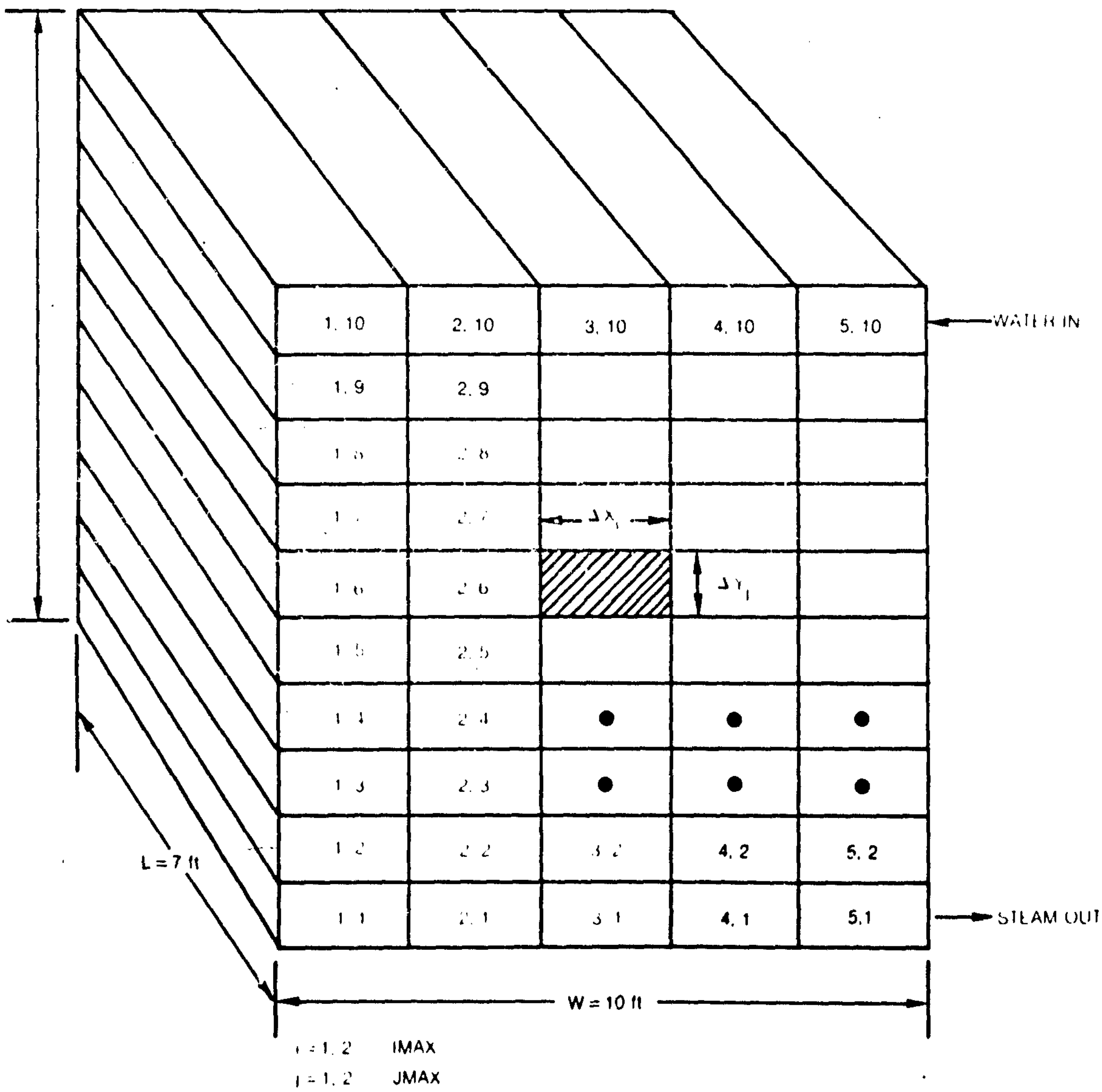
(A) Constant for Equation (1a), (1b), and (1c)

Laminar Flow :	$C_1 = 0.595$	$C_2 = 0.498$	$C_3 = 0.140$	
Turbulent Flow :	$C_1 = 0.0046$	$C_2 = 0.927$	$C_3 = 0.628$	
Supercritical Flow:	$C_1 = 0.003354$	$C_2 = 0.951$	$C_3 = 0.435$	$C_4 = 0.38$

(B) Constant for Equations (4a), (4b), (4c), (5a), and (5b)

	Turbulent-Turbulent $NRe_f>2000$, $NRe_g>2000$	Viscous-Turbulent $NRe_f<1000$, $NRe_g>200$	Turbulent-Viscous $NRe_f>2000$, $NRe_g<1000$	Viscous-Viscous $NRe_f<1000$, $NRe_g<1000$
m	0.25	0.25	1.0	1.0
n	0.25	1.0	0.25	1.0
C_ℓ	0.079	16.0	0.079	16.0
C_ν	0.079	0.079	16.0	16.0
N	4.0	3.50	3.50	2.75*

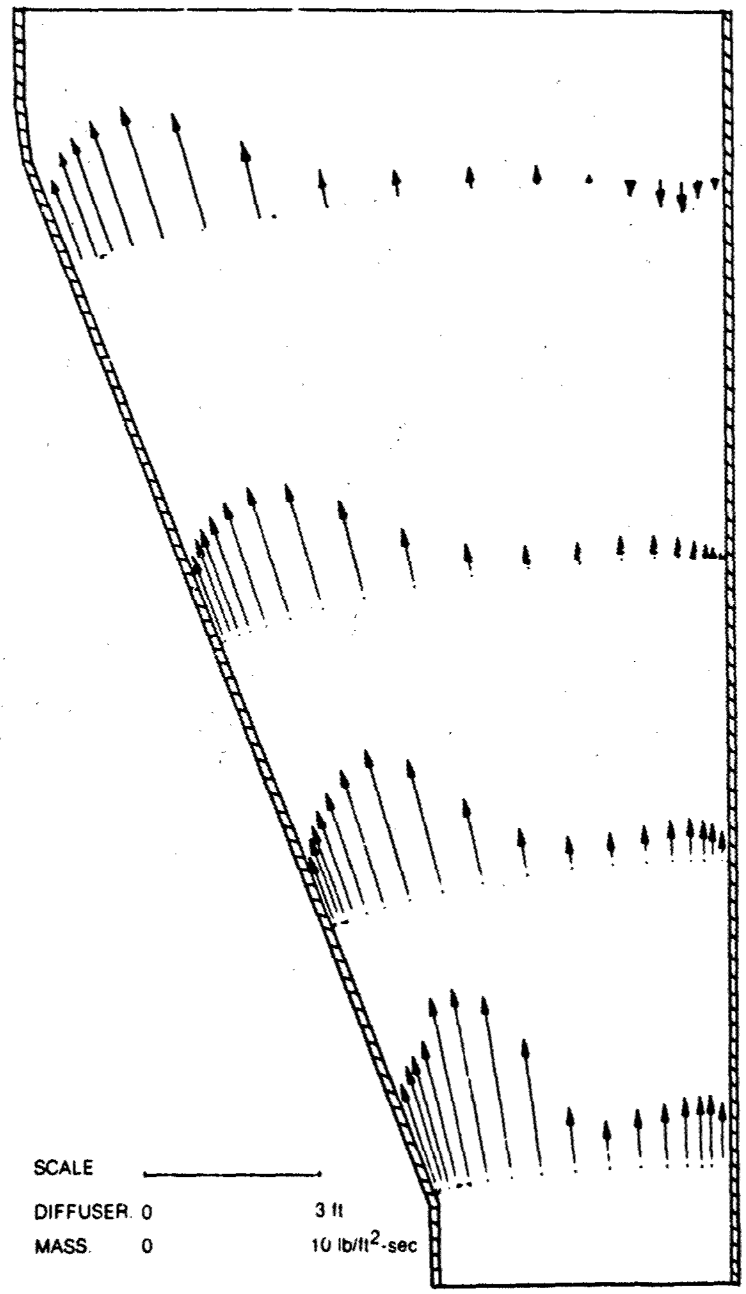
NODALIZATION OF MARINE G[illegible]BINE WASTE HEAT STEAM GENERATOR



81-12-58-6

ACTUAL FLOW DISTRIBUTION WITHOUT FLOW DISTRIBUTION CONTROL

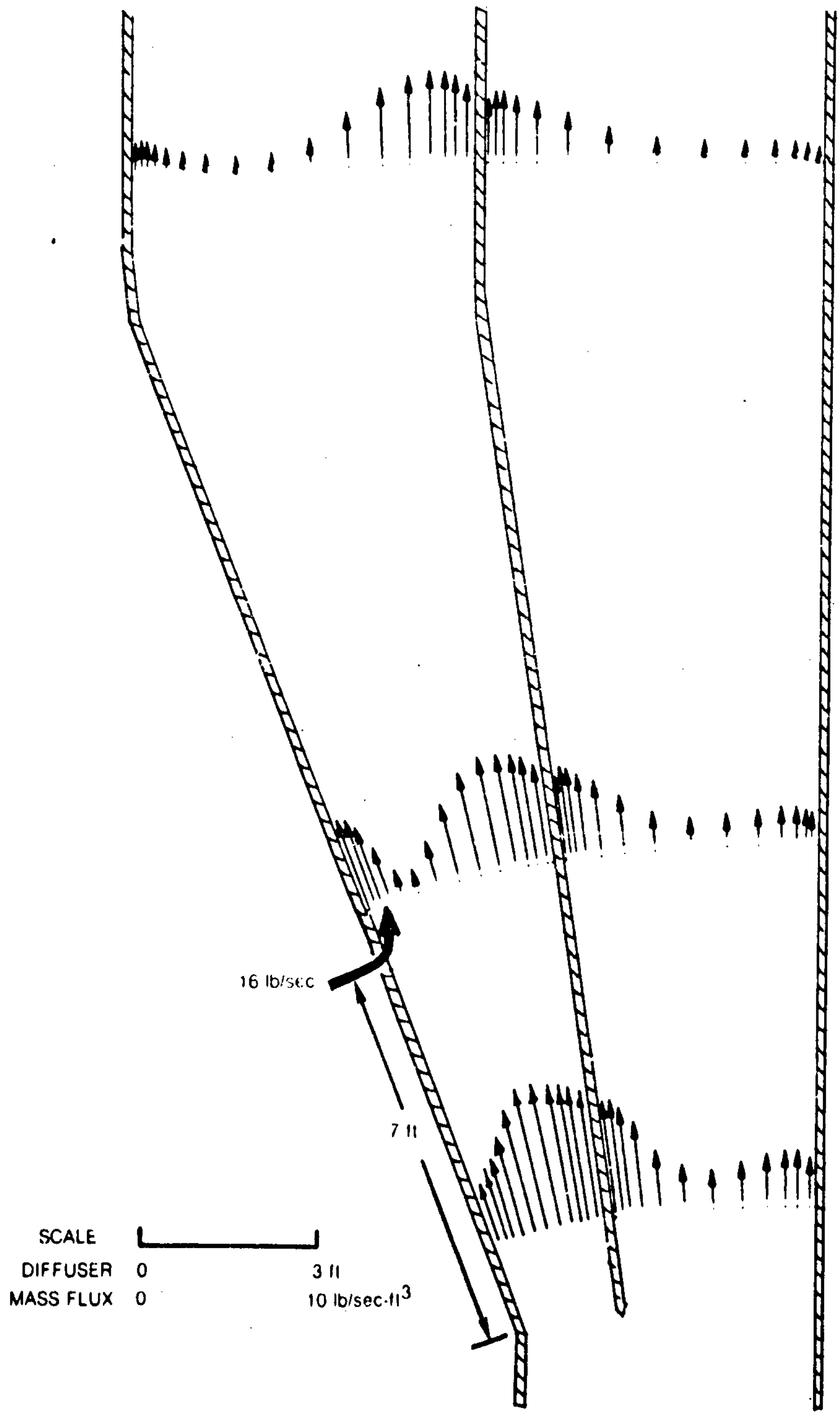
- GAS TURBINE 50% POWER



81-6-96-19

ACTUAL FLOW DISTRIBUTION WITH FLOW DISTRIBUTION CONTROL

- GAS TURBINE 50% POWER



81-6-158-8

GAS FLOW INLET CONDITIONS FOR MARINE GAS TURBINE WASTE HEAT BOILER — GAS TURBINE 100% POWER

ΔX = WIDTH OF THE GAS FLOW PATH, (in.)

$\dot{M}$ = AVERAGED FLOW RATE, (lb/sec)

P = AVERAGED STATIC PRESSURE, (psia)

T = AVERAGED STATIC TEMPERATURE, (°F)

FLOW DISTRIBUTION	AVERAGED FLOW PARAMETERS						
	PARA.	GAS FLOW PATH NUMBER					
		1	2	3	4	5	6
UNIFORM FLOW	ΔX	24	24	24	24	24	—
	$\dot{M}$	32	32	32	32	32	—
	T	856	856	856	856	856	—
	P	14.94	14.94	14.94	14.94	14.94	—
ACTUAL FLOW DISTRIBUTION WITHOUT CONTROL	ΔX	24	24	24	24	24	—
	$\dot{M}$	80.3	50.6	15.5	13.6	0.0	—
	T	856	856	856	856	856	—
	P	14.90	14 90	14.90	14.90	14.90	—
ACTUAL FLOW DISTRIBUTION WITH CONTROL	ΔX	24	24	12	12	24	24
	$\dot{M}$	16.7	45.8	33.4	27.3	33.8	19.0
	T	856	856	856	856	856	856
	P	14.96	14.96	14.96	14.89	14.89	14.89

82-5-86-18

GAS FLOW INLET CONDITIONS FOR MARINE GAS TURBINE WASTE HEAT BOILER — GAS TURBINE 50% POWER

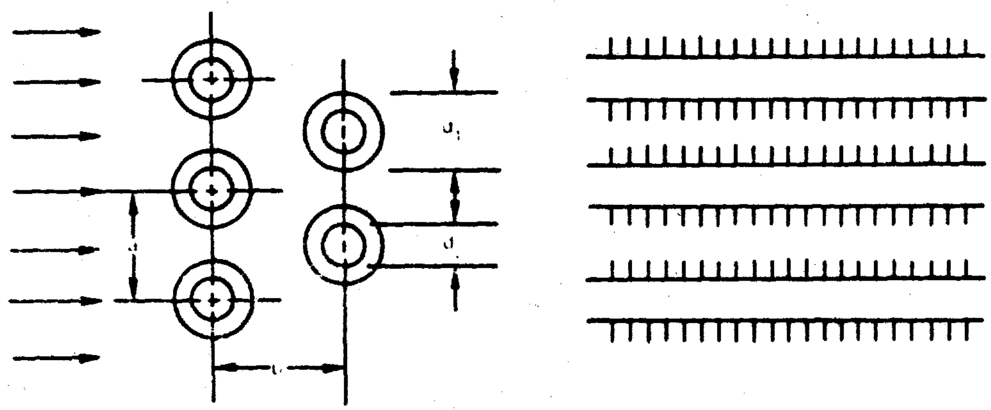
ΔX = WIDTH OF THE GAS FLOW PATH, (in.)
$\dot{M}$ = AVERAGED FLOW RATE, (lb/sec)
P = AVERAGED STATIC PRESSURE, (psia)
T = AVERAGED STATIC TEMPERATURE (°F)

FLOW DISTRIBUTION	AVERAGED FLOW PARAMETERS						
	PARA	GAS FLOW PATH NUMBER					
		1	2	3	4	5	6
UNIFORM FLOW	ΔX	24	24	24	24	24	—
	$\dot{M}$	20	20	20	20	20	—
	T	796	796	796	796	796	—
	P	14.83	14.83	14.83	14.83	14.83	—
ACTUAL FLOW DISTRIBUTION WITHOUT CONTROL	ΔX	24	24	24	24	24	—
	$\dot{M}$	50.2	31.6	9.7	8.5	0.0	—
	T	796	796	796	796	796	—
	P	14.82	14.82	14.82	14.82	14.82	—
ACTUAL FLOW DISTRIBUTION WITH CONTROL	ΔX	24	24	12	12	24	24
	$\dot{M}$	10.4	28.6	20.9	17.1	21.1	11.9
	T	796	796	796	796	796	796
	P	14.84	14.84	14.84	14.82	14.82	14.82

82-5-86-17

CONFIGURATIONS OF CIRCULAR FINNED TUBES FOR MARINE WASTE-HEAT BOILER APPLICATION

(FROM COMPACT HEAT EXCHANGER BY KAYS AND LONDON)



TUBE DESIGN CONFIGURATION	a (in.)	b (in.)	d_1 (in.)	d_2 (in.)	FINS/inch
1	[illegible]	[illegible]	[illegible]	[illegible]	8.8
2	[illegible]	[illegible]	[illegible]	[illegible]	8.8
3	[illegible]	[illegible]	[illegible]	[illegible]	9.05
4	[illegible]	[illegible]	[illegible]	[illegible]	9.05

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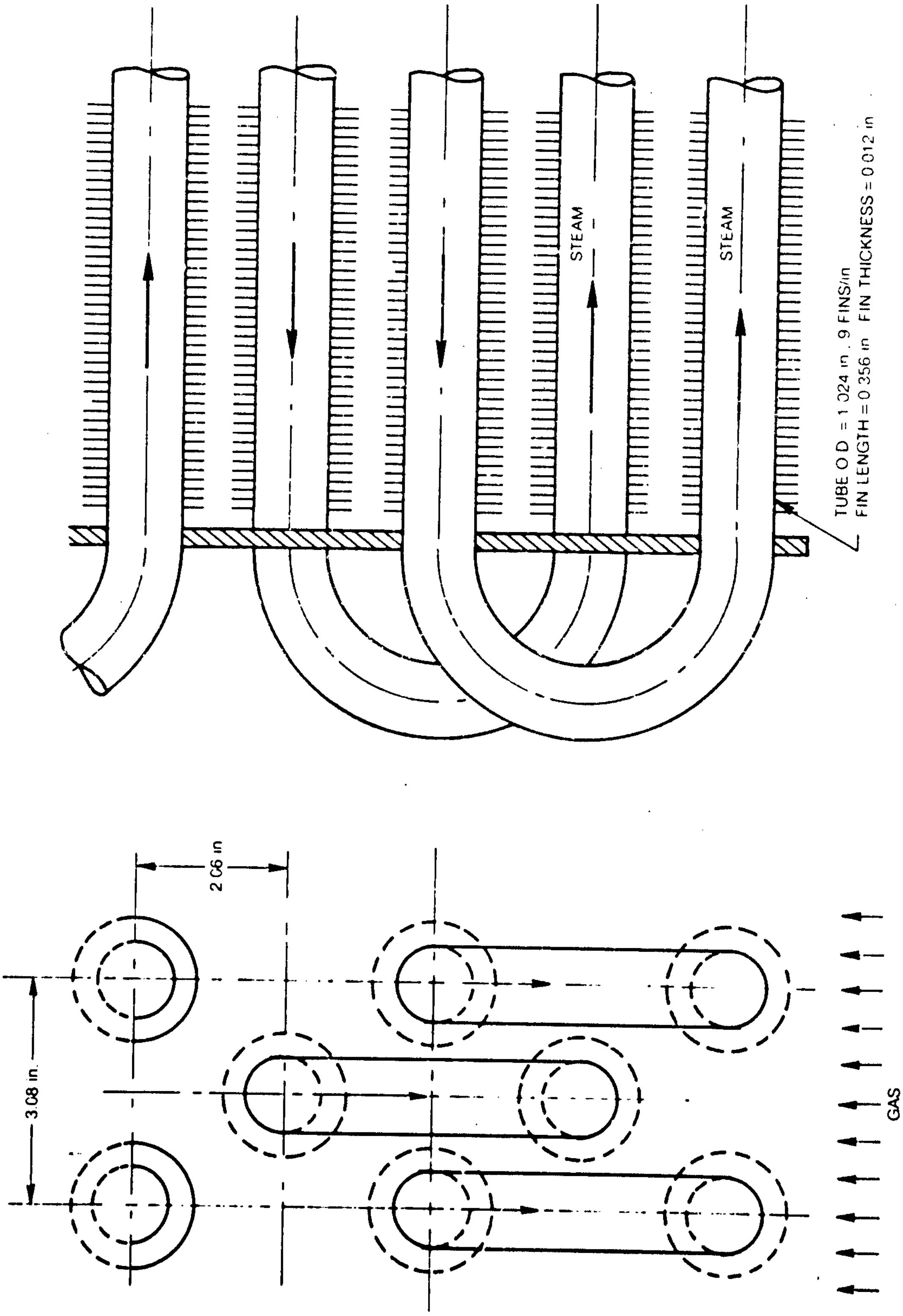
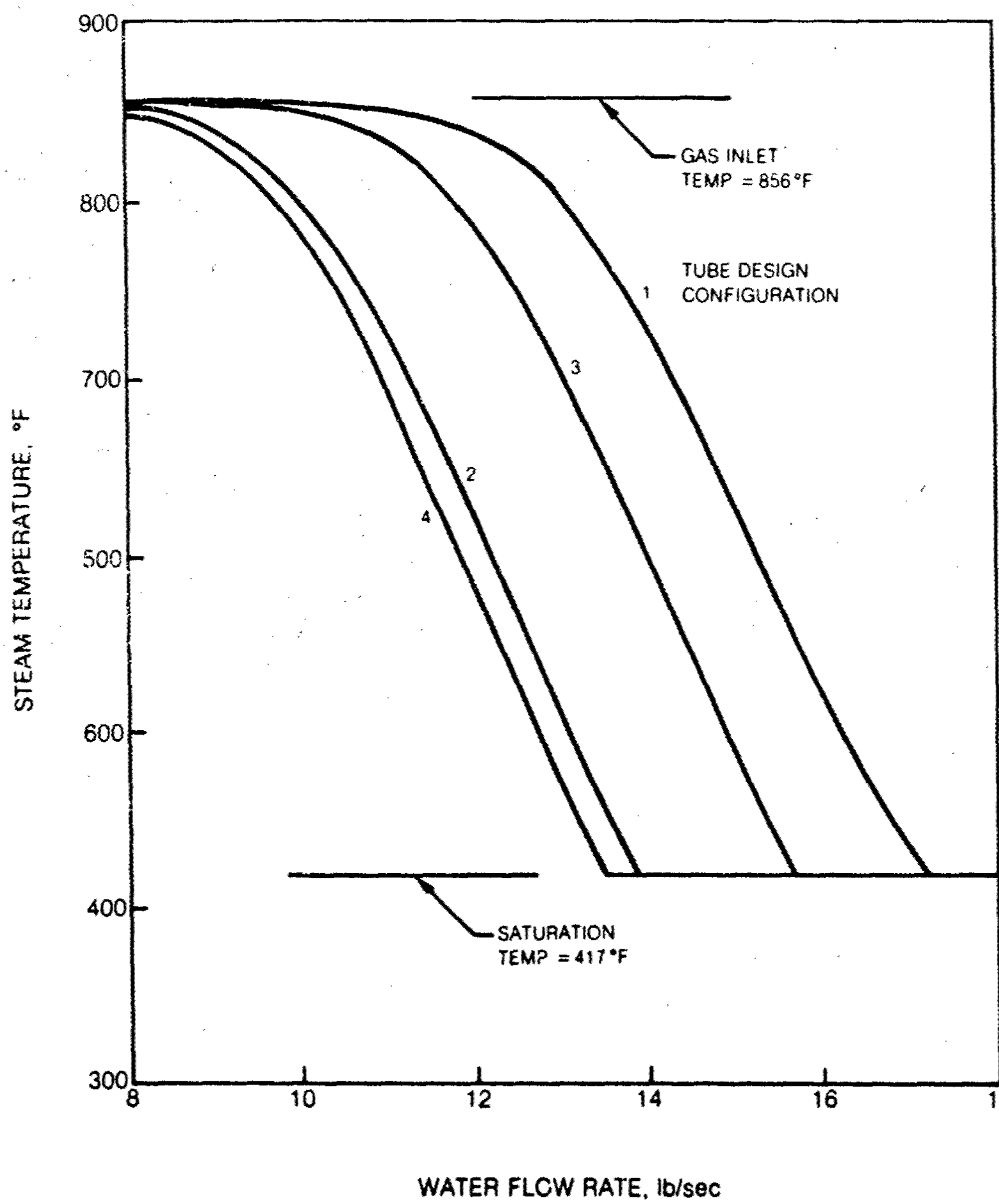
FIG. II.7

TUBE ARRANGEMENT FOR MARINE GAS TURBINE WASTE-HEAT STEAM GENERATOR APPLICATIONS



EFFECT OF TUBE DESIGN CONFIGURATION AND WATER FLOW RATE ON STEAM TEMPERATURE — GAS TURBINE 100% POWER

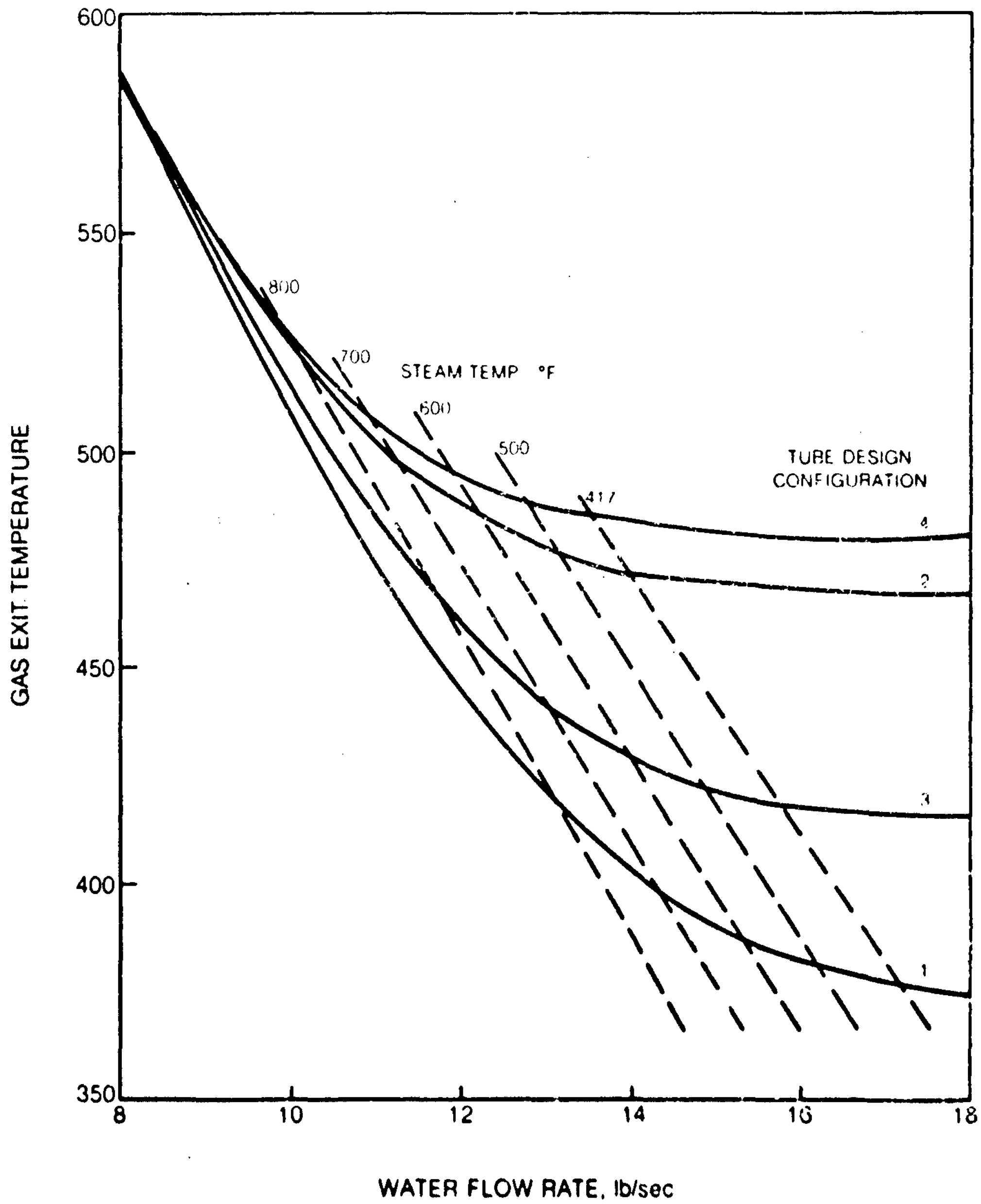
- GAS INLET CONDITION UNIFORM (160 lb/sec, 14.94 psia)
- WATER INLET CONDITION UNIFORM, 115.7 °F, 300 psia
- EFFECTIVE TUBE LENGTH = 200 ft



82-5-86-16

EFFECT OF TUBE DESIGN CONFIGURATION AND WATER FLOW RATE ON GAS EXIT TEMPERATURE — GAS TURBINE 100% POWER

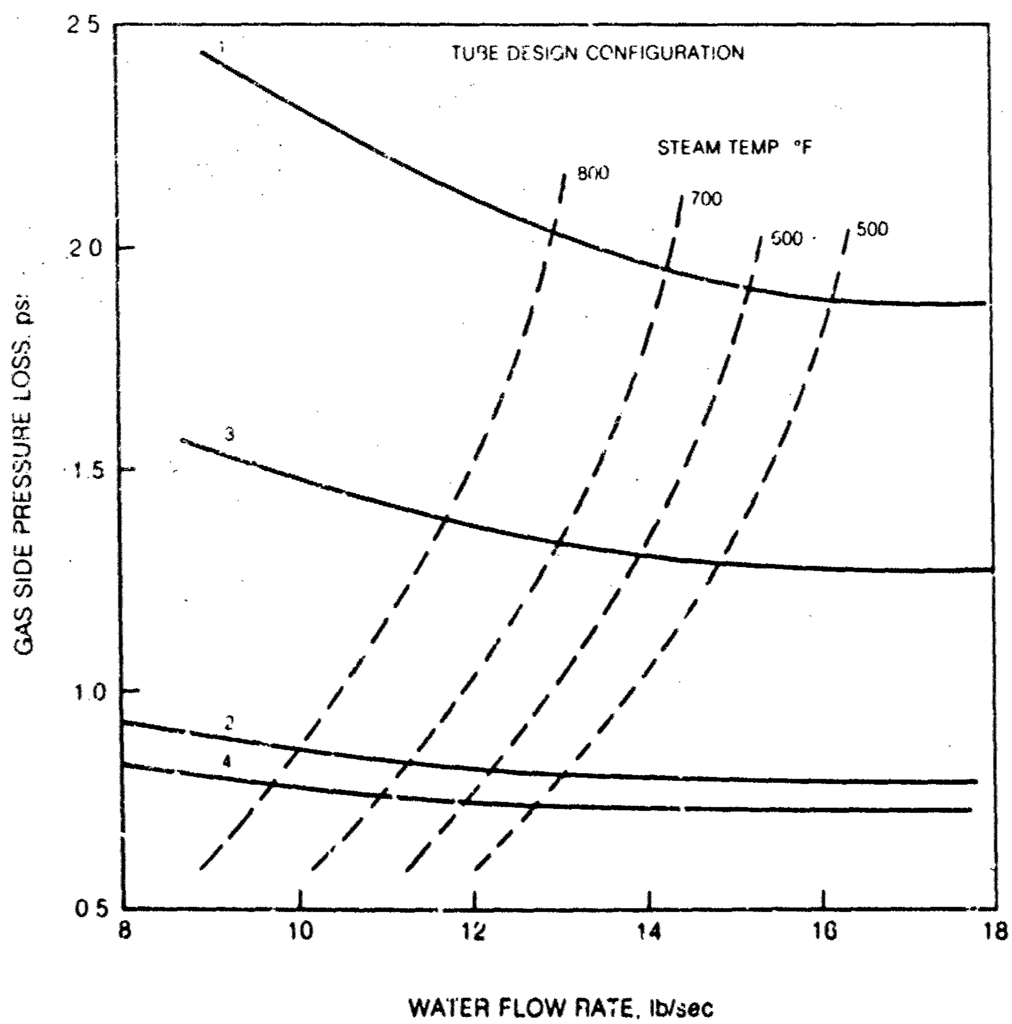
- GAS INLET CONDITION UNIFORM (160 lb/sec 14.94 psia)
- WATER INLET CONDITION UNIFORM (115.7°F, 300 psia)
- EFFECTIVE TUBE LENGTH - 200 ft



82-9-86-18

EFFECT OF TUBE DESIGN CONFIGURATION AND WATER FLOW RATE ON GAS SIDE PRESSURE LOSS — GAS TURBINE 100% POWER

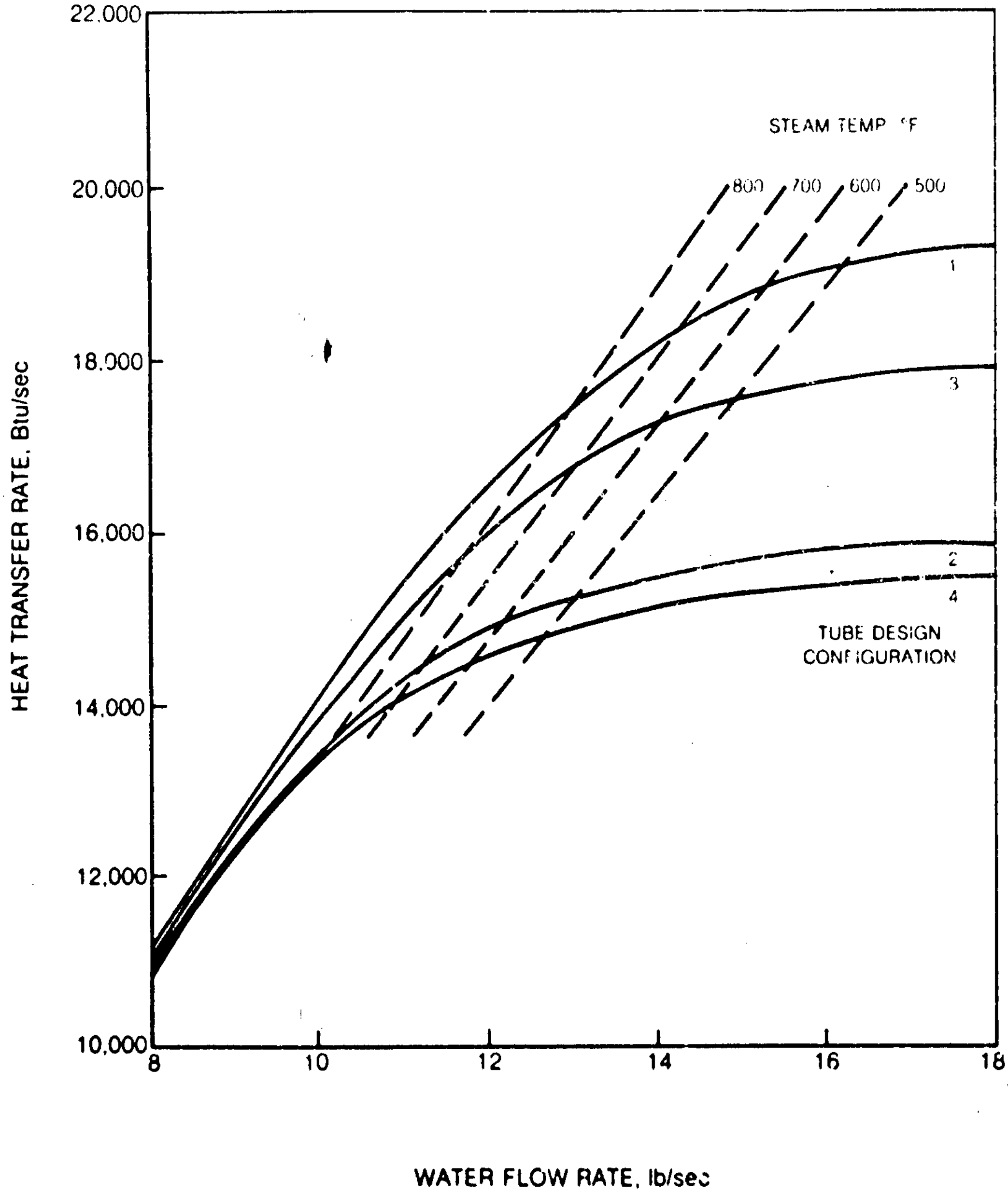
- GAS INLET CONDITION UNIFORM (160 lb/sec, 14.94 psia)
- WATER INLET CONDITION UNIFORM (115.7°F, 300 psia)
- EFFECTIVE TUBE LENGTH = 200 ft



82-6-86-13

EFFECT OF TUBE DESIGN CONFIGURATION AND WATER FLOW RATE ON HEAT TRANSFER RATE — GAS TURBINE 100% POWER

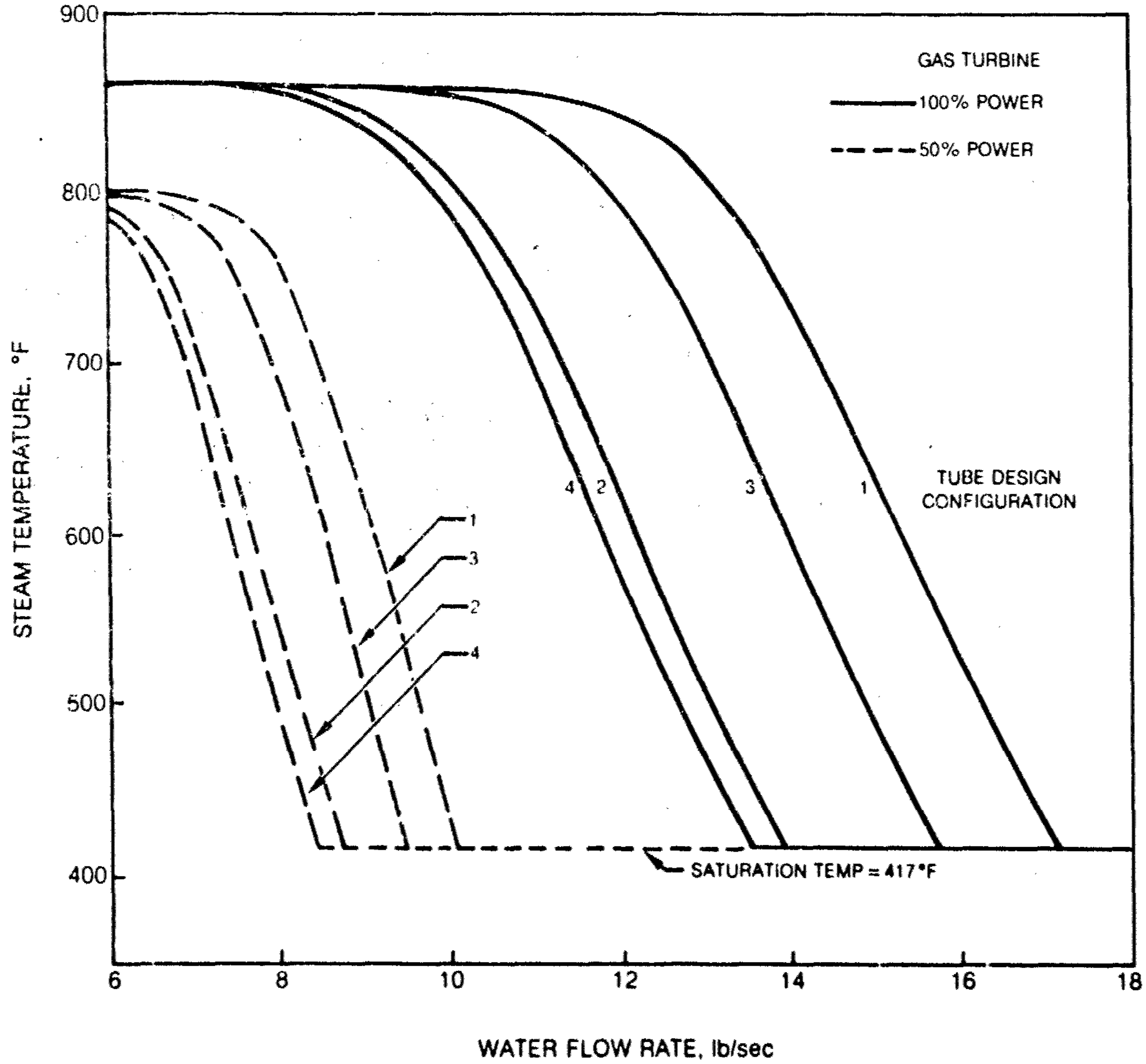
- GAS INLET CONDITION UNIFORM (160 lb/sec, 14.94 psia)
- WATER INLET CONDITION UNIFORM (115.7°F, 300 psia)
- EFFECTIVE TUBE LENGTH - 200 ft



82-8-86-12

COMPARISON OF STEAM TEMPERATURE FOR WASTE HEAT BOILERS OPERATED AT DESIGN AND OFF-DESIGN CONDITIONS

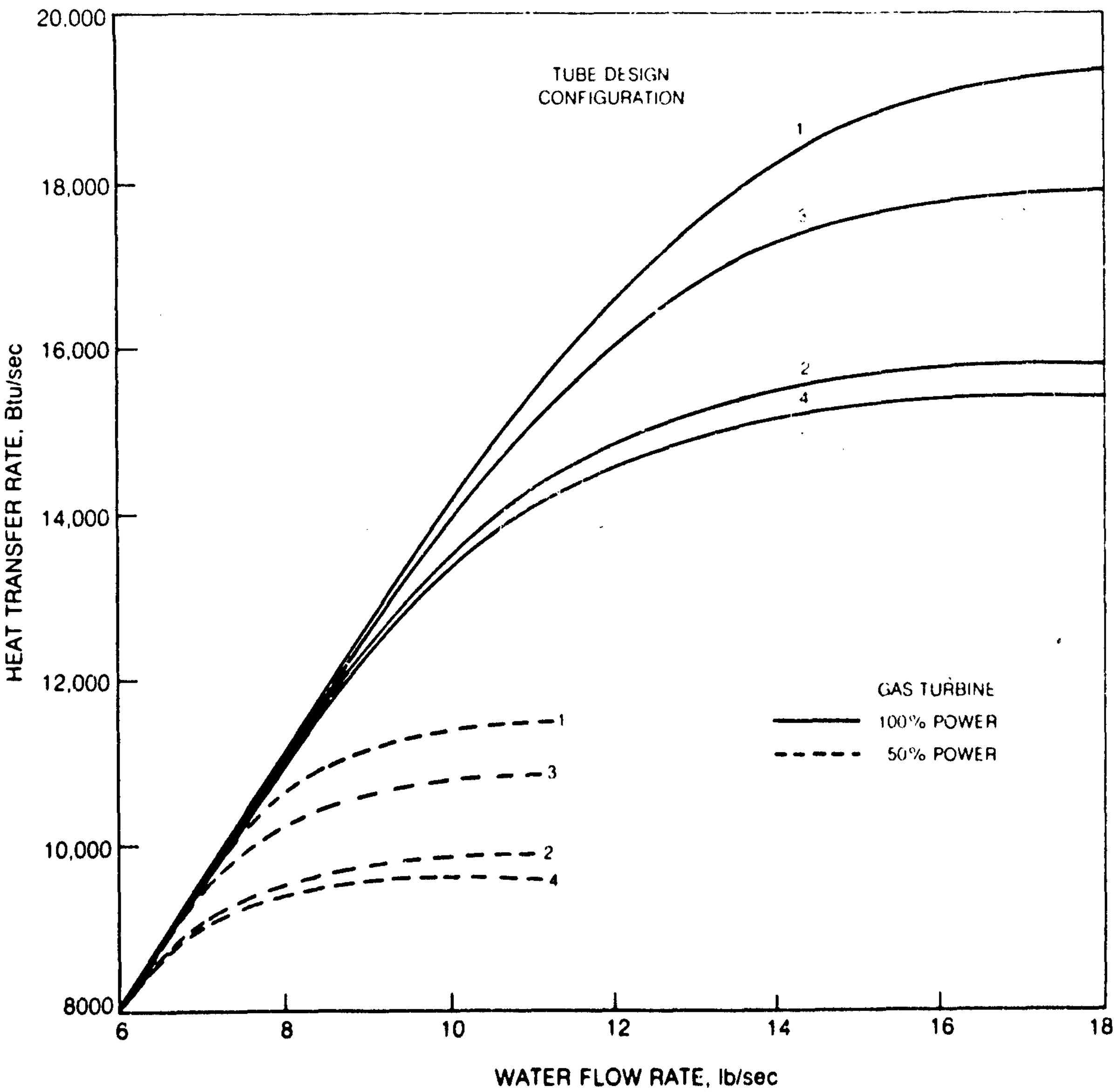
- UNIFORM FLOW AND EFFECTIVE TUBE LENGTH = 200 ft



82-5-86-14

COMPARISON OF HEAT TRANSFER RATE FOR WASTE HEAT BOILERS OPERATED AT DESIGN AND OFF-DESIGN CONDITIONS

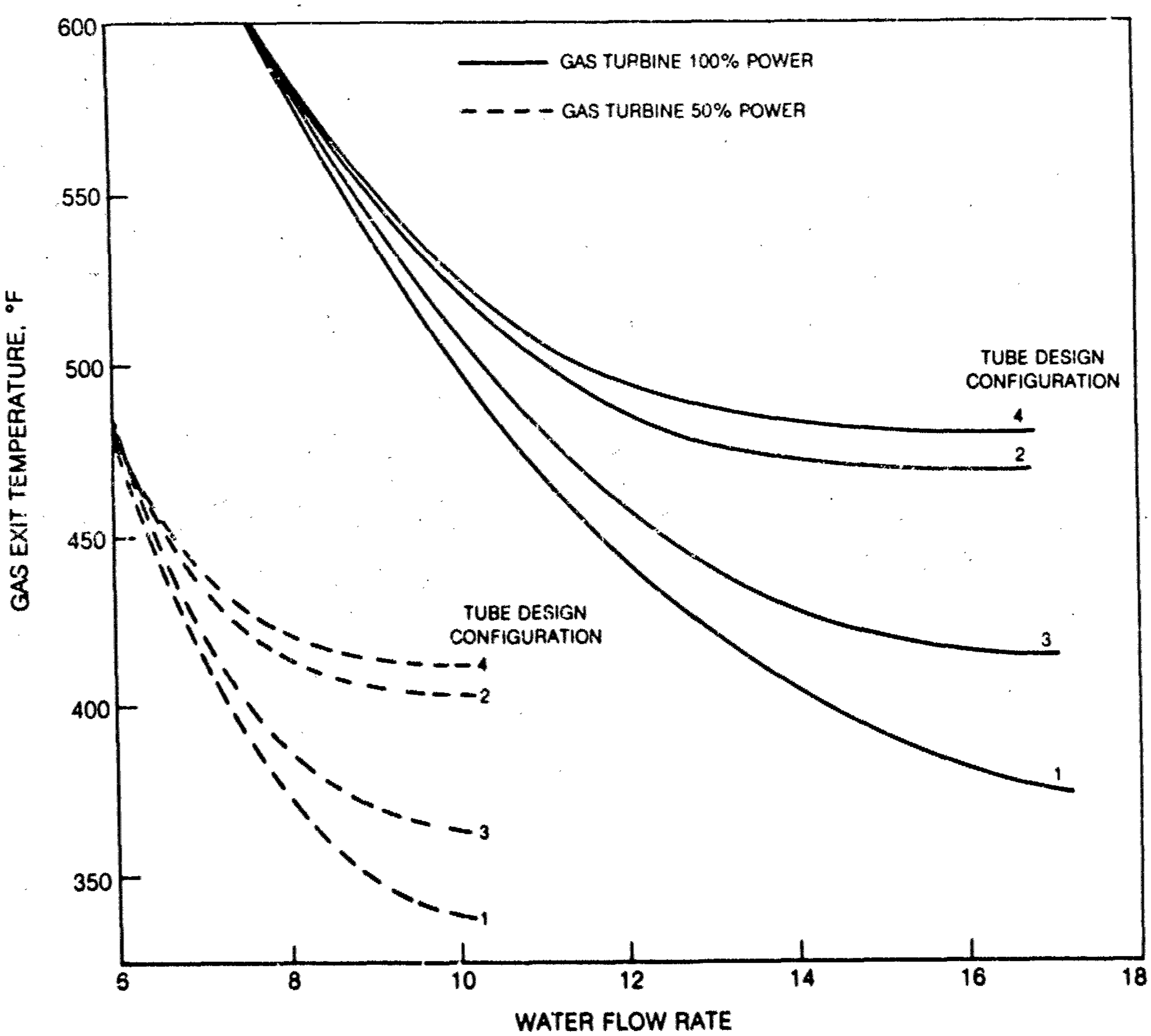
● UNIFORM FLOW AND EFFECTIVE TUBE LENGTH = 200 ft



82-6-86-11

COMPARISON OF GAS EXIT TEMPERATURE FOR WASTE HEAT BOILERS OPERATED UNDER DESIGN AND OFF-DESIGN CONDITIONS

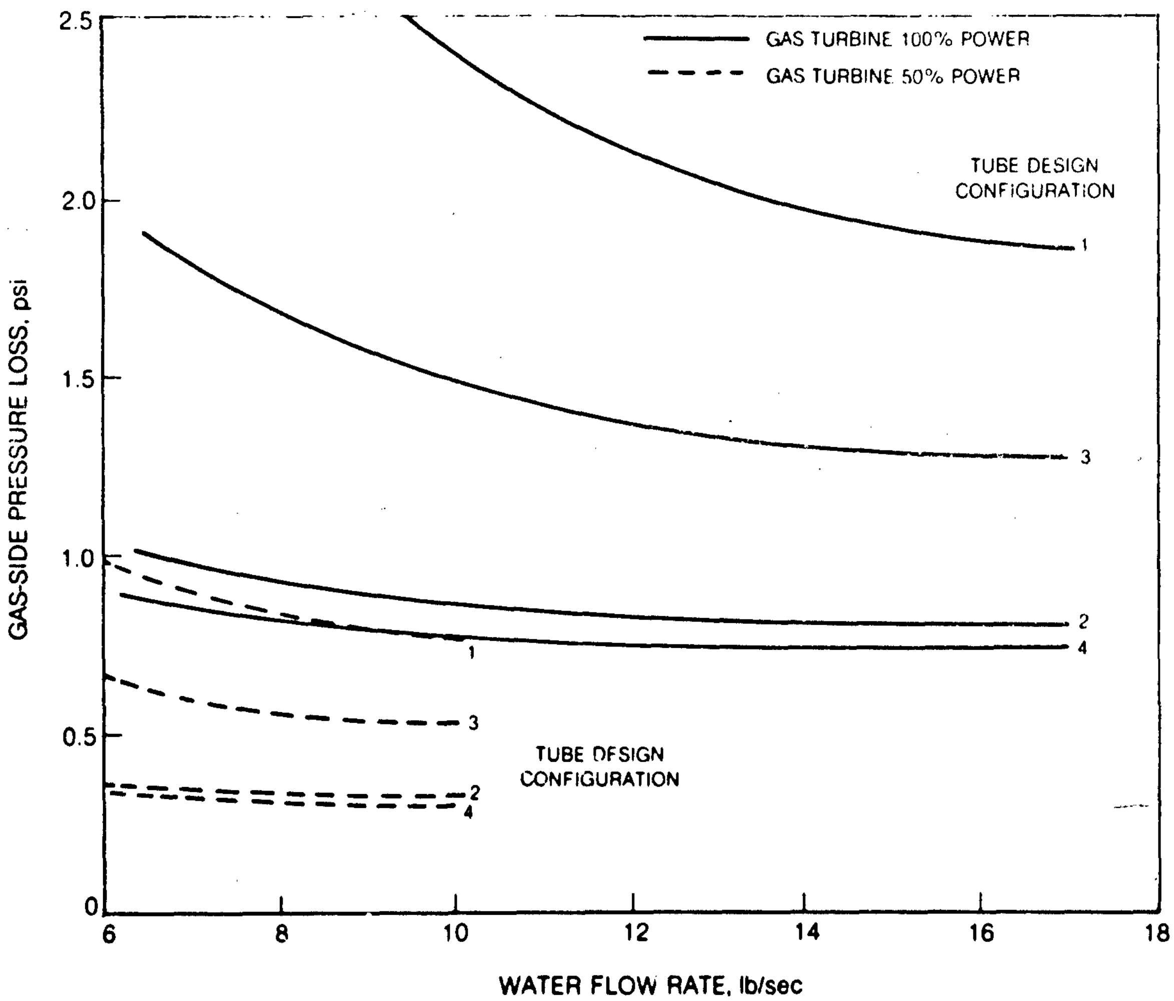
- UNIFORM FLOW AND EFFECTIVE TUBE LENGTH = 200 ft



82-8-88-9

COMPARISON OF GAS-SIDE PRESSURE LOSS FOR WASTE HEAT BOILERS OPERATED AT DESIGN AND OFF-DESIGN CONDITIONS

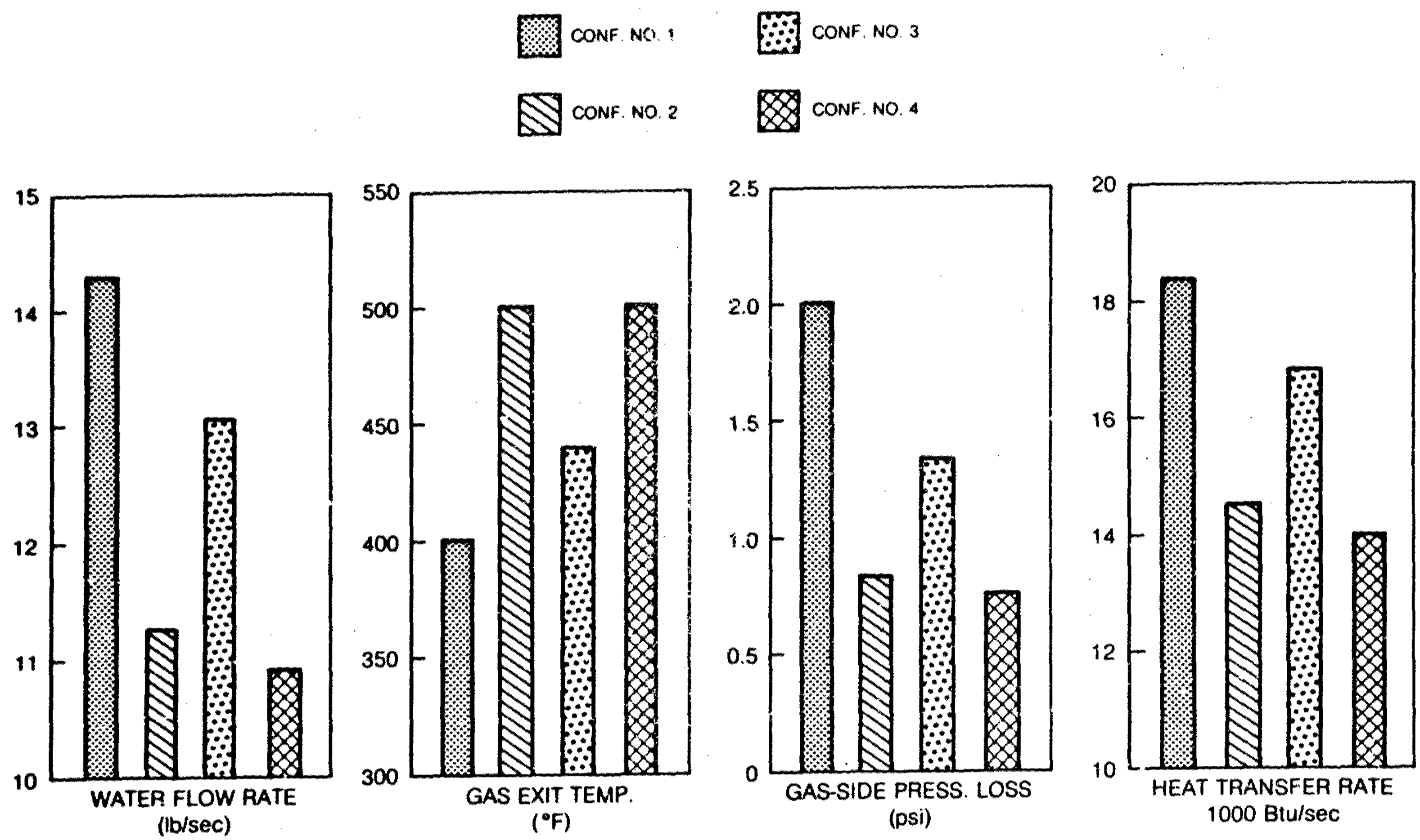
• UNIFORM FLOW AND EFFECTIVE TUBE LENGTH = 200 ft



82-5-86-10

PERFORMANCE CHARACTERISTICS OF WASTE HEAT BOILERS AT CONSTANT STEAM TEMPERATURE — 700°F

- EFFECTIVE TUBE LENGTH = 200 ft
- GAS TURBINE 100% POWER, UNIFORM FLOW DISTRIBUTION
- WATER INLET CONDITION 115.7°F, 300 psia

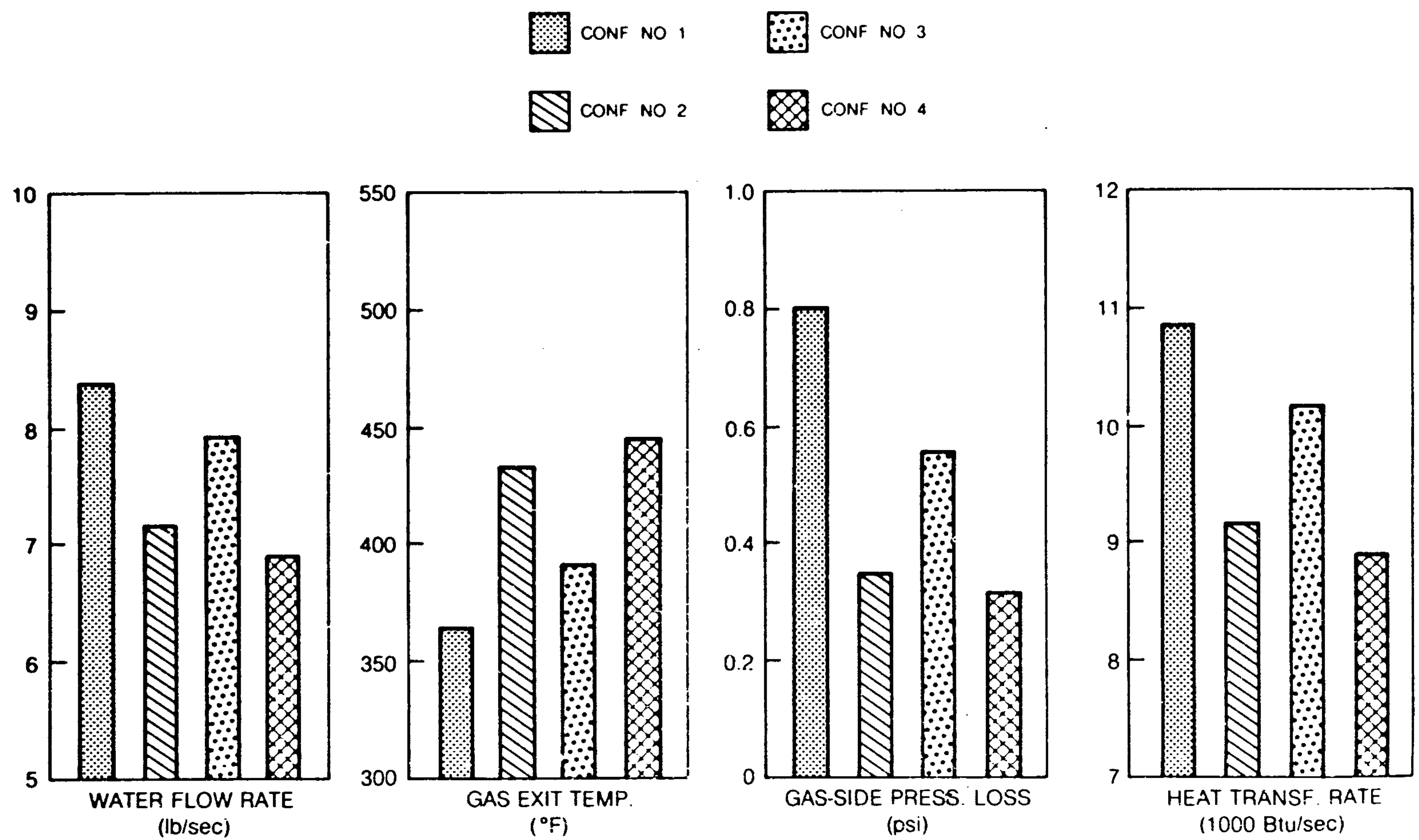


82-8-86-8

FIG. II.17

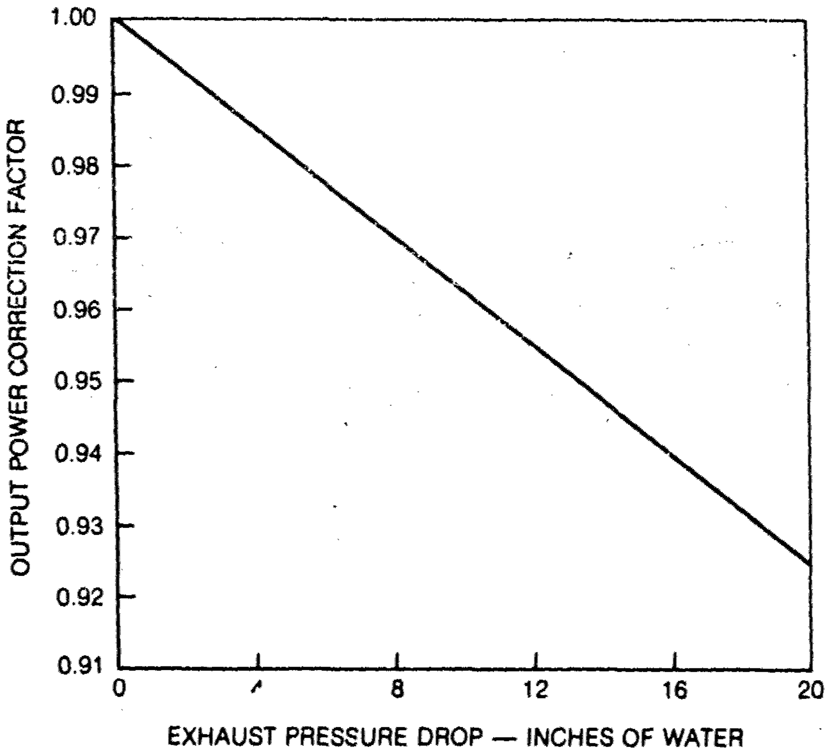
PERFORMANCE CHARACTERISTICS OF WASTE HEAT BOILER AT CONSTANT STEAM TEMPERATURE — 700°F

- EFFECTIVE TUBE LENGTH = 200 ft
- GAS TURBINE 50% POWER, UNIFORM FLOW
- WATER INLET CONDITION 115.7°F, 300 psia



82-5-86-7

APPROXIMATE OUTPUT POWER CORRECTION FACTOR FOR EXHAUST PRESSURE DROPS



82-5-86-6

COMPARISONS OF NET GAINS IN POWER BY INSTALLATIONS OF WASTE-HEAT BOILER

- NET-GAIN POWER (shp) = 0.22 X HEAT TRANSFER RATE/0.746 — CF X TURBINE POWER WHERE CF REPRESENTS CORRECTION FACTOR GIVEN IN FIG II.18

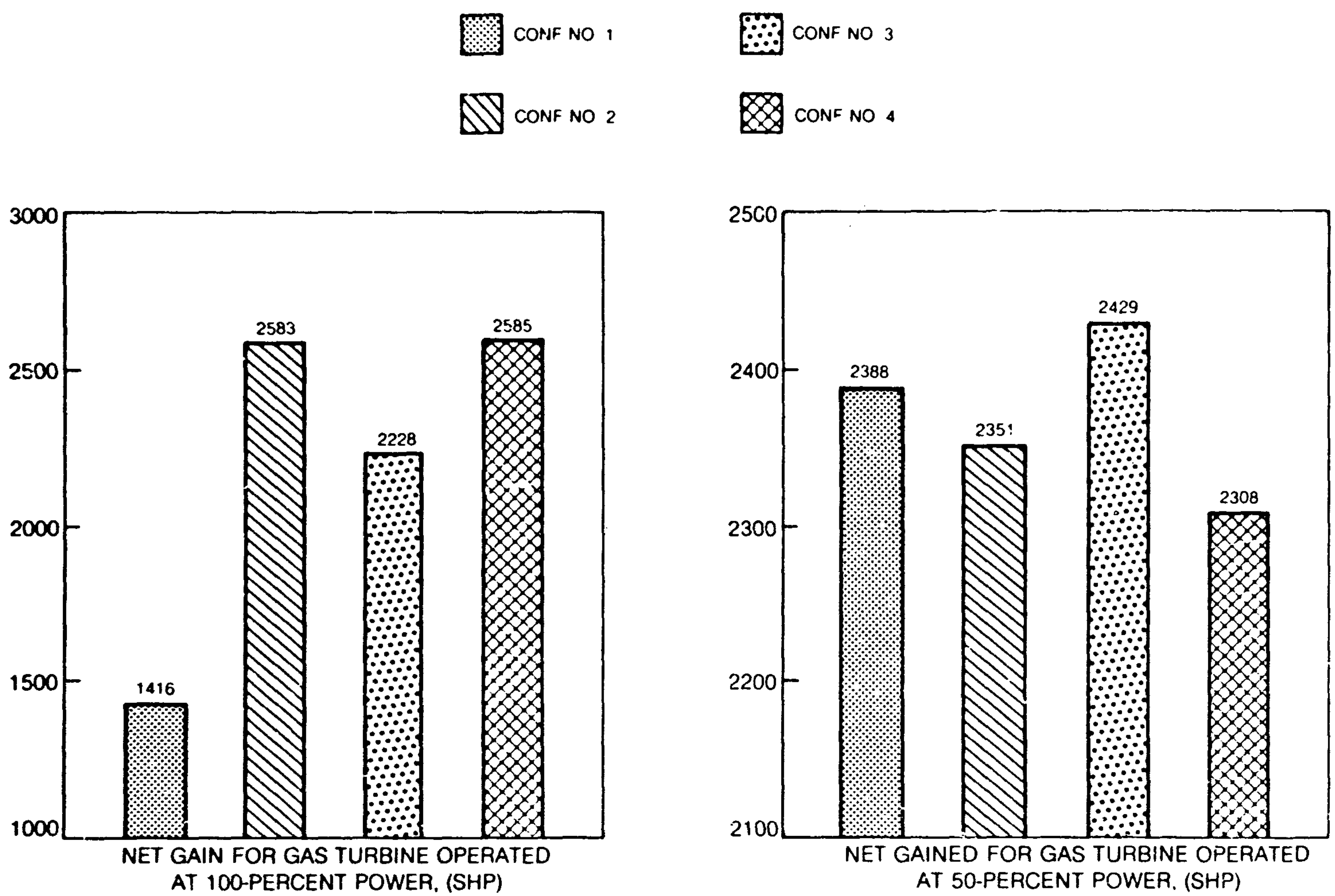
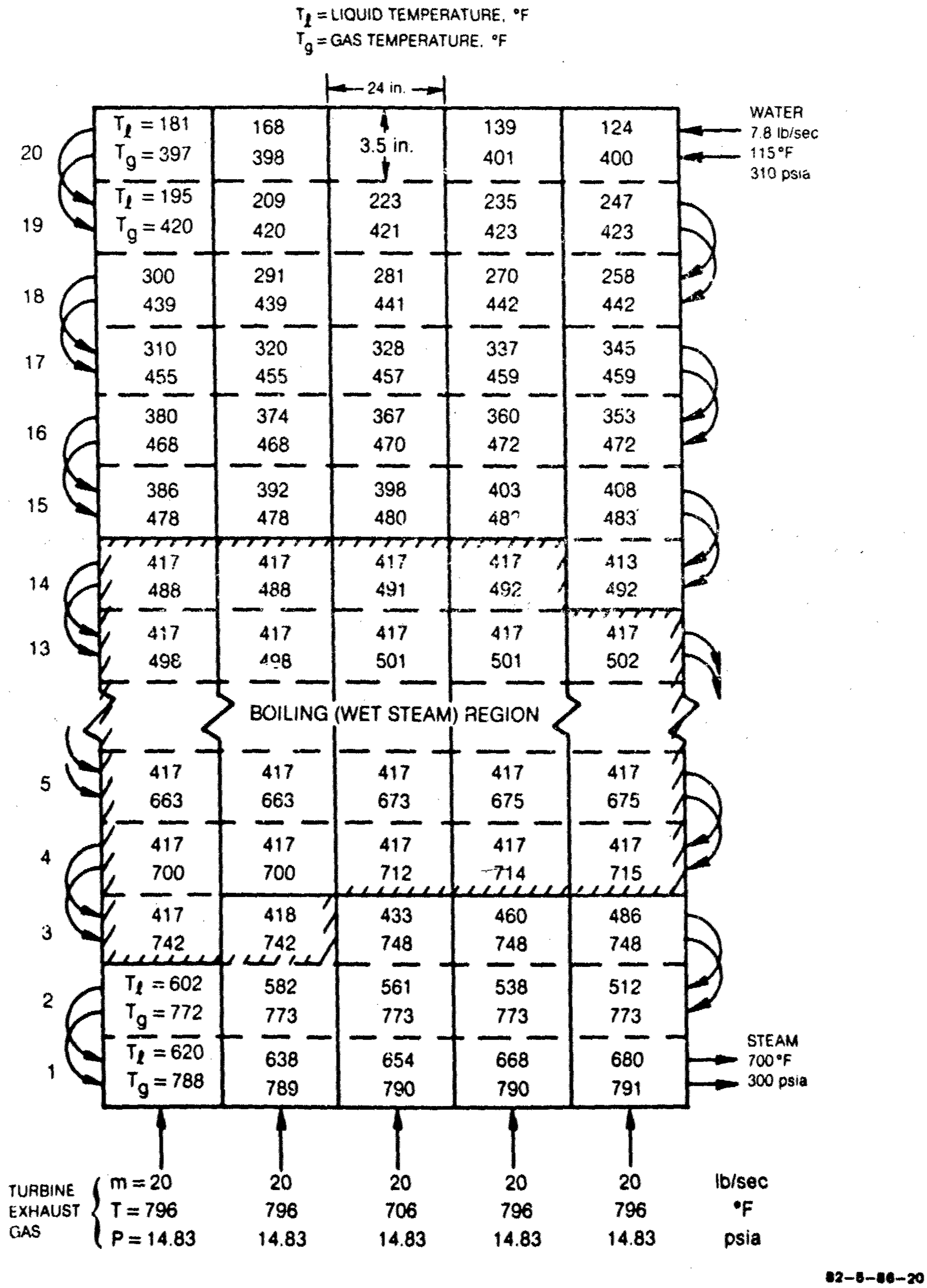


FIG. II.19

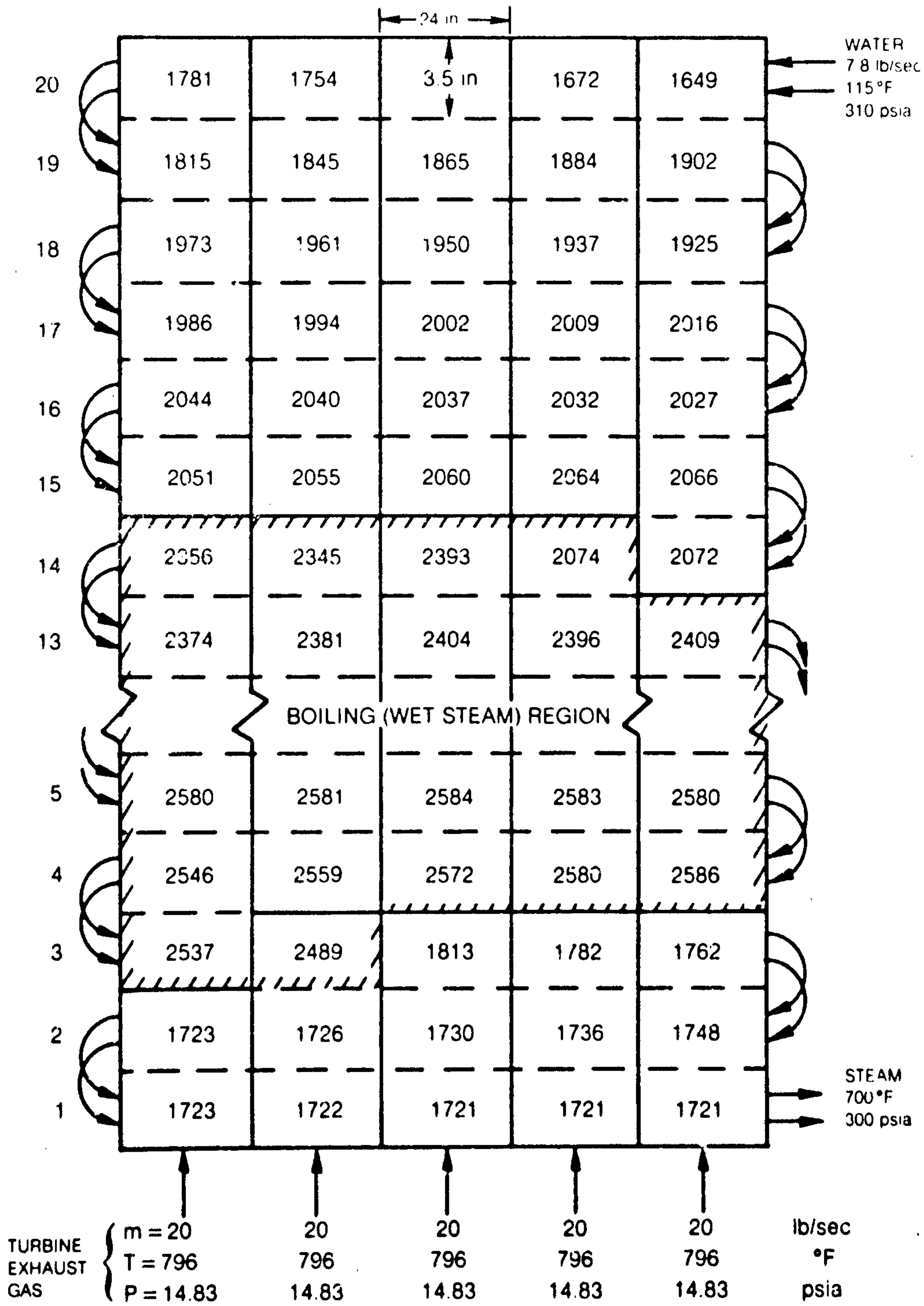
82-5-86-5

DISTRIBUTION OF AVERAGED TEMPERATURES FOR BASELINE WASTE HEAT BOILER OPERATED AT DESIGN CONDITION (GAS TURBINE 50% POWER, UNIFORM FLOW)



DISTRIBUTION OF OVERALL HEAT TRANSFER COEFFICIENT FOR BASELINE WASTE HEAT BOILER OPERATED AT DESIGN CONDITION (GAS TURBINE 50% POWER, UNIFORM FLOW)

• HEAT TRANSFER COEFFICIENT IN Btu/hr-F



82-6-86-21

DISTRIBUTION OF AVERAGED TEMPERATURES FOR BASELINE WASTE HEAT BOILER OPERATED AT OFF-DESIGN CONDITION (GAS TURBINE 100% POWER, UNIFORM FLOW)

T_l = LIQUID TEMPERATURE, °F
T_g = GAS TEMPERATURE, °F

Column width: 24 in; row height: 3.5 in

WATER: 14 lb/sec, 115 °F, 333 psia (inlet at row 20, right side)

Row	Column 1 (T_l / T_g)	Column 2	Column 3	Column 4	Column 5
20	T_l = 179 / T_g = 450	165 / 451	3.5 in	138 / 453	123 / 453
19	T_l = 192 / T_g = 471	205 / 473	218 / 474	230 / 475	242 / 475
18	297 / 491	287 / 492	276 / 494	265 / 494	253 / 495
17	307 / 507	317 / 509	326 / 511	336 / 511	344 / 512
16	384 / 522	377 / 524	369 / 525	361 / 526	353 / 527
15	391 / 534	398 / 537	405 / 538	411 / 539	416 / 539
14	417 / 547	417 / 549	417 / 551	417 / 551	413 / 551
13	417 / 560	417 / 562	417 / 564	417 / 564	417 / 565
	BOILING (WET STEAM) REGION				
5	417 / 735	417 / 743	417 / 744	417 / 745	417 / 746
4	417 / 769	417 / 777	417 / 779	417 / 780	417 / 781
3	418 / 805	431 / 809	457 / 810	482 / 811	506 / 811
2	T_l = 616 / T_g = 832	597 / 833	576 / 833	554 / 833	530 / 833
1	T_l = 634 / T_g = 848	652 / 849	669 / 849	684 / 850	699 / 850

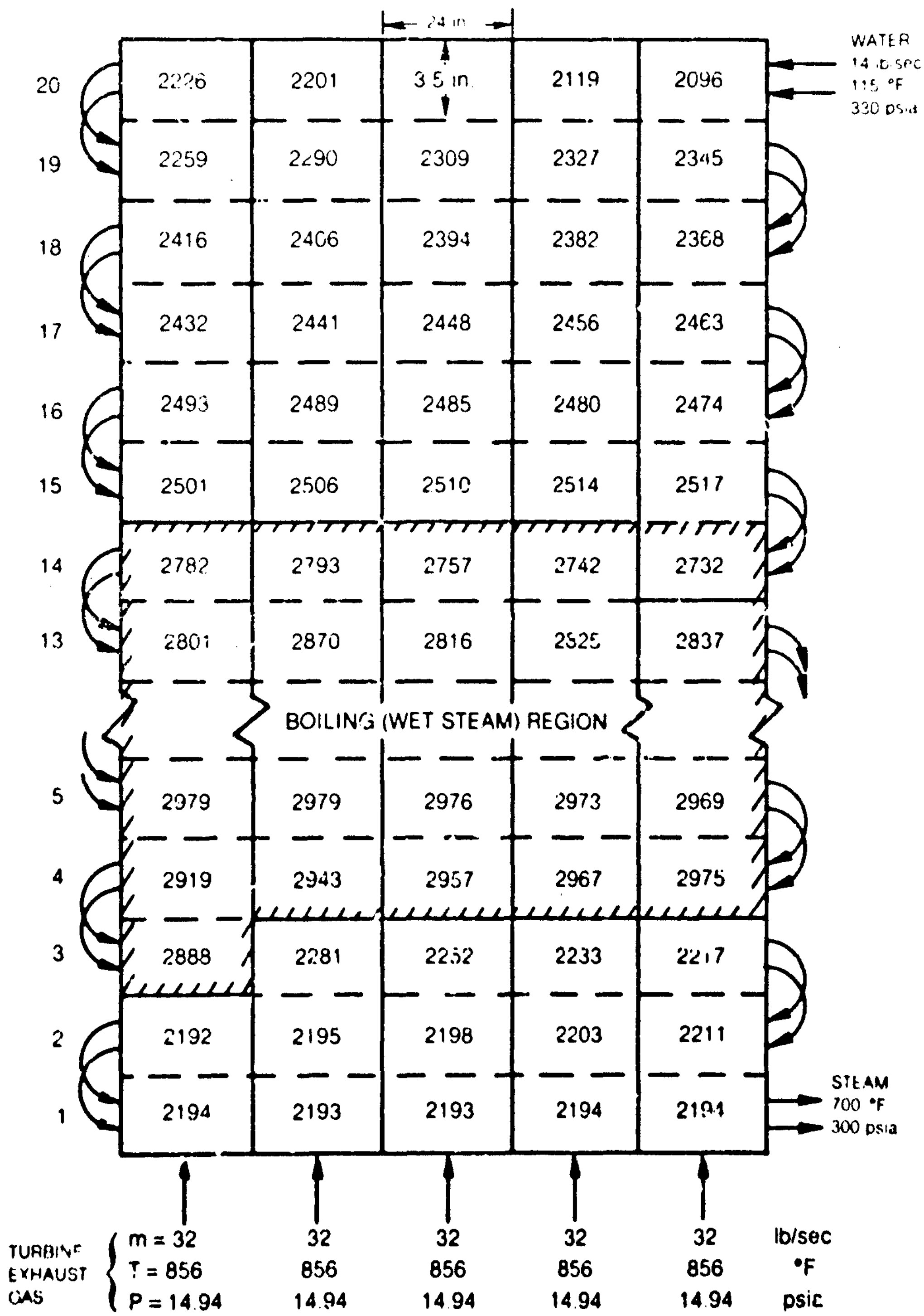
STEAM: 700 °F, 300 psia (outlet at row 1, right side)

TURBINE EXHAUST GAS						
	m = 32	32	32	32	32	lb/sec
	T = 856	856	856	856	856	°F
	P = 14.94	14.94	14.94	14.94	14.94	psia

82-8-88-3

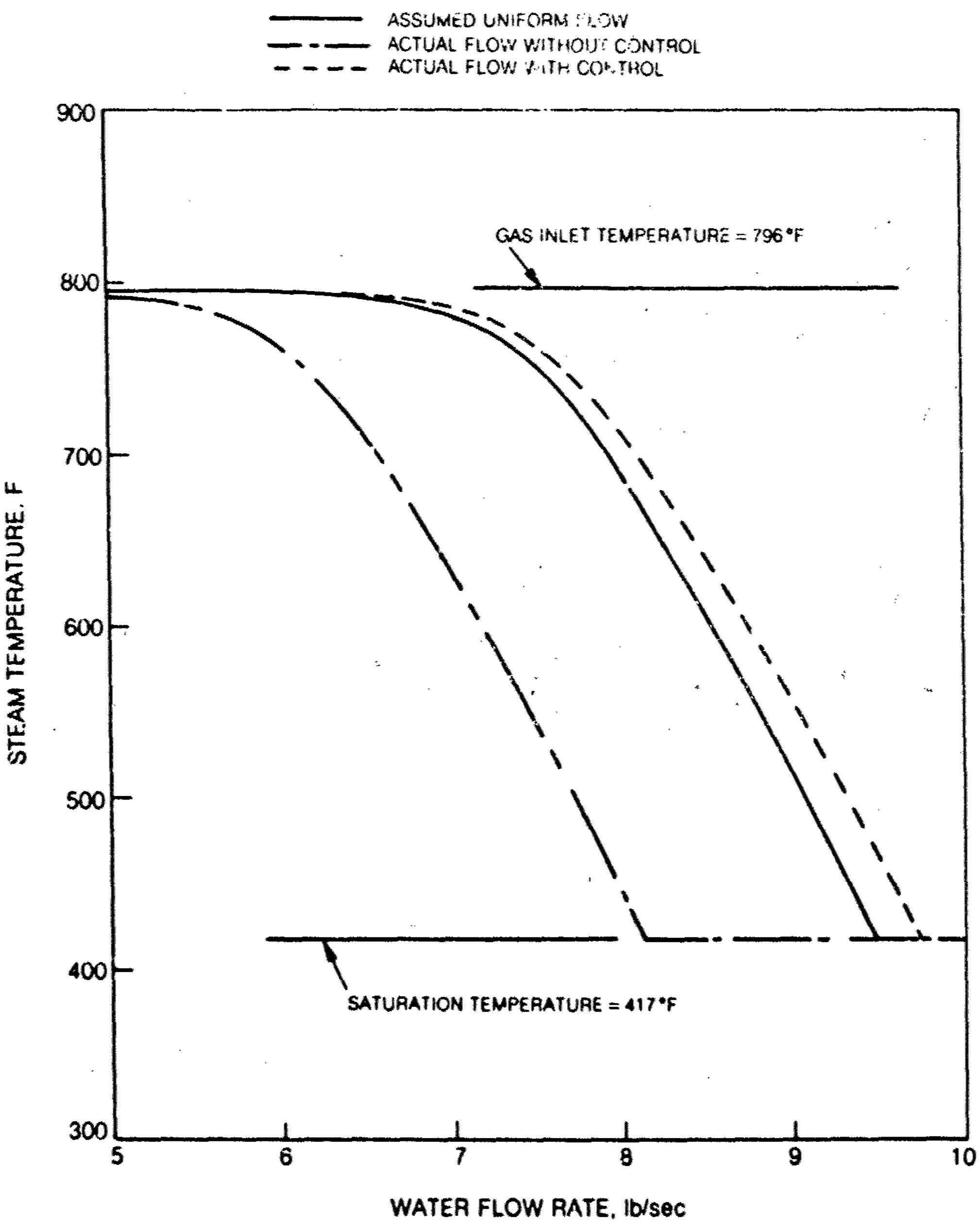
DISTRIBUTION OF OVERALL HEAT TRANSFER COEFFICIENT FOR BASELINE WASTE HEAT BOILER OPERATED AT OFF-DESIGN CONDITION (GAS TURBINE 100% POWER, UNIFORM FLOW)

• HEAT TRANSFER COEFFICIENT IN Btu/hr-F



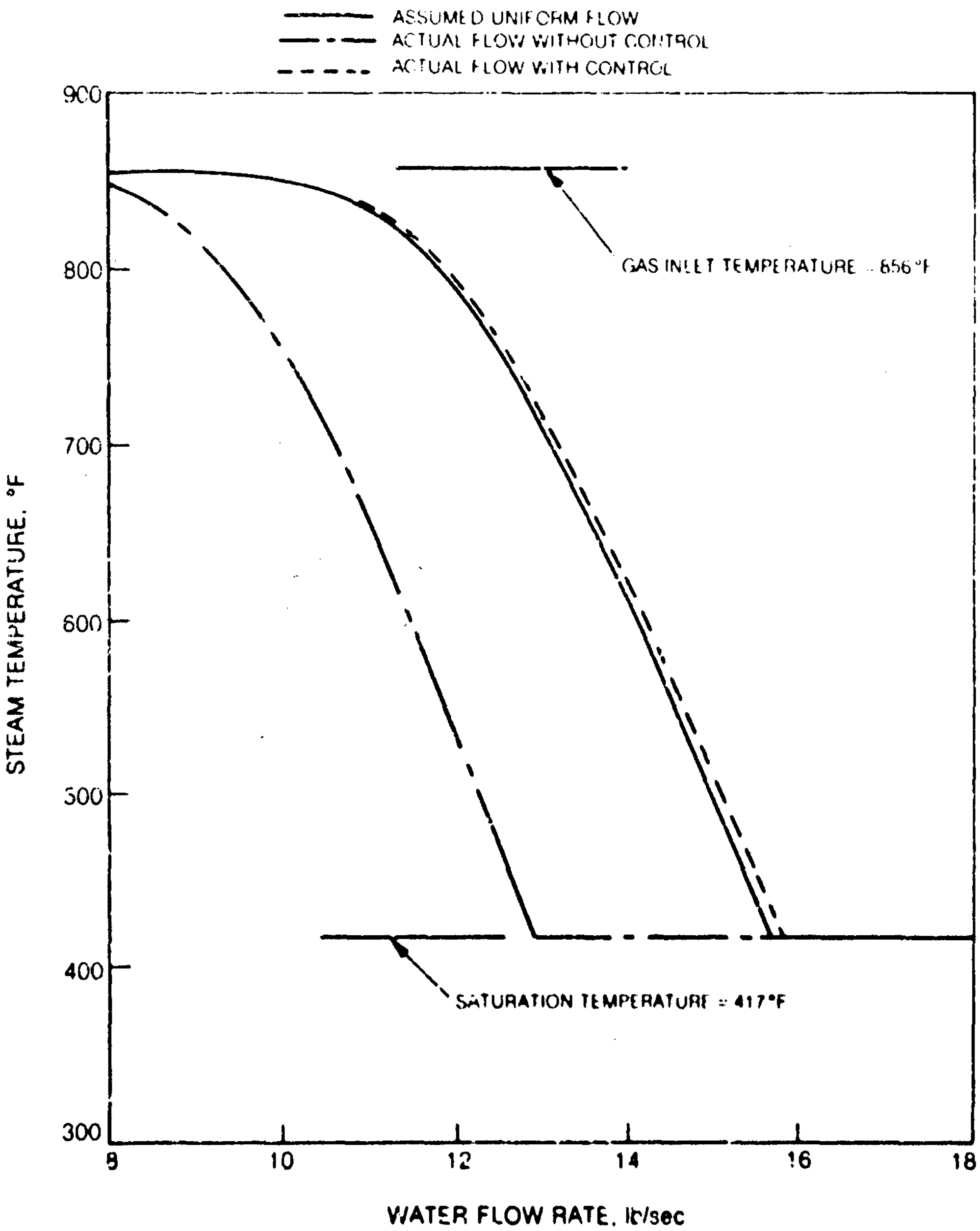
82-8--88-4

EFFECT OF FLOW DISTRIBUTION CONTROL ON STEAM TEMPERATURE OF BASELINE WASTE HEAT BOILER AT DESIGN CONDITION



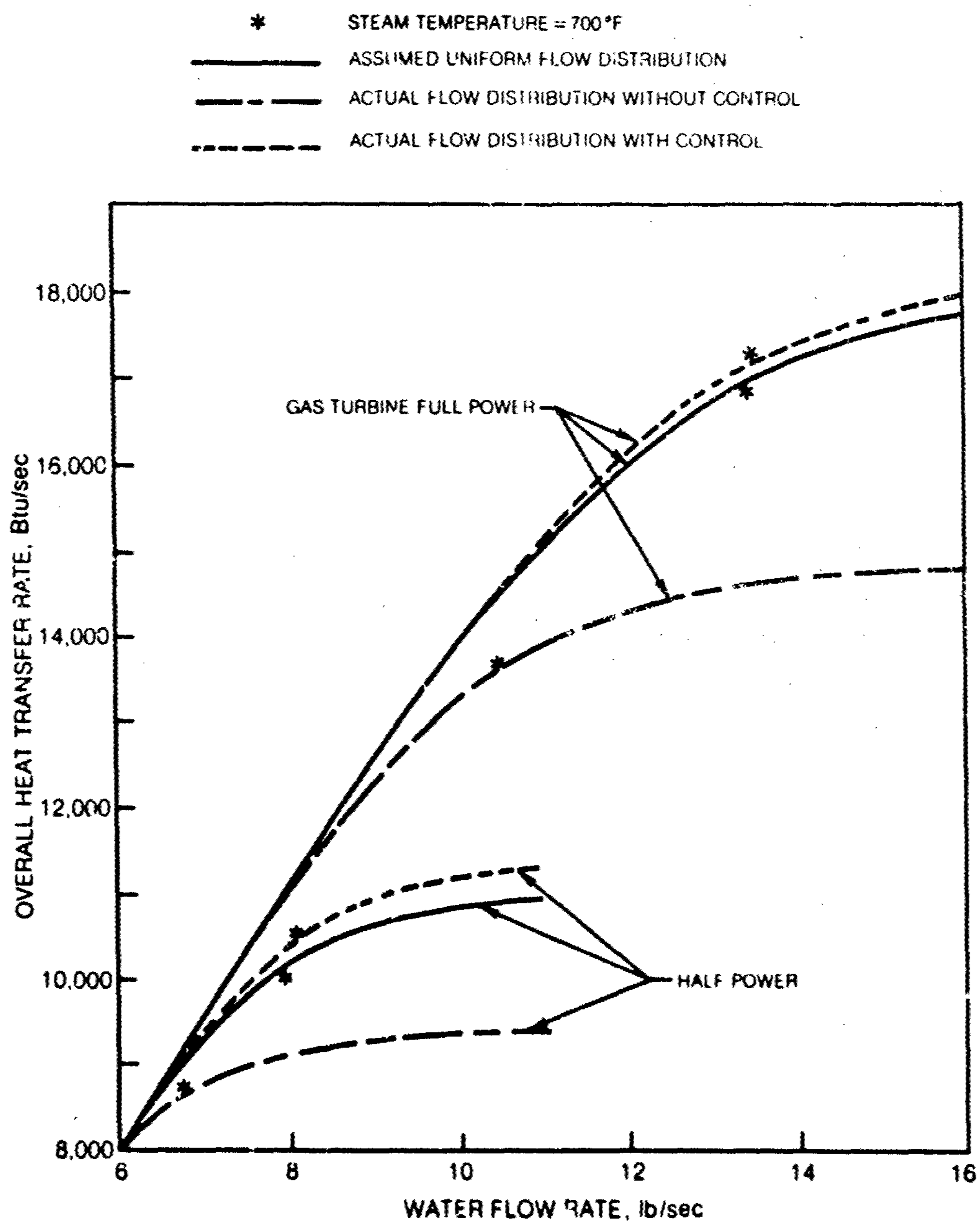
82-8-86-1

EFFECT OF FLOW DISTRIBUTION CONTROL ON STEAM TEMPERATURE OF BASELINE WASTE HEAT BOILER AT OFF-DESIGN CONDITION



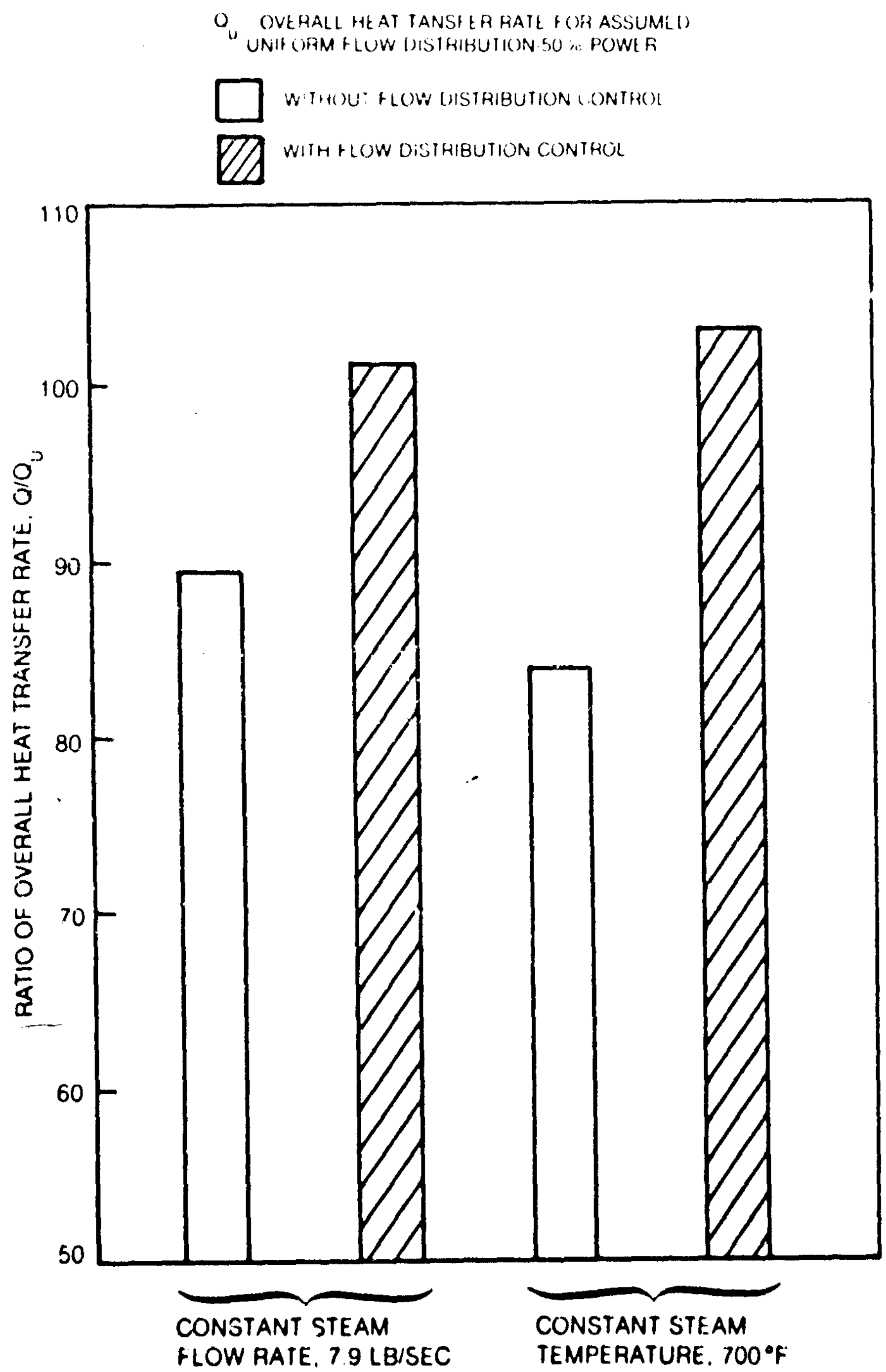
82-8-88-2

OFF-DESIGN PERFORMANCE CHARACTERISTICS OF GAS TURBINE WASTE-HEAT STEAM GENERATOR



82-3-108-1

EFFECT OF FLOW DISTRIBUTION CONTROL ON WASTE HEAT RECOVERY STEAM GENERATOR PERFORMANCE



82-3-106-2

DISTRIBUTION OF AVERAGED TEMPERATURE FOR BASELINE WASTE HEAT BOILER OPERATED AT DESIGN CONDITION WITHOUT FLOW DISTRIBUTION CONTROL

T_ℓ = LIQUID TEMPERATURE, °F
T_g = GAS TEMPERATURE, °F

Column width: 24 in; row height: 3.5 in.

WATER: 8.0 lb/sec, 115 °F, 310 psia

Row		Col 1	Col 2	Col 3	Col 4	Col 5
20	T_ℓ	166	145	3.5 in.	122	115
	T_g	494	434		277	115
19	T_ℓ	190	210	221	228	233
	T_g	509	452	380	320	233
18	T_ℓ	274	256	246	238	233
	T_g	523	469	399	359	233
17	T_ℓ	293	309	317	322	325
	T_g	536	483	415	390	325
16	T_ℓ	353	340	332	328	325
	T_g	547	496	427	413	325
15	T_ℓ	369	381	387	389	390
	T_g	558	507	437	430	390
14	T_ℓ	410	399	394	392	390
	T_g	567	517	443	442	390
13	T_ℓ	417	417	417	417	417
	T_g	576	527	447	451	417
		BOILING (WET STREAM) REGION				
5	T_ℓ	417	417	417	417	417
	T_g	693	658	553	548	417
4	T_ℓ	417	417	417	417	417
	T_g	713	684	588	581	417
3	T_ℓ	417	417	417	417	417
	T_g	735	712	632	625	417
2	T_ℓ	417	417	417	417	417
	T_g	758	744	688	684	417
1	T_ℓ	417	417	417	430	442
	T_g	783	778	758	757	442

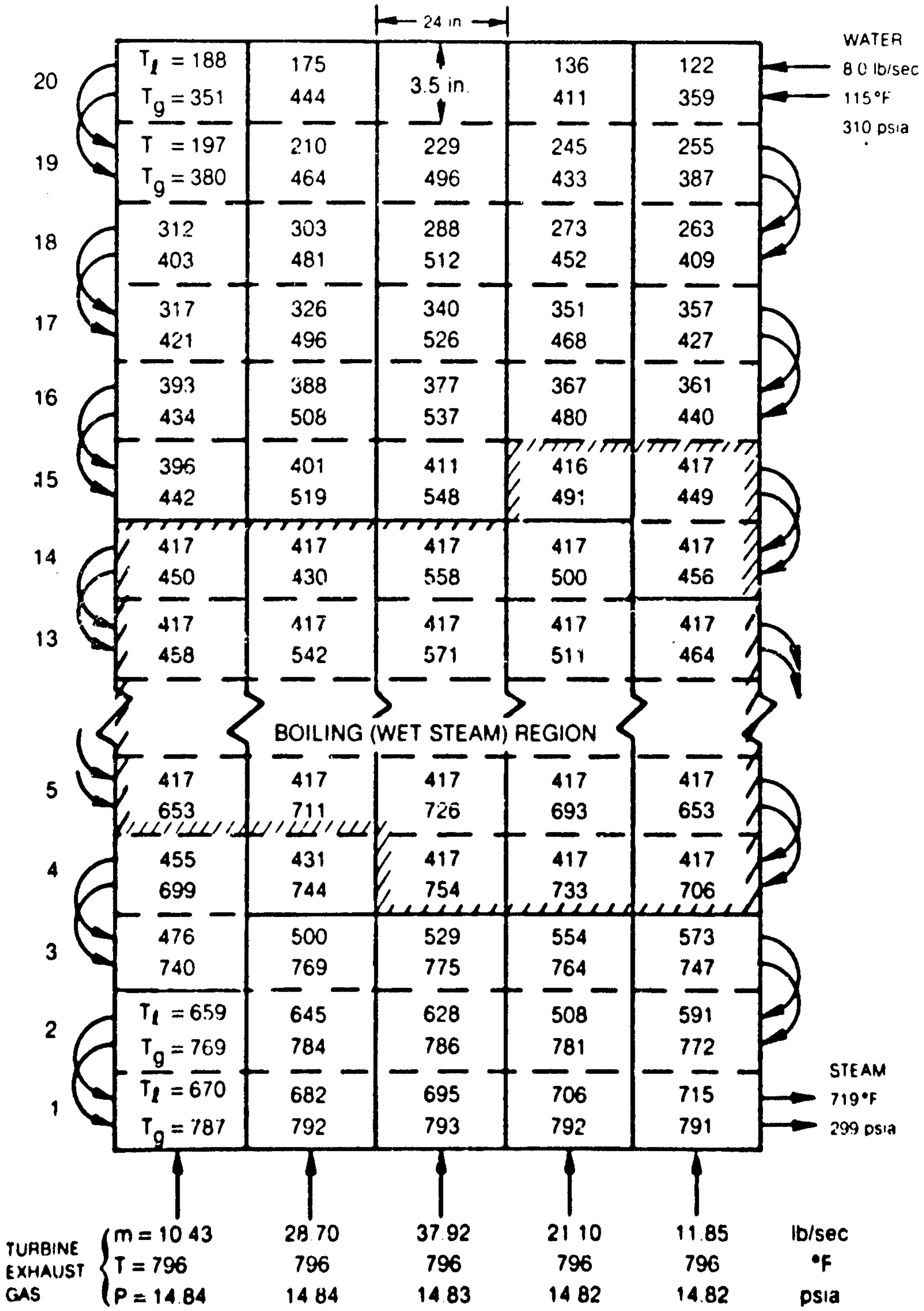
STEAM: 442 °F, 302 psia

TURBINE EXHAUST GAS	Col 1	Col 2	Col 3	Col 4	Col 5	Units
m	50.2	31.6	9.7	8.5	0.0	lb/sec
T	796	796	796	796	796	°F
P	14.82	14.82	14.82	14.82	14.82	psia

82-5-86-25

DISTRIBUTION OF AVERAGED TEMPERATURE FOR BASELINE WASTE HEAT BOILER OPERATED AT DESIGN CONDITION WITH FLOW DISTRIBUTION CONTROL

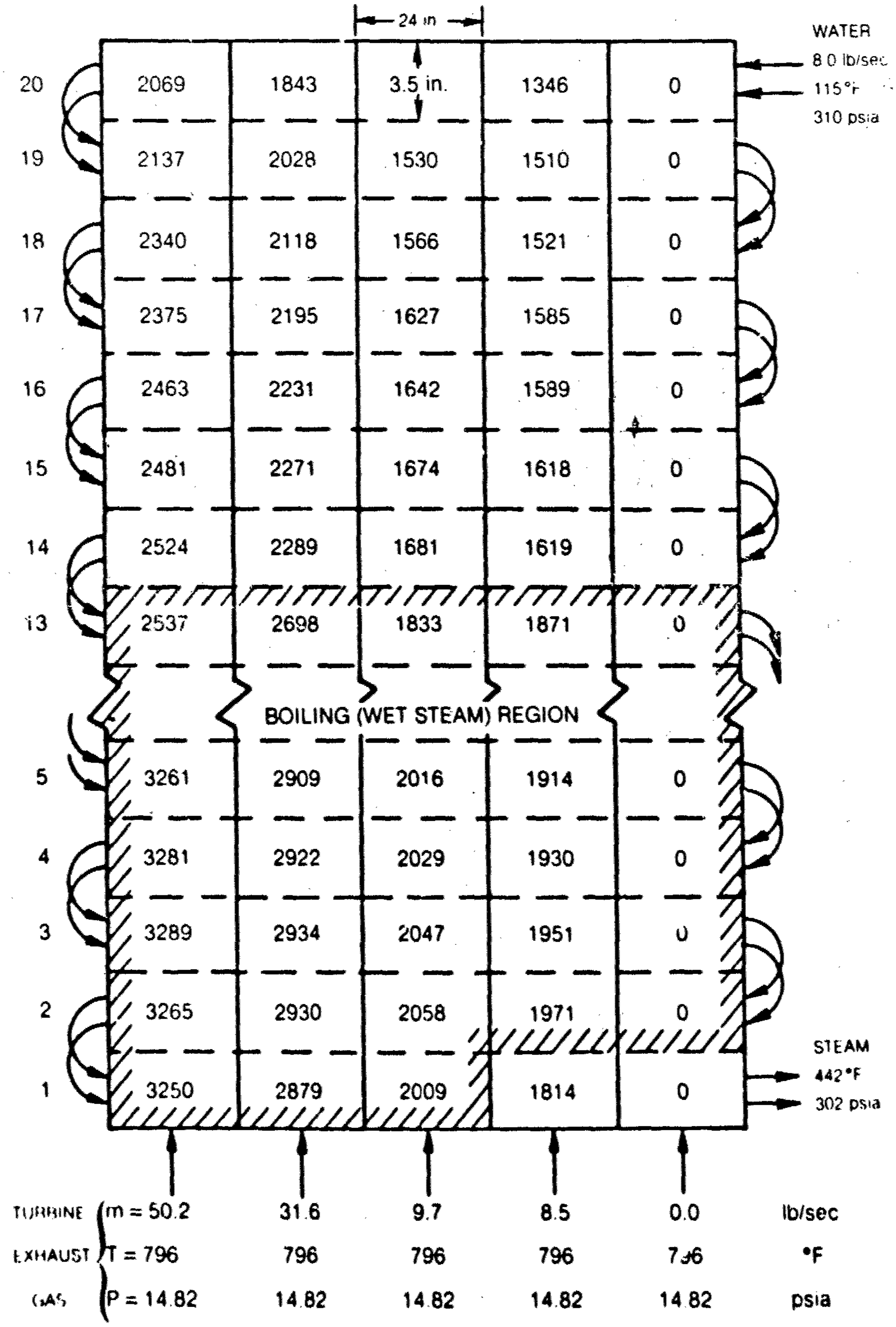
T_ℓ = LIQUID TEMPERATURE, °F
T_g = GAS TEMPERATURE, °F



82-5-86-27

DISTRIBUTION OF OVERALL HEAT TRANSFER COEFFICIENT FOR BASELINE WASTE HEAT BOILER OPERATED AT DESIGN CONDITION WITHOUT FLOW DISTRIBUTION CONTROL

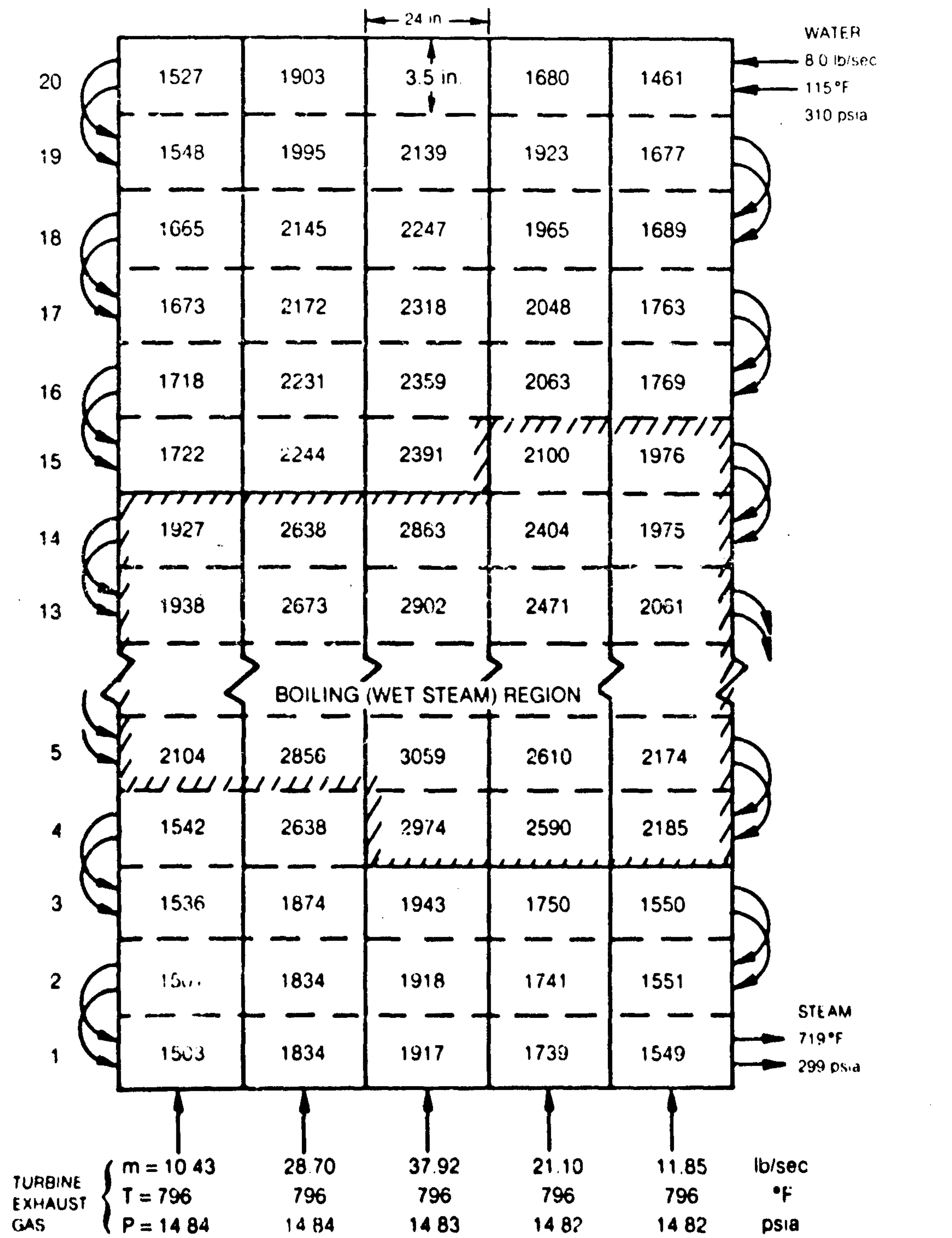
• HEAT TRANSFER COEFFICIENT (UA) IN Btu/hr-F



82-6-86-26

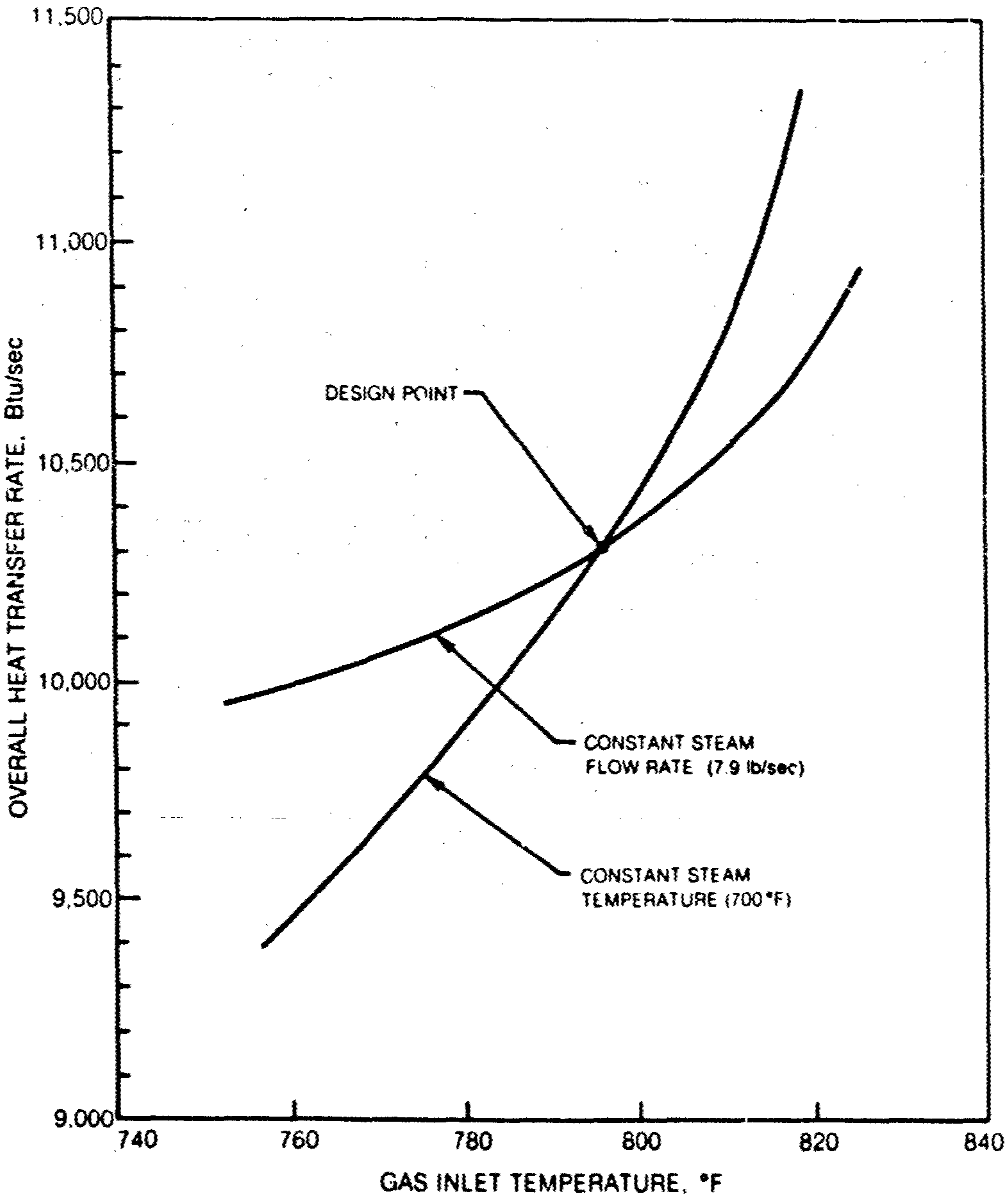
DISTRIBUTION OF OVERALL HEAT TRANSFER COEFFICIENT FOR BASELINE WASTE HEAT BOILER OPERATED AT DESIGN CONDITION WITH FLOW DISTRIBUTION CONTROL

• HEAT TRANSFER COEFFICIENT (UA) IN Btu/hr-F



82-5-86-28

EFFECT OF GAS INLET TEMPERATURE ON PERFORMANCE OF MARINE GAS TURBINE WASTE-HEAT STEAM GENERATOR



82-3-105-3

SECTION III

FORMULATION OF EXPERIMENTAL PROGRAM AND SCHEDULE

The effect of flow distribution control on a marine gas turbine waste-heat boiler has been analyzed, and the results of this analysis are presented in Section II. It is obvious that a complex system like a waste-heat boiler cannot be designed and operated successfully without first conducting a carefully designed experimental program to generate sufficient technical information and operational experience. In this section, an experimental program formulated for the candidate waste-heat boiler is presented. The technical information and operational experience desired from this experimental program, the experiment program plan, and the overall program schedule and effort are discussed in detail.

III.1 Technical Information and Operational Experience Desired from the Experimental Program

As shown in Table III.1 the objectives of this suggested experimental program can be divided into two categories: (1) that which would provide sufficient technical information so comparisons with the analytical results can be made, and (2) that which would allow operational experience to be gained with the use of gas turbine waste-heat recovery propulsion systems. In order to obtain this technical information and operational experience, an experimental program must first provide for the preparation of components and instrumentation necessary for testing. Such preparation would include design specification of the component and instrument designs, then fabrication, preliminary demonstrations, and testing apparatus check-out.

A demonstration of steady state operation of an experiment model would seem the first step in the experiment program following the preparation tasks. However, before the experimental model can be operated at its steady state condition, the start-up and shut-down procedures would have to be specified and evaluated. Then the technical information and operational experience expected to be gained from this steady state operation can be obtained from flow visualization, and temperature and pressure measurements. Once the steady state demonstration is completed, the transient characteristics of the model can be demonstrated, particularly as they relate to naval ship propulsion applications. The technical information and operational experience expected to be gained from this transient (dynamic) operation demonstration should include those related to flow and temperatue stability, thermal performance response, and possibly thermal stress concentration problems.

One major consideration in the design of a waste-heat steam generator for naval ship propulsion application is the characteristics and limitation of the additional shaft power obtainable from waste-heat recovery at different part-power operating condition of the gas turbine engine in order to match the duty-cycle operational (i.e. speed and time) requirements. The suggested experiment program should identify, at least qualitatively, the nature of these characteristics and limitations, if not specifically by estimating their magnitude. The effect of flow distribution control on power output limitation must also be estimated experimentally so that the results obtained can be compared with the analytical results of Section II in this report.

To assess control methodology, the experimental program should also provide sufficient information relating to the use of either pneumatic or electronic controls to regulate the performance of the waste-heat boiler system. This control system should be able to regulate the boiler pressure and feedwater flow rate so the temperature and flow rate of the gas turbine exhaust can be matched with the specified steam outlet temperatures. Since the waste-heat boiler will be required to operate under dry-running condition for self-cleaning purposes, the control system required to cope with the lost-of-coolant problem may not be critical, however appropriate devices to prevent such operating condition will be required.

The procedure to assess the dry-running operation of a marine gas turbine waste-heat boiler has yet to be established, although many of the routine operating procedures for marine waste-heat boilers may be similar to those for landbased combined cycle system operation. However, for the dry-running operation, special consideration must be given to the rate at which the feed water is drained and recharged to avoid undesirable damage or deterioration of the boiler tubes. This experimental program should produce valuable information to assist in establishing the dry-running procedure.

The U.S. Navy is expected to be quite interested in identifying the manpower requirements for a marine waste-heat recovery propulsion system. Again, the experimental program should clarify this question through an assessment of system maintainability and reliability. Areas of manpower needs should be quite similar to those of landbased waste-heat recovery plants, while the number of men needed in a marine propulsion application could be reduced if the waste-heat boiler were designed with less complexity and higher reliability. The importance of gaining as much data and operating experience as possible cannot be overemphasized when dealing with the maintainability, reliability and safety characteristics which are common concerns for any new system.

III.2 Experiment Program Plan

An experimental program plan for the flow distribution control study of marine gas turbine waste heat boiler has been prepared. This program consists of four major tasks as shown in Table III.2. The first task involves the design and fabrication of the experiment model, while the second task is devoted to the set-up of experimental apparatus including the acquisition of necessary auxiliary components. Tasks 3 and 4 are directed toward conducting the actual experiment, including data recording and post test evaluation.

III.2.1 Design and Fabrication of Experiment Model

The first step in the design and fabrication of the experimental model is to determine the model size. Because the cost of building a full-scale test model as well as the heat source required for the experiment would be enormous, a one-fifth scale model is suggested. It is believed that this scaled model can be designed and fabricated in a reasonable time frame and at an acceptable cost that would provide these desired information described in Table III.1.

The thermal condition (flow rate, temperature, and pressures) of the working fluid are usually determined from the availability of the test (auxiliary) equipment and by using the principles of similitude. In principle, the test model and the full-scale unit should have the same Nusselt, Prandtl, Reynolds, and Mach numbers. The flow passage in the test model and that of the full-scale unit should also be geometrically similar. Because the detailed temperature and flow distributions are the primary concerns in the present study, it is more desirable to use larger flow passages with fewer number of tubes in the model. As long as the flow conditions are based on the principles of similitude, the pressure loss and heat transfer characteristics in the test model should differ little from the full-scale unit.

The instrumentation needed for the present study must be capable of measuring temperature, pressure, and flow conditions. In a conventional heat exchanger experiment, as few as four temperature measurements might suffice (that is, the inlet and outlet temperatures for the hot and cold fluids). However, in the suggested program where the boiler is a single-pass counter crossflow heat exchanger, the outlet temperatures will not be uniform. Accordingly, at least fifteen temperature measurements would be required to identify the inlet and exit flow conditions. If internal temperature distributions are also to be measured (as shown in Figs. II.20 and II.22), additional temperature probes would be needed.

The magnitude of pressure drop across the heat-transfer matrix particularly on the gas side of the waste-heat boiler is as important as the heat-transfer performance. The test rig may be designed so the duct cross section is the same as that of the inlet face of the heat-transfer matrix under test, in which case simple static pressures in the duct may be satisfactory. If this is not practical, allowances should be made for differences in the kinetic pressure head which changes with flow passage size. It is important that at least ten diameters of straight duct preceed the heat-transfer matrix to assume a uniform velocity distribution across the face of the duct. Because pressure drop data are important, it is more desirable to use the piezometer ring.

The simplest and most accurate means of measuring the gas flow for this experimental program would be to use a flow nozzle mounted at the air inlet and a draft fan be mounted on the outlet side of the heat-transfer matrix. This would preclude errors stemming from turbulence and poor velocity distribution in the flow-rate measurements. To measure the flow distribution in each gas path (see Fig. II.20), pitot static tubes can be used. At least two pitot static tubes must be used for each gas path and each tube should be installed downstream of the heat transfer matrix in order to avoid disturbing the flow field in the test section. Finally, care must be exercised to minimize the flow leakage, heat loss, and boundary effect during the design and fabrication of the experiment model as severe flow leakage and heat loss could cause difficulties in the analysis of test results.

III.2.2 Auxiliary Equipment Set-Up

The auxiliary equipment needed for this experiment will include: a hot-air (or gas) supply and discharge system; a pressurized feedwater and steam handling system; a control device to regulate the flow rate, flow distribution, temperature, and pressure for both working fluids; and data acquisition and recording devices. One possible arrangement of the experimental apparatus is shown in Fig. III.1.

The hot-air/hot-gas supply and discharge system would require a draft fan which should be mounted at the downstream of the test model, and a combustor which burns either natural gas or propane for generating hot gas needed to simulate the gas turbine exhaust. Both draft fan and combustor could be controlled from a central control box to obtain desirable gas flow rates and gas temperature. The pressurized feedwater supply system would consist of a pressurized feedwater manifold, a flow rate regulator, a steam manifold, a radiator, a condensate tank, and a pump. Both the flow rate regulator and the pump would be controlled by the central control device. A baffle plate should be installed in the diffuser to regulate the desirable gas flow distribution. All the test data including temperature, pressure, flow rates would be recorded by means of an automatic data acquisition and recording device for later evaluation and analysis.

II.2.3 Test Procedure

The test procedures to be conducted in this suggested experimental program must include, as a minimum, all items shown in category C of Table III.2. The first step in conducting the experiment would be to assemble and check-out the major components according to the layout drawing. Shakedown testing would then follow to demonstrate the functional capability and strctural integrity of the experiment apparatus. Some minor modifications and adjustment might be necessary in the early stage of the experiment before substantive test program can be commenced. Piping and wiring details would be determined prior to the assembly of the experimental unit, and instrumentation and controls of the flow rate, temperature, and pressure would be installed and calibrated before the actual experiments were performed.

An extremely important aspect of the suggested program is flow visualization test in the flow distribution control study of gas turbine waste-heat recovery steam generator. As cited in Phase-I study (Section II.2 of Ref. II.3) the actual flow distribution at the exit of the gas turbine exhaust is highly irregular and nonuniform. The major portion of the flow was found to be near the rear section of the elbow and some reversed flow as observed in the regions near the front section. To complicate matters, these flow distributions are actually three-dimensional. In order to gain an insight into flow distribution nonuniformity in the waste-heat boiler performance, two-dimensional flow distributions were assumed in the analytical study. However, the results of such an analytical study can only be compared with those of the experimental study on the same basis, i.e. of a two-dimensional flow experiment. Therefore, for naval applicators, the experiments must also include three-dimensional flow distributions, since the results obtained from three-dimensional flow testing would be beneficial in any modifications of the analytical model, which is deemed necessary.

Flow visualization for the hot combustion gas can be conducted by attaching tufts of thread or yarn to the passage walls, or by attaching these tufts to a wire probe that can be moved about in the flow field. Smoke can also be employed, but its use is usually not very satisfactory because the smoke filament tends to be dispersed so rapidly by turbulence that the technique is applicable only for relatively low Reynolds numbers and simple geometries. It should be obvious that flow visualization tests can be conducted more conveniently if the models are made of a transparent plastic, such as Lucite.

When preparing for heat transfer performance testing, particularly with nonuniform flow distributions, consideration must be given to the flow stability to assure that the test data are consistent and repeatable. During the literature survey conducted in Phase-I study, it was noticed that the flow in the transitory stall region of a two-dimensional diffuser is inherently unstable, and any disturbance could shift the stall region from one wall to the other. Therefore, a flow stability test must be conducted in conjunction with flow visualization. A simple way of assuring that fluid flow is stable is to take periodic flow measurements (five to ten-minutes intervals are suggested) at each fixed operating condition. This procedure should be continued until three successive readings of flow measurement show negligible change.

The last item in the suggested test procedure of Table III.2 is the heat transfer performance test which should consist of a stead-state operation test and a transient (dynamic) operation test. In the steady-state operation, the thermal output characteristics and limitation of the waste heat boiler under various flow conditions should be determined. The effect of variations in flow rate and/or pressure of feedwater must be assessed, and the magnitude of such parameters as critical temperature, pressures, stresses, control feedbacks must be determined and examined as well.

The transient operation test would investigate the dynamic characteristics of the marine gas turbine waste heat boiler during the dry running and off-design operations. The first dynamic test should assess the effect of the heat input which varies according to the duty cycle operations. There are three possible operation modes: (1) variable gas temperature with constant flow rate; (2) variable gas flow rate with constant gas temperature; and (3) both variable gas temperature and flow rate. The response time and stability of heat exchanger performance under these dynamic tests should be determined and examined. If the steam temperature were maintained constant, the control procedure and control requirements would have to be identified. The most important information to be acquired from a dry running test would be the rate of draining and recharging the feedwater. In addition, following dry running, the metal temperature would be approximately 900 to 1000°F, and therefore the requirement of cool-down process must be determined. Finally, the possibility of wet running with static flow condition should also be explored during the transient.

III.2.4 Post Test Evaluation

The last task of the suggested experimental program plan should be the post experiment inspection and evaluation of the test results. This task would seek to assess the results of the experiment in terms of establishing requirements for future modifications to the waste heat boiler design and analysis.

The first phase of this last task would be routine inspection and examination of the test model to determine its general condition and to estimate whether any degradation in conditions may have affected the test results. Evaluation of the test results would then be made with particular emphasis being directed toward the technical information and operational experiences desired (refer to the discussion in Section III.I). Recommendations regarding to the future design of marine gas turbine waste heat recovery propulsion systems should be included as part of this last task; methods directed at removing operational limitations should be explored; and reliability and maintenance requirements should also be assessed.

III.3 Overall Program Schedule and Effort

The overall program schedule formulated and man-hour effort estimated to conduct this suggested experimental study are shown in Fig. III.2. Although overlaps in program schedule for certain activities are necessary because of the nature of a particular test or because of the need to shorten the performance period, it can be seen that the activities described are generally consistent with the program plan discussed in Section III.2.

The longest period required for this suggested experimental study would be those for model preparation (activities No. 1 and No. 2) and heat transfer performance testing (activity No. 8); these would require approximately five and four months, respectively. The experiment apparatus setup time (including that for the acquisition of control devices, data recording system, pumps, blower, burner test site preparation, utility hook-up, piping, and wiring) as well as the shakedown would require approximately three months. Collectively, the flow visualization and flow stability tests would require approximately two months, and finally, two months would be needed for post test evaluations, analysis of test results, recommendation, and reports preparations.

The last column of Fig. III.2 shows the man hours estimated to completed each task. It can be seen that most of the engineering effort would be spent in model design definition and post test evaluation while the technician's time would be directed toward model fabrication, test rig setup, testing, and data recording. It should also be emphasized that a joint effort from engineer and technician is also necessary during each task to assure the success of the experimental program. Therefore, for the entire suggested program the total engineering time is estimated to be approximately 1000 hours and that for technician, approximately 2050 hours.

TABLE III.1

Technical Information and Operational Experience
Wanted From Experimental Program

A. Related to Flow Distribution Control Study

- Design Specification of Test Apparatus
- Steady-State Operation Demonstration
- Transient (Dynamic) Operation Demonstration
- Output Characteristics and Limitation Identification

B. Related to Naval Propulsion System Applications

- Control Characteristics Assessment
- Dry Running and Duty Cycle Operating Procedure Assessment
- Maintainability, Reliability, and Safety Assessment
- Operational Manpower Requirement Assessment

TABLE III.2

Experiment Program Plan

A. Design and Fabrication of Experiment Model

- Size of experiment model
- Test condition and consideration
- Principles of similitude
- Adequate and potent instrumentation
- Leakage, heat loss, and boundary effects

B. Auxiliary Equipment Setup

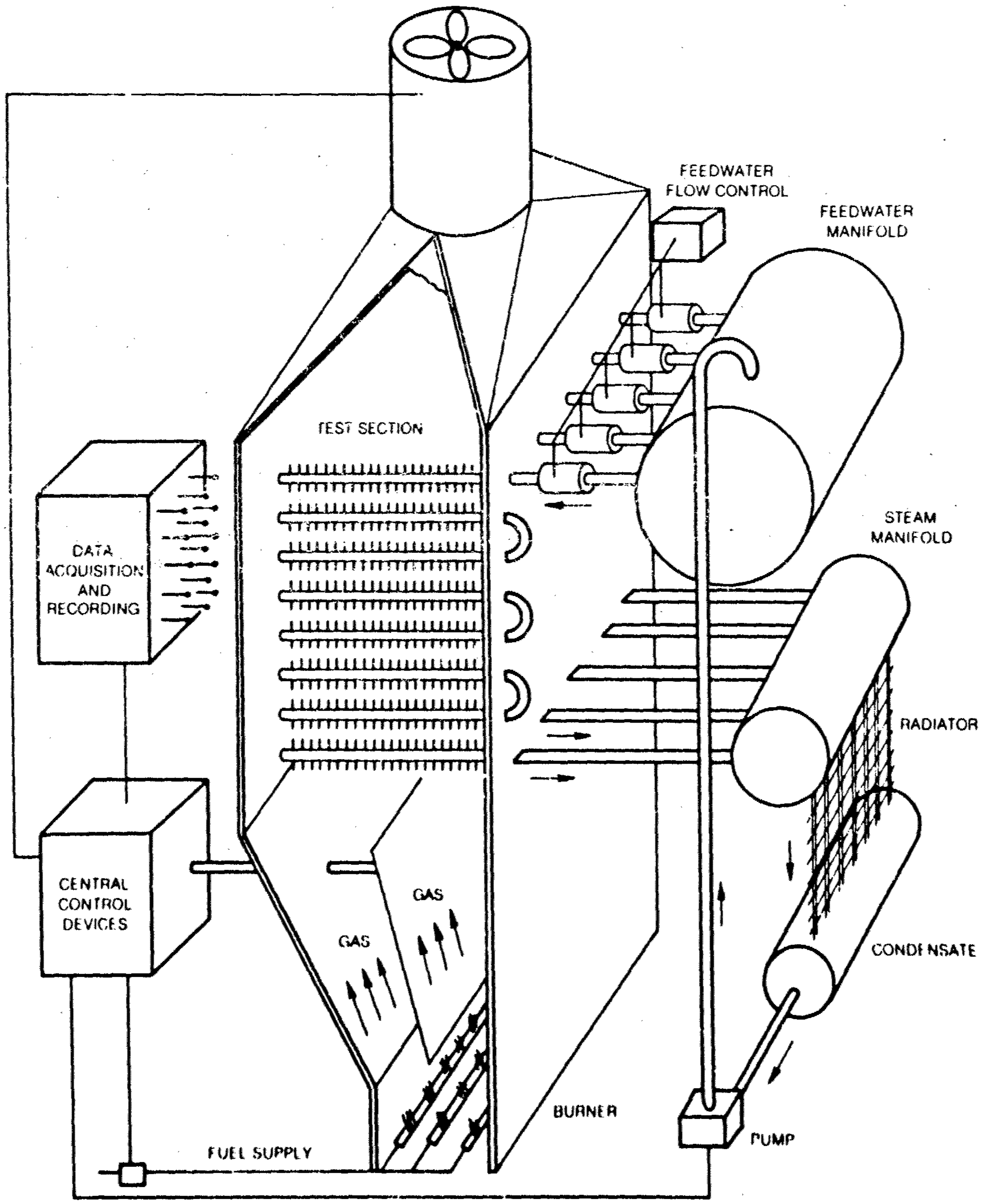
- Hot air/gas supply and discharge equipments
- Water supply and steam handling equipments
- Control devices
- Data acquisition and recording devices

C. Test Procedure

- Shake-down flow and structural tests
- Calibration of instrumentation
- Flow visualization test
- Flow stability test
- Heat transfer performance test

D. Post Test Evaluation

POTENTIAL LAYOUT OF EXPERIMENT APPARATUS FOR FLOW DISTRIBUTION CONTROL STUDY OF MARINE WASTE HEAT STEAM GENERATOR



87-5-86-23

FIG. III.2

PROGRAM SCHEDULE AND EFFORT FOR EXPERIMENTAL STUDY OF FLOW DISTRIBUTION CONTROLS IN MARINE GAS TURBINE WASTE HEAT STEAM GENERATOR

ACTIVITIES	SCHEDULE (MONTHS)																MAN-HOURS	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	ENG	TECH
MODEL DESIGN DEFINITION	■	■															300	40
MODEL FABRICATION (INCLUDING INSTRUMENTATION)		■	■	■	■												50	500
TEST SITE PREPARATION					■												0	50
AUXILIARY EQUIPMENT SET-UP					■	■	■										80	300
INSTALLATION AND SHAKEDOWN						■	■	■									50	200
FLOW VISUALIZATION TEST								■	■	■							50	200
FLOW STABILITY TEST									■	■							50	200
HEAT TRANSFER PERFORMANCE TEST											■	■	■	■			120	500
POST TEST EVALUATION															■	■	300	60
																TOTAL	1000	2050

82-6-86-22

APPENDIX A

DESCRIPTIONS OF WASTE-HEAT BOILER COMPUTER PROGRAM

The heat exchanger computer program which was used to study the effect of flow distribution control on marine waste-heat steam generator performance was developed from the analytical model presented in Section II of this report. This program can be used to predict the overall performance, size, and manufacturing cost for many types of crossflow heat exchangers. It is applicable to nearly any kind of gas and liquid provided that their heat transfer and pressure loss correlations are expressed in the form shown in the book "Compact Heat Exchangers" by Kays and London. The surfaces of the heat exchanger core can be of plate-fin, finned-tube, or screen-matrices geometries. Although the program can be easily extended to other heat exchanger applications, it is currently limited to the cases where the gases are flowing on the shell side and the liquid is on the tube side. The liquid may undergo phase changes (from liquid phase to boiling phase, and then to superheated vapor, but not in reverse process) depending on the design requirement specified.

Program Structure

The program was organized in hierarchical structure as shown in Fig. A.1. The main program which is called HXMAIN is the commanding portion used to call the three subroutines (HXINPUT, HXCALC, and HXOUTPUT) which perform the specific tasks as indicated in their respective boxes in the figure. The subroutine HXINPUT reads the input data, interprets and initializes these data prior to the heat exchanger performance calculations, and finally stores all of the relevant information in the common blocks. The input data consists of a job title, job control parameters, the inlet flow conditions, the interconnection of flow paths, flow properties, and heat transfer and pressure loss correlations, all of which are explained in the next section.

The subroutine HXCALC is the calculation section of the heat exchanger program which is based on the flow equations and the computation process described in Section II of this report. This program takes the input data from the common blocks as needed during the computation process and also stores the computed results in the common blocks. The function of the HXOUTPUT routine is to translate the results of the heat exchanger performance computed by the HXCALC routine into practical engineering units and print them as hard-copy. The output results consist of convergence information, summary results, temperature distributions for gas, liquid, and tube walls, and heat transfer coefficients throughout the entire heat exchanger core.

The program which is written in Fortran language is implemented on a UNIVAC 1110/80 computer system and requires approximately 50K core storage. The computational time required for a typical study varies according to the tolerance of convergence and the number of nodes specified for the heat exchanger core. For the cases studied, each of which consist of five gas paths and one liquid path, one hundred nodes in heat exchanger core, and a five-degree-fahrenheit tolerance on the exit temperatures for both working fluids, the computational time was approximately 30 to 40 seconds.

In the following section, the input parameters are discussed, the results of a example run are presented, and the listing of the Fortran statements for the main program and three major subroutines are given.

Description of Input Data

The input data for the Waste-Heat Boiler Computer Program are listed in Tables A.1 and A.2. Table A.1 contains four different types of input data; the job title, the job control parameters, the inlet flow conditions, and the nodal connection method for each flow path.

The job title, which may be comprised of up to 72 characteristics, must be punched on a BCD card. The job control parameters (there are twenty two of them) are defined as follows:

NI = No. of nodes in I-direction ($\leq$ 30)
NJ = No. of nodes in J-direction ($\leq$ 30)
NPTHA = No. of paths for gas side ($\leq$ 10)
NPTHB = No. of paths for liquid side ($\leq$ 10)
NPRNT = option for printing the intermediate iteriation results (=0 or 1)
NDUMP = option for dumping the detail calculation for each iteration (=0 or 1)
KOMPLX = option for using or not using the boiling heat transfer model (=0 or 1)
NITER = maximum No. of iterations (default value = 25)
YLEN = overall core height (= $\Sigma N_j \Delta j_j$ inches)
XLEN = overall core width (= $\Sigma N_i \Delta X_i$ inches)
ZA=ZB = overall core depth (inches)
THKWAL = tube wall thickness (inches)
TOTITR = convergence tolerance for iteration of the exit temperature of the fluids (°F)
TURNLA = factor for turn loss on the gas-side
TURNLB = factor for turn loss on the liquid side
NCOST = option for cost estimate (=0 or 1)
NTYPE = types of heat exchanger (1 to 5)
MTCORE = types of tubes material (1 to 8)
MTSHEL = types of shell material (1 to 8)
FACTF = fabrication complexity factor
FACTE = escalation factor from Mid '70 dollar value

In addition to the job control parameters, there are several sets of input data which were used to describe the inlet flow conditions and the nodal connection method for each flow path (see line 6 to line 28, or line 29 to 51, etc. of Table A.1). The number of these data sets is equal to the number of gas paths (NPTHA) plus the liquid paths (NPTHB). The first two data cards for each data set contain ten parameters which are defined as follows:

WDOT = gas flow rate (lb/sec)
PZRO = gas inlet pressure (psia)
TZRO = gas inlet temperature (°F)
DHYD = hydraulic diameter (inches)
DELTAX = nodal width (inches)
FAOFA = flow area/frontal area
SAOV = surface area/volume
FINTHK = fin thickness (inches)
FINLEN = fin length (inches)
FINSRF = fin area/surface area

The remainder of the input data are for flow direction, number of nodes, and nodal connection sequence. The liquid-side flow conditions and nodal connections (lines 122 to 223) are similar to those for the gas flow except that the last five parameters are replaced by a NTUBES parameter which is used to specify the number of tubes for that path.

The development of this heat exchanger computer code was developed to be independent of the working fluids, and therefore the user has complete freedom of choosing a working fluid to meet a specific need. Consequently, the thermal and physical properties of working fluids must be specified as part of the input data for the program. For application in the present study, the properties of air and water are tabulated in a special format as shown in Table A.2. It should be noted that each data set is preceeded by an integer number which specifies the number of entries to be read.

The thermal and physical properties for the liquid-side working fluid are given in lines No. 1 through 209 of Table A.2. Lines No. 1 to No. 24 (which were not used in the present study) are the coke (scale) properties, the coke thickness as function of temperature, and the coke formation history as function of time. Lines 26 to 30 tabulate the saturation pressures (psia) and temperatures (°F). The formats for these entries are E10.5. Lines 31 to 33 are the empirical constants for computing the convective heat transfer coefficients (see Eqs. 1a to 1c in Section II of this report) for laminar-, turbulent-, or supercritical-flow.

Lines 35 to 56 provide the heat transfer correlations in terms of Reynolds number and $StPr^{2/3}$ for the vapor phase. Lines 58 to 66 tabulate the liquid properties including its the temperature (°F), viscosity (lb_m/ft-sec), thermal conductivity (Btu/ft-F-Hr), specific heat at constant pressure (Btu/lb_mF) and density (lb_m/ft^3). The input format is also in E10.5. Line 67 consists of three parameters which represent the critical pressure (psia), critical temperature (°F), and molecular weight.

Lines 68 to 119 are the tabulations of vapor properties which consist of the pressure (psia), temperature (°F), density (lb/ft^3), viscosity (lb_m/ft-sec), thermal conductivity (Btu/ft-F-Hr) and specific heat at constant pressure (Btu/lb_m-F). Each parameter will be read in E10.5 format. The number of the pressure entries is specified by the first parameter on line 68 and the numbers of entries for other parameters at a given pressure are specified on line 69. The second parameter shown on line 68 represent the type of the working fluid: 1 for distillate and 2 for pure substance.

Lines 121 through 125 tabulate the saturation pressure (psia) and the heat capacity (Btu/lb_m-F) for the boiling mixture if the boiling heat transfer model is not used (i.e. KONFLX=0). Lines 128 to 139 are the pressure (psia), the temperature (°F) and the density (lb_m/ft^3) above the critical point. These data are also read in E10.5 format. There are three sets of pressure data (as shown on line 126) and at each pressure value, there are four sets of data for the temperature and density. Lines 141 to 1 45 give five saturation pressures (psia) and their corresponding values of heat of vaporization (Btu/lb). They all have the same input format of E10.5.

Lines 147 and 148 presents the data for temperature (°F) and surface tension (dyne/cm). The F-function and the S-function required for boiling phase heat transfer computations (see Eqs. 3a and 3b in Section II of this report) are presented in lines 150 to 170 and lines 172 to 186, respectively. Finally, the friction coefficient (which was defined as $\Delta p = 4f\rho V^2 L/(2gD)$ as function of Reynolds number are presented in lines 188 to line 209.

The gas-side thermal and physical properties are tabulated in lines 210 to 265. Line 210 specifies the molecular weight of the gas while the temperature (°F), molecular viscosity (lb_m/ft-sec), thermal conductivity (Btu/ft-F-Hr), and specific heat at constant pressure (Btu/lb_m-F) are presented in lines 212 to 230. The friction coefficient and the Stanton numbers as functions of Reynolds number are given in lines 232 to 246 and lines 248 to 262, respectively. Finally the wall (tube) thermal conductivity (Btu/ft-F-Hr) as function of temperature (°F) are tabulated in lines 264 and 265. All these entries are also read in E10.5 format.

Sample Results

Based on the input data shown in Table A.1 and A.2, the computed results for heat exchanger performance are presented in Tables A.3 through A.7.

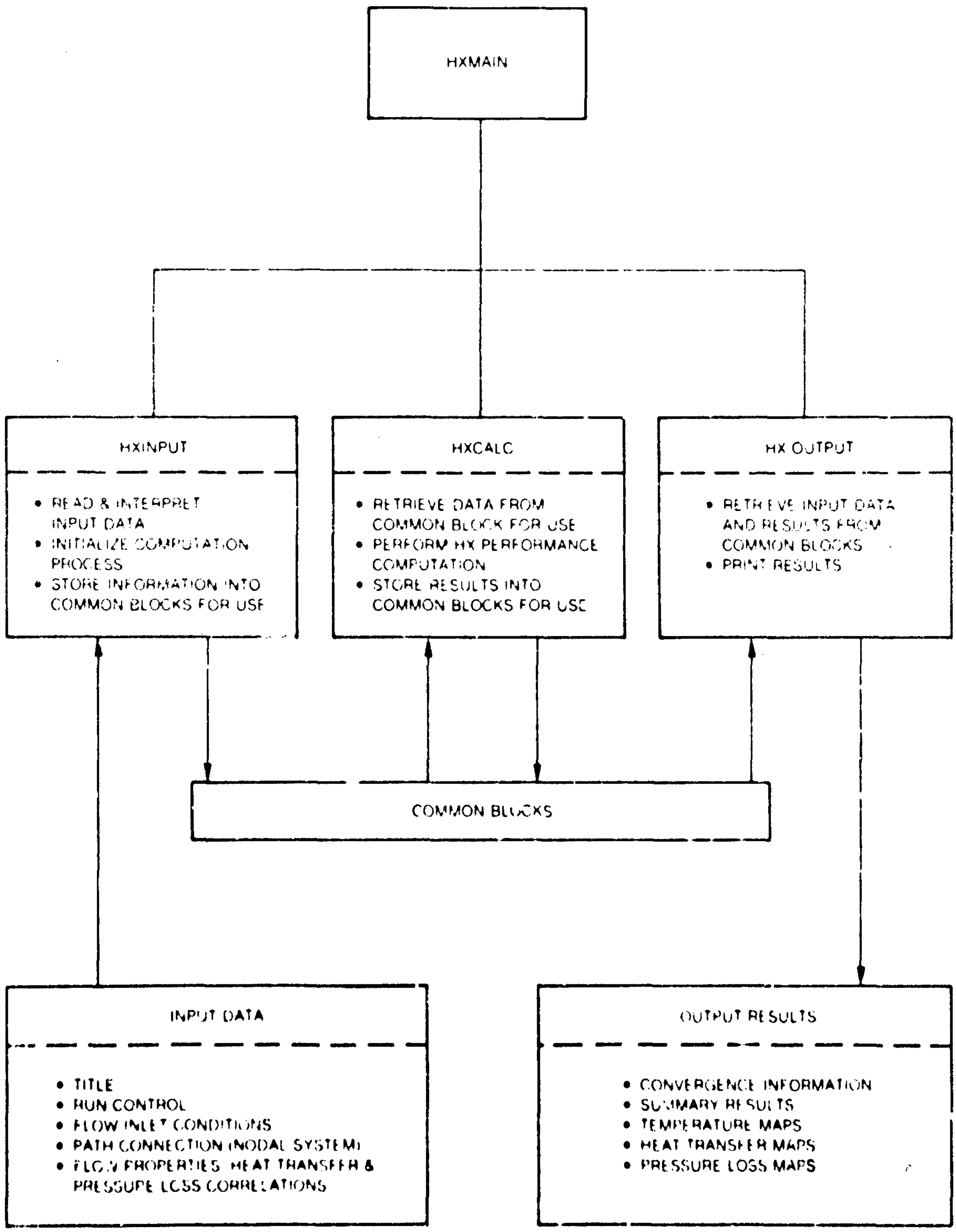
Table A.3 presents the convergence information; i.e., number of iterations and the tolerated errors in exit temperature of the working fluids between the last two iterations. The summary results, which include the flow conditions, the heat exchanger size, and the manufacturing cost estimate (not shown in this example), are shown in Table A.4.

Table A.5 shows the temperature distribution for the entire heat exchanger core, including the inlet, and the outlet as well as the mean temperatures for both working fluids and the wall temperatures on each side of the tubes for each node. The distributions of the convective heat transfer coefficient, the Reynolds number, and the overall heat transfer coefficient are shown in Table A.6. The liquid-side pressure loss characteristics, the steam quality, and the boiling heat transfer coefficients are shown in Table A.7.

List of Computer Programs

The listing for Fortran statement for the four major computer programs (HXMAIN, HXINPUT, HXCALC, HXOUTPUT) and the common block allocations are shown in Tables A.8 to A.12.

STRUCTURE OF WASTE-HEAT BOILER COMPUTER PROGRAM



82-5-66-24

TABLE A.1 INPUT DATA FOR MARINE WASTE-HEAT BOILER STUDY

```
MARINE WASTE-HEAT BOILER DESIGN STUDY (UNIFORM FLOW, 50% POWER)
$RUNCON NI=20,NJ=5,NPTHA=5,NPTHB=1,NPRNT=0,NDUMP=0,KOMPLX=1,
        YLEN=70.0,XLEN=120.0,ZA=84.0,ZB=84.0,THKWAL=0.095,
        TOLITR=5.0,TURNLA=0.0,TURNLB=0.0,NCOST=0,NTYPE=4,
        MTCORE=1,MTSHEL=1,FACTF=1.25,FACTE=3.11,$END
     2       20
  20.0   14.834    796.0    0.322    24.0
 0.572    85.10    0.012   0.3445   0.835
     1        1
     2        1
     3        1
     4        1
     5        1
     6        1
     7        1
     8        1
     9        1
    10        1
    11        1
    12        1
    13        1
    14        1
    15        1
    16        1
    17        1
    18        1
    19        1
    20        1
     2       20
  20.0   14.834    796.0    0.322    24.0
 0.572    85.10    0.012   0.3445   0.835
     1        2
     2        2
     3        2
     4        2
     5        2
     6        2
     7        2
     8        2
     9        2
    10        2
    11        2
    12        2
    13        2
    14        2
    15        2
    16        2
    17        2
    18        2
    19        2
    20        2
     2       20
  20.0   14.834    796.0    0.322    24.0
 0.572    85.10    0.012   0.3445   0.835
     1        3
     2        3
     3        3
     4        3
     5        3
     6        3
     7        3
     8        3
     9        3
    10        3
    11        3
    12        3
    13        3
    14        3
    15        3
    16        3
    17        3
    18        3
    19        3
```

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TABLE A.1 Cont'd

74	20	1				
75	2	20				
76	20.0	14.834	796.0	0.322	24.0	
77	0.572	85.10	0.012	0.3445	0.835	
78	1	4				
79	2	4				
80	3	4				
81	4	4				
82	5	4				
83	6	4				
84	7	4				
85	8	4				
86	9	4				
87	10	4				
88	11	4				
89	12	4				
90	13	4				
91	14	4				
92	15	4				
93	16	4				
94	17	4				
95	18	4				
96	19	4				
97	20	4				
98	[illegible]	[illegible]				
99	20.0	14.934	796.0	0.322	24.0	
100	0.572	85.10	0.012	0.3445	0.835	
101	1	5				
102	2	5				
103	3	5				
104	4	5				
105	5	5				
106	6	5				
107	7	5				
108	8	5				
109	9	5				
110	10	5				
111	11	5				
112	12	5				
113	13	5				
114	14	5				
115	15	5				
116	16	5				
117	17	5				
118	18	5				
119	19	5				
120	20	5				
121	1	100	63			
122	9.75	300.0	115.7	83	0.665	4.0
123	20	1				
124	20	2				
125	20	3				
126	20	4				
127	20	5				
128	19	[illegible]				
129	19	4				
130	19	3				
131	19	2				
132	19	1				
133	18	1				
134	18	[illegible]				
135	18	3				
136	19	4				
137	18	5				
138	17	5				
139	17	4				
140	17	3				
141	17	2				
142	17	1				
143	16	1				
144	16	2				
145	16	[illegible]				

TABLE A.1 Cont'd

146	16	4
147	16	5
148	15	5
149	15	4
150	15	3
151	15	2
152	15	1
153	14	1
154	14	2
155	14	3
156	14	4
157	14	5
158	13	5
159	13	4
160	13	3
161	13	2
162	13	1
163	12	1
164	12	2
165	12	3
166	12	4
167	12	5
168	11	5
169	11	4
170	11	3
171	11	2
172	11	1
173	10	1
174	10	2
175	10	3
176	10	4
177	10	5
178	9	5
179	9	4
180	9	3
181	9	2
182	9	1
183	8	1
184	8	2
185	8	3
186	8	4
187	8	5
188	7	5
189	7	4
190	7	3
191	7	2
192	7	1
193	6	1
194	6	2
195	6	3
196	6	4
197	6	5
198	5	5
199	5	4
200	5	3
201	5	2
202	5	1
203	4	1
204	4	2
205	4	3
206	4	4
207	4	5
208	3	5
209	3	4
210	3	3
211	3	2
212	3	1
213	2	1
214	2	2
215	2	3
216	2	4
217	2	5

TABLE A.1 Cont'd

218		1	5
219		1	4
220		1	3
221		1	2
222		1	1
223	@ADD .PROPTY3		

TABLE A.2 THERMAL AND PHYSICAL PROPERTIES FOR WATER AND AIR

0.33					
19					
150.0	0.0				
200.0	1.720E-07				
250.0	5.640E-07				
300.0	1.800E-06				
350.0	5.580E-06				
400.0	3.960E-05				
450.0	1.590E-04				
500.0	3.960E-04				
550.0	9.900E-04				
600.0	2.350E-03				
650.0	3.960E-03				
700.0	1.550E-0[illegible]				
710.0	1.780E-0[illegible]				
750.0	[illegible]				
790.0	2.150E-02				
800.0	1.760E-02				
1000.0	5.940E-03				
1200.0	1.465E-03				
1300.0	7.920E-0[illegible]				
100.0					
1					
0.0					
5					
.2000+03	.3619+03				
.2500+03	.4010+03				
.3000+03	.4174+03				
.3500+03	.4318+03				
.4000+03	.4447+03				
0.596	0.498	0.140			
0.0046	0.927	0.426			
0.003354	0.951	0.435			
22					
500.	.0096[illegible]				
600.	.00820				
700.	.00730				
800.	.00660				
900.	.00600				
1000.	.00560				
1500.	.00410				
2000.	.00340				
3000.	.00280				
4000.	.00280				
5000.	.00300				
6000.	.00340				
8000.	.00355				
10000.	.00350				
15000.	.00330				
20000.	.00310				
30000.	.00280				
40000.	.00270				
50000.	.00260				
80000.	.00240				
100000.	.00220				
500000.	.00200				
9					
.5000+02	.8776-03	.3369+00	.1005+01	.6246+02	
.1000+03	.4582-03	.3622+00	.9987+00	.6205+02	
.1500+03	.2897-03	.3795+00	.1001+01	.6124+02	
.2000+03	.2044-03	.3904+00	.1006+01	.6017+02	
.2500+03	.1550-03	.3957+00	.1016+01	.5887+02	
.3000+03	.1237-03	.3959+00	.1030+01	.5736+02	
.3500+03	.1027-03	.3911+00	.1051+01	.5564+02	
.4000+03	.8786-04	.3818+00	.1079+01	.5367+02	
.4174+03	.8366-04	.3774+00	.1092+01	.5292+02	
.3206+04	.7054+03	.1800+02			
5	2				
10	10	10	10	10	
.2000+03	.3619+03	.4368+00	.1047-04	.2196-01	.6488+00
.2000+03	.4000+03	.4235+00	.1077-04	.2199-01	.6236+00
.2000+03	.4500+03	.3925+00	.1159-04	.2269-01	.5762+00

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TABLE A.2 Cont'd

73	.2000+03	.5000+03	.3671+00	.1240-04	.2388-01	.5486+00
74	.2000+03	.5500+03	.3456+00	.1320-04	.2532-01	.5325+00
75	.2000+03	.6000+03	.3270+00	.1400-04	.2690-01	.5233+00
76	.2000+03	.6500+03	.3106+00	.1480-04	.2859-01	.5194+00
77	.2000+03	.7000+03	.2959+00	.1559-04	.3033-01	.5163+00
78	.2000+03	.7500+03	.2627+00	.1638-04	.3214-01	.5160+00
79	.2000+03	.8000+03	.2707+00	.1717-04	.3401-01	.5169+00
80	.2500+03	.4011+03	.5420+00	.1073-04	.2316-01	.6525+00
81	.2500+03	.4500+03	.4995+00	.1154-04	.2337-01	.6135+00
82	.2500+03	.5000+03	.4651+[illegible]	.1236-04	.2433-01	.5731+[illegible]
83	.2500+03	.5500+03	.4366+00	.1317-04	.2565-01	.5496+00
84	.2500+03	.6000+03	.4122+00	.1398-04	.2716-01	.5357+00
85	.2500+03	.6500+03	.3909+00	.1476-04	.2860-01	.5279+00
86	.2500+03	.7000+03	.3720+00	.1556-04	.3052-01	.5237+00
87	.2500+03	.7500+03	.3551+00	.1636-04	.3232-01	.5220+00
88	.2500+03	.8000+03	.3398+00	.1716-04	.3417-01	.5219+00
89	.2500+03	.8500+03	.3259+00	.1795-04	.3608-01	.5226+00
90	.3000+03	.4174+03	.6475+00	.1094-04	.2426-01	.7155+00
91	.3000+03	.4500+03	.6111+00	.1149-04	.2417-01	.6565+00
92	.3000+03	.5000+03	.5661+00	.1273-04	.2484-01	.6075+00
93	.3000+03	.5500+03	.5297+00	.1315-04	.2601-01	.5682+00
94	.3000+03	.6000+03	.4989+00	.1396-04	.2744-01	.5490+00
95	.3000+03	.6500+03	.4724+00	.1477-04	.2904-01	.5376+00
96	.3000+03	.7000+03	.4490+00	.1557-04	.3073-01	.5314+00
97	.3000+03	.7500+03	.4252+00	.1637-04	.3250-01	.5292+00
98	.3000+03	.8000+03	.4094+00	.1716-04	.3434-01	.5270+00
99	.3000+03	.8500+03	.3924+00	.1795-04	.3624-01	.5271+00
100	.3500+03	.4318+03	.7536+00	.1114-04	.2532-01	.7482+00
101	.3500+03	.4500+03	.7281+00	.1145-04	.2511-01	.7067+00
102	.3500+03	.5000+03	.6705+00	.1229-04	.2541-01	.6310+00
103	.3500+03	.5500+03	.6250+00	.1313-04	.2640-01	.5683+00
104	.3500+03	.6000+03	.5873+[illegible]	.1395-04	.2775-01	.5632+00
105	.3500+03	.6500+03	.5551+00	.1476-04	.2929-01	.5482+00
106	.3500+03	.7000+03	.5269+00	.1557-04	.3094-01	.5394+00
107	.3500+03	.7500+03	.5020+00	.1637-04	.3269-01	.5346+00
108	.3500+03	.8000+03	.4797+00	.1716-04	.3452-01	.5322+00
109	.3500+03	.8500+03	.4595+00	.1795-04	.3640-01	.5315+00
110	.4000+03	.4447+03	.8605+00	.1131-04	.2631-01	.7806+00
111	.4000+03	.4500+03	.8513+00	.1140-04	.2620-01	.7657+00
112	.4000+03	.5000+03	.7785+00	.1226-04	.2605-01	.6653+00
113	.4000+03	.5500+03	.7228+00	.1310-04	.2684-01	.6102+00
114	.4000+03	.6000+03	.6774+00	.1393-04	.2807-01	.5782+00
115	.4000+03	.6500+03	.6391+00	.1475-04	.2955-01	.5592+00
116	.4000+03	.7000+03	.6059+00	.1556-04	.3116-01	.5476+00
117	.4000+03	.7500+03	.5766+00	.1636-04	.3289-01	.5411+00
118	.4000+03	.8000+03	.5505+00	.1716-04	.3470-01	.5375+00
119	.4000+03	.8500+03	.5270+00	.1795-04	.3656-01	.5359+00
120	5					
121	.2000+03	.1000+23				
122	.2500+03	.1000+23				
123	.3000+03	.1000+23				
124	.3500+03	.1000+23				
125	.4000+03	.1000+23				
126	3					
127	4	4	4			
128	.3500+04	.7000+03	.3271+02			
129	.3500+04	.8000+03	.7338+01			
130	.3500+04	.9000+03	.5673+01			
131	.3500+04	.1000+04	.4839+01			
132	.4000+04	.7000+03	.3497+02			
133	.4000+04	.8000+03	.9502+01			
134	.4000+04	.9000+03	.6838+01			
135	.4000+04	.1000+04	.5707+01			
136	.5000+04	.7000+03	.3737+02			
137	.5000+04	.8000+03	.1685+02			
138	.5000+04	.9000+03	.9625+01			
139	.5000+04	.1000+04	.7621+01			
140	5					
141	.2300+03	.8456+03				
142	.2500+03	.8279+03				
143	.3000+03	.8118+03				
144	.3500+03	.7970+03				

TABLE A.2 Cont'd

145	.4000+03	.7632+03			
146	2				
147	0.0	73.00			
148	550.0	73.00			
149	21				
150	.1	1.0			
151	.2	1.2			
152	.3	1.4			
153	.4	1.55			
154	.5	1.75			
155	.5	2.			
156	.6	[illegible]			
157	1.	3.7			
158	2.	4.			
159	3.	5.5			
160	4.	6.5			
161	6.	9.			
162	5.	11.			
163	10.	12.5			
164	20.	[illegible]			
165	30.	30.			
166	40.	36.			
167	50.	43.			
168	20.	46.			
169	30.	60.			
170	100.	70.			
171	15				
172	1.0E4	1.			
173	2.0E4	.8			
174	3.0E4	.7			
175	4.0E4	.63			
176	5.0E4	.56			
177	6.0E4	.53			
178	7.0E4	.49			
179	8.0E4	.46			
180	9.0E4	.43			
181	1.0E5	.39			
182	1.5E5	.32			
183	2.0E5	.24			
184	3.0E5	.16			
185	4.0E5	.13			
186	5.0E5	.11			
187	22				
188	6000.	.0500			
189	7000.	.0238			
190	8000.	.0200			
191	9000.	.0180			
192	10000.	.0160			
193	15000.	.0105			
194	20000.	.0080			
195	30000.	.0110			
196	40000.	.0105			
197	50000.	.0100			
198	60000.	.0090			
199	80000.	.0085			
200	100000.	.0080			
201	150000.	.0073			
202	200000.	.0070			
203	400000.	.0063			
204	600000.	.0059			
205	800000.	.0058			
206	1000000.	.0056			
207	1500000.	.0055			
208	2000000.	.0054			
209	8000000.	.005			
210	28.966				
211	19				
212	-100.0		6.893E-06	0.01045	0.2403
213	80.0		1.241E-05	0.01516	0.2402
214	260.0		1.536E-05	0.01944	0.2422
215	440.0		1.795E-05	0.02333	0.2459
216	620.0		2.028E-05	0.02692	0.2520

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TABLE A.2 Cont'd

217	800.0	2.259E-05	0.03022	0.2568
218	980.0	2.436E-05	0.03339	0.2622
219	1160.0	2.620E-05	0.03628	0.2676
220	1340.0	2.790E-05	0.03901	0.2727
221	1520.0	2.955E-05	0.04178	0.2772
222	1700.0	3.109E-05	0.04410	0.2815
223	1880.0	3.258E-05	0.04641	0.2860
224	[illegible]	3.398E-05	0.04860	0.2900
225	2240.0	3.533E-05	0.05098	0.2939
226	2420.0	3.668E-05	0.05345	0.2980
227	2600.0	3.792E-05	0.05550	0.3028
228	2780.0	3.915E-05	0.05750	0.3075
229	2960.0	4.029E-05	0.05910	0.3128
230	3140.0	4.168E-05	0.06120	0.3196
231	15			
232	1000.	.05059		
233	1500.	.04569		
234	2000.	.04250		
235	2500.	.04018		
236	3000.	.03839		
237	4000.	.03571		
238	5000.	.03376		
239	6000.	.03225		
240	7[illegible].	.031[illegible]		
241	8000.	.030[illegible]		
242	9000.	.02913		
243	10000.	.02837		
244	15000.	.02562		
245	20000.	.0236[illegible]		
246	50000.	.01893		
247	15			
248	1000.	.01029		
249	1500.	.00901		
250	2000.	.00820		
251	2500.	.00762		
252	3000.	.00716		
253	4000.	.00653		
254	5000.	.00607		
255	6000.	.00572		
256	7000.	.00543		
257	8000.	.00520		
258	9000.	.00500		
259	10000.	.00483		
260	15000.	.00427		
261	20000.	.00385		
262	50000.	.00265		
263	2			
264	0.0	10.0		
265	100000.0	10.0		

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TABLE A.3 CONVERGENCE INFORMATION FOR HEAT EXCHANGER PERFORMANCE STUDY

PROGRAM CONVERGED AFTER 19 ITERATIONS

SIDE	PATH	ERROR-DEG F
A	1	1.450
A	2	2.553
A	3	-4.571
A	4	2.486
A	5	.661
B	1	-2.499

TABLE A.4 RESULTS OF HEAT EXCHANGER PERFORMANCE STUDY

A. FLOW CONDITIONS FOR MARINE WASTE-HEAT BOILER DESIGN STUDY (UNIFORM FLOW, 50% POWER)

SIDE	PATH	START	END	FLOW LB/SEC	T-IN DEG F	T-OUT DEG F	P-IN PSIA	P-OU PSIA	QDOT BTU/SEC
A	1	1, 1	20, 1	20.00	796.00	343.94	14.83	14.23	2521.54
A	2	1, 2	20, 2	20.00	796.00	345.38	14.83	14.23	2514.04
A	3	1, 3	20, 3	20.00	796.00	343.35	14.83	14.23	2525.39
A	4	1, 4	20, 4	20.00	796.00	345.57	14.83	14.23	2514.85
A	5	1, 5	20, 5	20.00	796.00	345.77	14.83	14.23	2514.48
B	1	20, 1	1, 1	9.75	115.70	794.00	300.00	286.84	12590.30

B. THE CORE SIZE OF THIS HEAT EXCHANGER IS APPROXIMATELY = 5.83 FT. BY 10.00 FT. BY 7.00 FT.

TABLE A.5 TEMPERATURE DISTRIBUTION FOR HEAT EXCHANGER CORE

RESULTS OF MARINE WASTE-HEAT BOILER DESIGN STUDY (UNIFORM FLOW, 50% POWER)

I	J	TA-IN DEG F	TA-OUT DEG F	TA-MEAN DEG F	TWALL-A DEG F	TWALL-B DEG F	TCOKE DEG F	TB-IN DEG F	TB-OUT DEG F	TB-MEAN DEG F
1	1	796.000	784.873	790.437	744.015	738.603	738.603	691.604	704.002	697.803
1	2	796.000	783.377	789.688	737.023	730.884	730.884	677.586	691.604	684.595
1	3	796.000	781.686	788.843	729.123	722.163	722.163	661.753	677.586	669.670
1	4	796.000	779.774	787.887	720.192	712.303	712.303	643.904	661.753	652.829
1	5	796.000	777.611	786.806	710.087	701.148	701.148	623.847	643.904	633.876
2	1	784.873	753.217	769.045	637.013	621.673	621.673	496.248	527.194	511.721
2	2	783.377	755.529	769.453	653.306	639.811	639.811	527.194	555.436	541.315
2	3	781.686	757.253	769.470	667.557	655.727	655.727	555.436	580.954	568.195
2	4	779.774	758.367	769.070	679.787	669.414	669.414	580.954	603.701	592.327
2	5	777.611	758.926	768.268	690.339	681.286	681.286	603.701	623.847	613.774
3	1	753.217	721.116	737.167	603.345	587.880	587.880	466.670	496.248	481.459
3	2	755.529	718.932	737.230	584.663	567.031	567.031	435.192	466.670	450.931
3	3	757.253	697.887	727.570	480.076	451.523	451.523	417.400	435.192	426.296
3	4	758.367	697.004	727.685	471.344	441.771	441.771	417.400	417.400	417.400
3	5	758.926	696.695	727.810	467.840	437.848	437.848	417.400	417.400	417.400
4	1	721.116	664.322	692.719	456.010	428.868	428.868	417.400	417.400	417.400
4	2	718.932	662.621	690.777	456.088	429.186	429.186	417.400	417.400	417.400
4	3	697.887	645.691	671.789	454.222	429.372	429.372	417.400	417.400	417.400
4	4	697.004	645.256	671.130	455.411	430.778	430.778	417.400	417.400	417.400
4	5	696.695	645.248	670.972	456.500	432.011	432.011	417.400	417.400	417.400
5	1	664.322	618.059	641.191	448.303	426.400	426.400	417.400	417.400	417.400
5	2	662.621	616.700	639.661	448.049	426.296	426.296	417.400	417.400	417.400
5	3	645.691	603.378	624.535	446.422	426.264	426.264	417.400	417.400	417.400
5	4	645.256	603.152	624.204	446.912	426.849	426.849	417.400	417.400	417.400
5	5	645.248	603.175	624.211	447.049	427.002	427.002	417.400	417.400	417.400
6	1	618.059	581.558	599.808	443.646	426.065	426.065	417.400	417.400	417.400
6	2	616.700	580.372	598.536	443.116	425.624	425.624	417.400	417.400	417.400
6	3	603.378	569.504	586.441	441.512	425.246	425.246	417.400	417.400	417.400
6	4	603.152	569.382	586.267	441.771	425.557	425.557	417.400	417.400	417.400
6	5	603.175	569.390	586.283	441.720	425.498	425.498	417.400	417.400	417.400
7	1	581.558	551.699	566.628	438.882	424.610	424.610	417.400	417.400	417.400
7	2	580.372	550.754	565.563	438.850	424.697	424.697	417.400	417.400	417.400
7	3	569.504	541.968	555.736	437.910	424.781	424.781	417.400	417.400	417.400
7	4	569.382	541.973	555.678	438.387	425.320	425.320	417.400	417.400	417.400
7	5	569.390	542.019	555.705	438.575	425.526	425.526	417.400	417.400	417.400
8	1	551.699	527.568	539.633	436.371	424.910	424.910	417.400	417.400	417.400
8	2	550.754	526.731	538.742	435.941	424.533	424.533	417.400	417.400	417.400
8	3	541.968	519.555	530.762	434.833	424.210	424.210	417.400	417.400	417.400
8	4	541.973	519.577	530.775	434.909	424.293	424.293	417.400	417.400	417.400
8	5	542.019	519.602	530.811	434.856	424.231	424.231	417.400	417.400	417.400
9	1	527.568	507.832	517.700	433.217	423.891	423.891	417.400	417.400	417.400
9	2	526.731	507.183	516.957	433.275	424.039	424.039	417.400	417.400	417.400
9	3	519.555	501.405	510.480	432.766	424.204	424.204	417.400	417.400	417.400
9	4	519.577	501.477	510.527	433.027	424.489	424.489	417.400	417.400	417.400
9	5	519.602	501.536	510.569	433.214	424.691	424.691	417.400	417.400	417.400
10	1	507.832	491.955	499.894	431.901	424.430	424.430	417.400	417.400	417.400
10	2	507.183	491.385	499.284	431.632	424.199	424.199	417.400	417.400	417.400
10	3	501.405	486.680	494.043	430.964	424.045	424.045	417.400	417.400	417.400
10	4	501.477	486.703	494.090	430.804	423.861	423.861	417.400	417.400	417.400
10	5	501.536	486.722	494.129	430.673	423.712	423.712	417.400	417.400	417.400

TABLE A.5 Cont'd

RESULTS OF MARINE WASTE-HEAT BOILER DESIGN STUDY (UNIFORM FLOW, 50% POWER)

I	J	TA-IN DEG F	TA-OUT DEG F	TA-MEAN DEG F	TWALL-A DEG F	TWALL-B DEG F	TCOKE DEG F	TB-IN DEG F	TB-OUT DEG F	TB-MEAN DEG F
11	1	491.955	478.941	485.448	429.691	423.568	423.588	417.400	417.400	417.400
11	2	491.385	478.540	484.963	429.929	423.906	423.906	417.400	417.400	417.400
11	3	486.680	474.810	480.745	429.878	424.318	424.318	417.400	417.400	417.400
11	4	486.703	474.817	480.760	429.828	424.261	424.261	417.400	417.400	417.400
11	5	486.722	474.849	480.785	429.905	424.343	424.343	417.400	417.400	417.400
12	1	478.941	468.604	473.773	429.473	424.639	424.639	417.400	417.400	417.400
12	2	478.540	468.250	473.395	429.293	424.482	424.482	417.400	417.400	417.400
12	3	474.810	465.200	470.005	428.808	424.318	424.318	417.400	417.400	417.400
12	4	474.817	465.127	469.972	428.435	423.906	423.906	417.400	417.400	417.400
12	5	474.849	465.089	469.969	428.131	423.571	423.571	417.400	417.400	417.400
13	1	468.604	460.111	464.358	427.945	423.982	423.982	417.400	417.400	417.400
13	2	468.250	459.901	464.075	428.279	424.384	424.384	417.400	417.400	417.400
13	3	465.200	457.376	461.288	427.739	424.091	424.091	417.400	417.400	417.400
13	4	465.127	457.398	461.263	428.122	424.519	424.519	417.400	417.400	417.400
13	5	465.089	458.522	461.805	433.137	430.019	430.019	416.820	417.400	417.110
14	1	460.111	451.497	455.804	419.863	414.852	414.852	397.795	402.335	400.065
14	2	459.901	451.962	455.931	421.882	418.185	418.185	402.335	406.508	404.421
14	3	457.376	450.467	453.922	423.760	420.487	420.487	406.508	410.192	408.350
14	4	457.398	451.027	454.213	426.393	423.374	423.374	410.192	413.581	411.886
14	5	458.522	452.421	455.472	428.837	425.945	425.945	413.581	416.820	415.201
15	1	451.497	443.514	447.505	413.256	409.545	409.545	393.586	397.795	395.690
15	2	451.962	443.332	447.647	410.624	406.614	406.614	389.026	393.586	391.306
15	3	450.467	441.340	445.903	406.747	402.507	402.507	384.192	389.026	386.609
15	4	451.027	441.200	446.114	403.949	399.384	399.384	378.974	384.192	381.583
15	5	452.421	441.567	446.994	400.429	395.385	395.385	373.191	378.974	376.082
16	1	443.514	429.260	436.387	377.105	370.703	370.703	341.469	348.924	345.197
16	2	443.332	430.151	436.741	381.899	375.977	375.977	348.924	355.801	352.363
16	3	441.340	429.183	435.261	385.012	379.586	379.586	355.801	362.079	358.940
16	4	441.200	430.138	435.669	389.641	384.672	384.672	362.079	367.810	364.945
16	5	441.567	431.169	436.368	393.030	388.350	388.350	367.810	373.191	370.500
17	1	429.260	415.961	422.611	367.807	361.913	361.913	334.585	341.469	338.027
17	2	430.151	415.786	422.968	363.764	357.397	357.397	327.126	334.585	330.856
17	3	429.183	413.666	421.424	357.497	350.621	350.621	319.045	327.126	323.086
17	4	430.138	413.575	421.856	353.581	346.240	346.240	310.389	319.045	314.717
17	5	431.169	413.088	422.128	347.618	339.604	339.604	300.901	310.389	305.645
18	1	415.961	393.710	404.836	312.899	303.064	303.064	249.805	261.614	255.710
18	2	415.786	395.072	405.429	319.835	310.678	310.678	261.614	272.573	267.094
18	3	413.666	394.258	403.962	323.817	315.240	315.240	272.573	282.808	277.690
18	4	413.575	395.808	404.691	331.266	323.413	323.413	282.808	292.152	287.480
18	5	413.088	396.410	404.749	335.848	328.476	328.476	292.152	300.901	296.527
19	1	393.710	373.241	383.476	298.613	289.595	289.595	238.954	249.805	244.380
19	2	395.072	373.199	384.136	293.444	283.807	283.807	227.332	238.954	233.143
19	3	394.258	370.602	382.430	284.456	274.037	274.037	214.734	227.332	221.033
19	4	395.808	371.005	383.406	280.547	269.620	269.620	201.488	214.734	208.111
19	5	396.410	371.018	383.214	273.818	262.192	262.192	187.372	201.488	194.430
20	1	373.241	343.941	358.591	236.600	223.743	223.743	115.700	131.388	123.544
20	2	373.199	345.384	359.292	243.456	231.248	231.248	131.388	146.278	138.833
20	3	370.602	343.352	356.977	243.681	231.725	231.725	146.278	160.850	153.564
20	4	371.005	345.573	358.289	252.371	241.212	241.212	160.850	174.436	167.643
20	5	370.018	345.766	357.892	256.931	246.290	246.290	174.436	187.372	180.904

TABLE A.6 DISTRIBUTIONS OF HEAT TRANSFER COEFFICIENTS FOR HEAT EXCHANGER CORE

RESULTS OF MARINE WASTE-HEAT BOILER DESIGN STUDY (UNIFORM FLOW, 50% POWER)

I	J	H-A BTU/HR-SQFT-F	ETA-F	ETA-O	REN NO.-A	H-B BTU/HR-SQFT-F	REN NO.-B	J*A BTU/HR-F	QDOT BTU/SEC
1	1	.21301+02	.509089	.590089	.30080+04	.19417+03	.16975+06	.25209+04	64.370
1	2	.21298+02	.509125	.590119	.30091+04	.19414+03	.17225+06	.25206+04	73.019
1	3	.21294+02	.509165	.590153	.30104+04	.19409+03	.17517+06	.25201+04	82.788
1	4	.21289+02	.509211	.590191	.30119+04	.19416+03	.17859+06	.25203+04	93.830
1	5	.21284+02	.509263	.590234	.30136+04	.19450+03	.18264+06	.25220+04	106.318
2	1	.21197+02	.510119	.590950	.30412+04	.20379+03	.21359+06	.25693+04	182.448
2	2	.21199+02	.510100	.590933	.30406+04	.19992+03	.20508+06	.25485+04	160.507
2	3	.21199+02	.510099	.590933	.30406+04	.19714+03	.19793+06	.25332+04	140.822
2	4	.21197+02	.510118	.590949	.30412+04	.19585+03	.19193+06	.25260+04	123.376
2	5	.21193+02	.510158	.590982	.30425+04	.19483+03	.18689+06	.25201+04	107.672
3	1	.21039+02	.511695	.592265	.30921+04	.21052+03	.22261+06	.25974+04	183.944
3	2	.21039+02	.511691	.592262	.30919+04	.22053+03	.23311+06	.26472+04	209.714
3	3	.20987+02	.512209	.592694	.31086+04	.13001+04	.23950+06	.39741+04	339.607
3	4	.20986+02	.512219	.592703	.31090+04	.19672+04	.23950+06	.41174+04	351.735
3	5	.20986+02	.512216	.592700	.31089+04	.24477+04	.23950+06	.41750+04	356.719
4	1	.20806+02	.514031	.594216	.31674+04	.37862+04	.96810+04	.42390+04	322.829
4	2	.20796+02	.514130	.594299	.31706+04	.35931+04	.23950+06	.42293+04	319.967
4	3	.20690+02	.515205	.595197	.32053+04	.33293+04	.23950+06	.42030+04	295.556
4	4	.20683+02	.515275	.595255	.32076+04	.30639+04	.23950+06	.41668+04	292.977
4	5	.20681+02	.515290	.595267	.32080+04	.27736+04	.23950+06	.41666+04	291.268
5	1	.20521+02	.516927	.596634	.32608+04	.37147+04	.10712+05	.42006+04	260.521
5	2	.20513+02	.517009	.596703	.32635+04	.36777+04	.11736+05	.41980+04	258.727
5	3	.20424+02	.517923	.597466	.32929+04	.36391+04	.12684+05	.41852+04	239.763
5	4	.20419+02	.517974	.597508	.32945+04	.36117+04	.13629+05	.41833+04	238.618
5	5	.20419+02	.517979	.597512	.32947+04	.35827+04	.14572+05	.41820+04	238.439
6	1	.20272+02	.519501	.598783	.33439+04	.31528+04	.18515+05	.41415+04	209.106
6	2	.20264+02	.519580	.598850	.33465+04	.32755+04	.17687+05	.41474+04	208.057
6	3	.20182+02	.520431	.599560	.33740+04	.33599+04	.16864+05	.41417+04	193.461
6	4	.20176+02	.520474	.599596	.33754+04	.34380+04	.16099+05	.41451+04	192.854
6	5	.20178+02	.520478	.599599	.33755+04	.35128+04	.15335+05	.41486+04	192.940
7	1	.20053+02	.521786	.600692	.34178+04	.30226+04	.19186+05	.41066+04	169.751
7	2	.20046+02	.521856	.600750	.34201+04	.29196+04	.19853+05	.40992+04	168.338
7	3	.19977+02	.522584	.601357	.34436+04	.28189+04	.20470+05	.40837+04	156.151
7	4	.19974+02	.522613	.601382	.34445+04	.27498+04	.21085+05	.40784+04	155.426
7	5	.19974+02	.522615	.601383	.34446+04	.26698+04	.21700+05	.40739+04	155.211
8	1	.19869+02	.523730	.602314	.34806+04	.22919+04	.24276+05	.40254+04	136.324
8	2	.19863+02	.523791	.602366	.34826+04	.23864+04	.23736+05	.40341+04	135.688
8	3	.19805+02	.524410	.602882	.35026+04	.24758+04	.23199+05	.40353+04	126.354
8	4	.19804+02	.524426	.602895	.35031+04	.25627+04	.22699+05	.40426+04	126.266
8	5	.19804+02	.524426	.602895	.35031+04	.26135+04	.22200+05	.40468+04	126.382
9	1	.19715+02	.525368	.603682	.35335+04	.21813+04	.24714+05	.39949+04	110.922
9	2	.19710+02	.525423	.603728	.35353+04	.20967+04	.25149+05	.39843+04	109.850
9	3	.19661+02	.525947	.604165	.35522+04	.20151+04	.25552+05	.39682+04	101.837
9	4	.19661+02	.525950	.604168	.35523+04	.19690+04	.25954+05	.39620+04	101.555
9	5	.19661+02	.525948	.604166	.35522+04	.19103+04	.26355+05	.39536+04	101.367
10	1	.19589+02	.526739	.604827	.35777+04	.16195+04	.28037+05	.38965+04	88.862
10	2	.19583+02	.526787	.604867	.35793+04	.16689+04	.27685+05	.39053+04	88.402
10	3	.19542+02	.527230	.605237	.35936+04	.17077+04	.27335+05	.39075+04	82.303
10	4	.19543+02	.527223	.605231	.35933+04	.17761+04	.27009+05	.39192+04	82.576
10	5	.19543+02	.527219	.605228	.35932+04	.18304+04	.26683+05	.39279+04	82.799

TABLE A.6 Cont'd

RESULTS OF MARINE WASTE-HEAT BOILER DESIGN STUDY (UNIFORM FLOW, 50% POWER)

I	J	H-A BTU/HR-SQFT-F	ETA-F	ETA-D	REN NO.-A	H-B BTU/HR-SQFT-F	REN NO.-B	U*A BTU/HR-F	QDOT BTU/SEC
11	1	.19483+02	.527878	.605778	.36144+04	.15369+04	.28324+05	.38675+04	72.592
11	2	.19479+02	.527920	.605813	.36156+04	.14430+04	.28607+05	.38459+04	71.641
11	3	.19444+02	.528294	.606126	.36276+04	.13431+04	.28869+05	.38165+04	66.134
11	4	.19446+02	.528279	.606113	.36273+04	.13303+04	.29131+05	.38132+04	66.221
11	5	.19446+02	.528274	.606109	.36272+04	.13055+04	.29393+05	.38063+04	66.156
12	1	.19396+02	.528816	.606562	.36446+04	.10361+04	.30486+05	.37064+04	57.494
12	2	.19393+02	.528854	.606593	.36458+04	.10668+04	.30256+05	.37189+04	57.231
12	3	.19364+02	.529165	.606853	.36559+04	.11096+04	.30032+05	.37327+04	53.405
12	4	.19366+02	.529150	.606841	.36554+04	.11552+04	.29820+05	.37495+04	53.851
12	5	.19366+02	.529145	.606836	.36552+04	.12258+04	.29607+05	.37733+04	54.239
13	1	.19326+02	.529586	.607204	.36694+04	.94981+03	.30672+05	.36590+04	47.137
13	2	.19323+02	.529621	.607234	.36705+04	.88941+03	.30856+05	.36267+04	46.333
13	3	.19301+02	.529862	.607435	.36783+04	.94119+03	.31027+05	.36520+04	43.390
13	4	.19300+02	.529869	.607440	.36785+04	.83377+03	.31197+05	.35916+04	42.860
13	5	.19305+02	.529812	.607393	.36767+04	.42157+03	.31267+05	.31466+04	37.084
14	1	.19261+02	.530291	.607793	.36921+04	.41083+03	.29601+05	.31230+04	47.707
14	2	.19261+02	.530299	.607800	.36923+04	.41356+03	.30014+05	.31282+04	43.972
14	3	.19247+02	.530445	.607922	.36970+04	.41582+03	.30365+05	.31315+04	38.932
14	4	.19246+02	.530458	.607932	.36974+04	.41785+03	.30681+05	.31352+04	35.908
14	5	.19258+02	.530326	.607822	.36932+04	.41974+03	.30978+05	.31397+04	34.393
15	1	.19199+02	.530982	.608370	.37143+04	.40606+03	.29190+05	.31127+04	44.130
15	2	.19198+02	.530995	.608380	.37147+04	.40511+03	.28756+05	.31068+04	47.701
15	3	.19189+02	.531091	.608461	.37178+04	.40206+03	.28310+05	.31001+04	50.434
15	4	.19185+02	.531137	.608499	.37193+04	.39685+03	.27844+05	.30933+04	54.299
15	5	.19195+02	.531018	.608400	.37154+04	.39537+03	.27345+05	.30871+04	59.990
16	1	.19113+02	.531927	.609159	.37457+04	.37569+03	.24653+05	.30391+04	76.141
16	2	.19113+02	.531928	.609160	.37458+04	.38145+03	.25401+05	.30516+04	70.439
16	3	.19110+02	.531958	.609185	.37468+04	.38545+03	.25948+05	.30600+04	64.533
16	4	.19103+02	.532034	.609249	.37495+04	.38894+03	.26436+05	.30668+04	59.097
16	5	.19115+02	.531908	.609143	.37450+04	.39222+03	.26897+05	.30745+04	55.667
17	1	.19005+02	.533133	.610166	.37881+04	.37059+03	.24000+05	.30198+04	70.105
17	2	.19004+02	.533144	.610176	.37885+04	.36529+03	.23330+05	.30078+04	75.731
17	3	.19007+02	.533111	.610148	.37874+04	.35979+03	.22646+05	.29953+04	81.782
17	4	.18994+02	.533254	.610267	.37924+04	.35416+03	.21956+05	.29811+04	87.303
17	5	.19004+02	.533141	.610173	.37884+04	.34826+03	.21247+05	.29677+04	95.312
18	1	.18861+02	.534734	.611503	.38443+04	.30846+03	.16883+05	.28525+04	116.977
18	2	.18861+02	.534736	.611505	.38444+04	.31664+03	.17736+05	.28755+04	108.905
18	3	.18874+02	.534598	.611389	.38395+04	.32471+03	.18600+05	.28983+04	102.019
18	4	.18855+02	.534812	.611568	.38471+04	.33279+03	.19486+05	.29183+04	93.399
18	5	.18865+02	.534694	.611469	.38429+04	.34067+03	.20372+05	.29390+04	87.678
19	1	.18685+02	.536730	.613170	.39141+04	.29754+03	.15792+05	.28087+04	107.255
19	2	.18684+02	.536742	.613180	.39145+04	.28693+03	.14770+05	.27761+04	114.618
19	3	.18706+02	.536487	.612966	.39056+04	.27651+03	.13802+05	.27439+04	123.927
19	4	.18677+02	.536814	.613240	.39170+04	.26658+03	.12912+05	.27085+04	129.964
19	5	.18688+02	.536693	.613138	.39128+04	.25137+03	.11597+05	.26543+04	138.279
20	1	.18472+02	.539159	.615198	.39986+04	.18667+03	.69205+04	.23642+04	152.928
20	2	.18469+02	.539188	.615222	.39997+04	.19641+03	.74347+04	.24039+04	145.198
20	3	.18503+02	.538808	.614904	.39864+04	.21386+03	.86691+04	.24891+04	142.197
20	4	.18463+02	.539265	.615286	.40030+04	.22717+03	.96617+04	.25453+04	132.731
20	5	.18472+02	.539154	.615193	.39985+04	.23876+03	.10565+05	.25932+04	126.567

TABLE A.7 PRESSURE DROP CHARACTERISTICS AND STEAM QUALITY

B-SIDE PRESSURE DROP/QUALITY AND OTHER DETAILS FOR MARINE WASTE-HEAT BOILER DESIGN STUDY

I	J	DELTA-P-FP PSIA	DELTA-P-MOM PSIA	DELTA-P-TOT PSIA	QUALITY PERCENT	BIGX BTU/HR-SQFT-F	HB-CONV BTU/HR-SQFT-F	HB-GURGLING
20	1	.00409	.00000	.00409	.00000	.00000	.18867+03	.00000
20	2	.00403	.00000	.00403	.00000	.00000	.19641+03	.00000
20	3	.00398	.00000	.00398	.00000	.00000	.21386+03	.00000
20	4	.00392	.00000	.00392	.00000	.00000	.22717+03	.00000
20	5	.00390	.00000	.00390	.00000	.00000	.23876+03	.00000
19	5	.00386	.00000	.00386	.00000	.00000	.25137+03	.00000
19	4	.00383	.00000	.00383	.00000	.00000	.26658+03	.00000
19	3	.00381	.00000	.00381	.00000	.00000	.27651+03	.00000
19	2	.00378	.00000	.00378	.00000	.00000	.28693+03	.00000
19	1	.00379	.00000	.00379	.00000	.00000	.29754+03	.00000
18	1	.00377	.00000	.00377	.00000	.00000	.30846+03	.00000
18	2	.00378	.00000	.00378	.00000	.00000	.31664+03	.00000
18	3	.00379	.00000	.00379	.00000	.00000	.32471+03	.00000
18	4	.00379	.00000	.00379	.00000	.00000	.33279+03	.00000
18	5	.00380	.00000	.00380	.00000	.00000	.34067+03	.00000
17	5	.00380	.00000	.00380	.00000	.00000	.34826+03	.00000
17	4	.00381	.00000	.00381	.00000	.00000	.35416+03	.00000
17	3	.00383	.00000	.00383	.00000	.00000	.35979+03	.00000
17	2	.00384	.00000	.00384	.00000	.00000	.36529+03	.00000
17	1	.00385	.00000	.00385	.00000	.00000	.37059+03	.00000
16	1	.00385	.00000	.00385	.00000	.00000	.37569+03	.00000
16	2	.00386	.00000	.00386	.00000	.00000	.38145+03	.00000
16	3	.00388	.00000	.00388	.00000	.00000	.38545+03	.00000
16	4	.00388	.00000	.00388	.00000	.00000	.38894+03	.00000
16	5	.00389	.00000	.00389	.00000	.00000	.39222+03	.00000
15	5	.00390	.00000	.00390	.00000	.00000	.39537+03	.00000
15	4	.00390	.00000	.00390	.00000	.00000	.39885+03	.00000
15	3	.00391	.00000	.00391	.00000	.00000	.40206+03	.00000
15	2	.00392	.00000	.00392	.00000	.00000	.40511+03	.00000
15	1	.00393	.00000	.00393	.00000	.00000	.40806+03	.00000
14	1	.00393	.00000	.00393	.00000	.00000	.41083+03	.00000
14	2	.00394	.00000	.00394	.00000	.00000	.41356+03	.00000
14	3	.00395	.00000	.00395	.00000	.00000	.41582+03	.00000
14	4	.00396	.00000	.00396	.00000	.00000	.41785+03	.00000
14	5	.00397	.00000	.00397	.00000	.00000	.41974+03	.00000
13	5	.00748	.00923	.01672	.39049	16.63175	.42157+03	.00000
13	4	.01274	.00101	.01375	.93199	8.46162	.56677+03	.26701+03
13	3	.01582	.00103	.01685	1.48019	5.61764	.57633+03	.36487+03
13	2	.01883	.00112	.01996	2.06557	4.17500	.63892+03	.25049+03
13	1	.02174	.00116	.02291	2.66110	3.32712	.70321+03	.24660+03
12	1	.02516	.00144	.02660	3.38749	2.67614	.76676+03	.26939+03
12	2	.02846	.00146	.02992	4.11055	2.24458	.82540+03	.24142+03
12	3	.03148	.00139	.03287	4.78527	1.95297	.88872+03	.22092+03
12	4	.03447	.00143	.03590	5.46564	1.72764	.95662+03	.19854+03
12	5	.03745	.00146	.03891	6.15090	1.54811	.10424+04	.18333+03
11	5	.04104	.00180	.04284	6.96673	1.37399	.10996+04	.20585+03
11	4	.04460	.00183	.04643	7.82338	1.23473	.11363+04	.19401+03
11	3	.04812	.00186	.04997	8.65892	1.12086	.11735+04	.16962+03
11	2	.05190	.00204	.05394	9.56404	1.01856	.12758+04	.16716+03
11	1	.05501	.00003	.05504	10.48118	.93178	.13857+04	.15118+03

TABLE A.7 Cont'd

B-SIDE PRESSURE DROP/QUALITY AND OTHER DETAILS FOR MARINE WASTE-HEAT BOILER DESIGN STUDY

I	J	DELTA-P-FF PSIA	DELTA-P-MOM PSIA	DELTA-P-TOT PSIA	QUALITY PERCENT	BIGX BTU/HR-SQFT-F	HB-CONV BTU/HR-SQFT-F	HB-GURGLING
10	1	.06035	.00004	.06039	11.60387	.84304	.14525+04	.16706+03
10	2	.06559	.00006	.06564	12.72076	.76930	.15156+04	.15330+03
10	3	.07039	.00006	.07045	13.76059	.71069	.15779+04	.12978+03
10	4	.07513	.00008	.07520	14.80388	.65961	.16355+04	.14064+03
10	5	.07979	.00009	.07988	15.84997	.61467	.16930+04	.13745+03
9	5	.08559	.00013	.08572	17.13066	.56662	.17503+04	.16004+03
9	4	.09173	.00016	.09189	18.41372	.52470	.18202+04	.14887+03
9	3	.09784	.00019	.09803	19.70034	.48776	.18898+04	.12534+03
9	2	.10435	.00024	.10459	21.06820	.45260	.19672+04	.12948+03
9	1	.11084	.00029	.11113	22.48961	.42117	.20576+04	.12378+03
8	1	.11868	.00043	.11910	24.21195	.38714	.21485+04	.14344+03
8	2	.12699	.00051	.12750	25.92625	.35742	.22600+04	.12638+03
8	3	.13531	.00055	.13586	27.52263	.33281	.23707+04	.10505+03
8	4	.14363	.00064	.14427	29.11789	.31069	.24548+04	.10792+03
8	5	.15195	.00074	.15268	30.71461	.29066	.25091+04	.10435+03
7	5	.16214	.00106	.16320	32.67558	.26851	.25634+04	.12640+03
7	4	.17186	.00124	.17310	34.63925	.24862	.26301+04	.11976+03
7	3	.18123	.00145	.18268	36.61208	.23059	.27135+04	.10532+03
7	2	.19114	.00181	.19295	38.73889	.21301	.28133+04	.10632+03
7	1	.20092	.00211	.20303	40.88355	.19696	.29212+04	.10144+03
6	1	.21391	.00307	.21698	43.52543	.17915	.30303+04	.12254+03
6	2	.22728	.00359	.23086	46.15404	.16324	.31653+04	.11020+03
6	3	.23952	.00385	.24337	48.59826	.14982	.32642+04	.95677+02
6	4	.25151	.00439	.25591	51.03480	.13757	.33429+04	.95161+02
6	5	.26327	.00500	.26826	53.47244	.12629	.34220+04	.90740+02
5	5	.27738	.00716	.28454	56.46492	.11353	.34743+04	.10841+03
5	4	.29099	.00828	.29926	59.49966	.10188	.35053+04	.10643+03
5	3	.30403	.00955	.31359	62.52887	.09113	.35371+04	.10204+03
5	2	.31642	.01187	.32829	65.79766	.08047	.35701+04	.10755+03
5	1	.32779	.01370	.34150	69.08912	.07057	.36074+04	.10726+03
4	1	.34012	.01987	.35999	73.16779	.05930	.36471+04	.13911+03
4	2	.35004	.02293	.37298	77.21031	.04904	.34616+04	.13156+03
4	3	.35671	.02425	.38096	80.94440	.04023	.32081+04	.12124+03
4	4	.36096	.02730	.38826	84.64592	.03203	.29530+04	.11087+03
4	5	.[illegible]6276	.03064	.39340	88.32565	.02428	.26741+04	.99517+02
3	5	.35695	.04308	.40003	92.83269	.01517	.23609+04	.86776+02
3	4	.30076	.04856	.34933	97.27657	.00707	.18992+04	.67993+02
3	3	.26399	.04339	.30738	100.00000	.00000	.12582+04	.41912+02
3	2	.27602	.03191	.30793	100.00000	.00000	.22053+03	.00000
3	1	.28930	.03513	.32443	100.00000	.00000	.21052+03	.00000
2	1	.30264	.03529	.33793	100.00000	.00000	.20379+03	.00000
2	2	.31503	.03278	.34781	100.00000	.00000	.19992+03	.00000
2	3	.32698	.02868	.35567	100.00000	.00000	.19714+03	.00000
2	4	.33803	.02589	.36392	100.00000	.00000	.19585+03	.00000
2	5	.34750	.02209	.36959	100.00000	.00000	.19483+03	.00000
1	5	.35630	.02049	.37679	100.00000	.00000	.19450+03	.00000
1	4	.36477	.01981	.38458	100.00000	.00000	.19416+03	.00000
1	3	.37165	.01643	.38828	100.00000	.00000	.19409+03	.00000
1	2	.37830	.01503	.39333	100.00000	.00000	.19414+03	.00000
1	1	.38416	.01369	.39785	100.00000	.00000	.19417+03	.00000

TABLE A.8 LISTS OF HEAT EXCHANGER MAIN PROGRAM

```
      INCLUDE PROCO, LIST
      DIMENSION TBAR(2,MAXY,MAXX)
C-----SET DATA
C
      DATA  LOTTA/29244/
      DATA  NCKSTR,NCKSAV/10,0/
      DATA  NSTORE/9/
      ISDYN=1
      CALL INPUT($100,$200)
  100 CONTINUE
      NUMREC = 2* NI * NJ
      NUMWRD = 10
      NSAVE  = 8
      CALL ERTRAN(6,'@ASG,T   8 . ' )
      CALL ERTRAN(6,'@ASG,T   9 . ' )
C
      DEFINE FILE NSAVE (NUMREC,NUMWRD,U,LREC )
      CALL CALC(LOTTA)
 1000 CONTINUE
      DO 1100 I=1,NI
      DO 1100 J=1,NJ
      TBAR(1,I,J)= 0.5*(TWALL(1,I,J)+TWALL(2,I,J))
 1100 CONTINUE
      IF(ISDYN.EQ.1)GO TO 1050
      WRITE(KW,650) QNET,SUMCP,DTAU,TAU
  650 FORMAT(//10X,'FROM DYNAMIC RESPONSE MODEL...'/
     X/10X,'Q-NET             =',E12.5,1X,'BTU/SEC',
     X/10X,'SUM(M*CP*DT)      =',E12.5,1X,'BTU',
     X/10X,'DELTA TAU         =',E12.5,1X,'SECONDS',
     X/10X,'TAU               =',E12.5,1X,'SECONDS',
     X//)
 1050 CONTINUE
      ISDYN=ISDYN+1
      CALL INPUT($300,$400)
  300 CONTINUE
      CALL CALC(LOTTA)
      DO 1200 I=1,NI
      DO 1200 J=1,NJ
      TBAR(2,I,J)=0.5*(TWALL(1,I,J)+TWALL(2,I,J))
 1200 CONTINUE
C-----MASS PER NODE
      DMASS=ELMASS/(NI*NJ)
      SUMCP=0.0
      DO 1300 I=1,NI
      DO 1300 J=1,NJ
      TEE=0.5*(TBAR(1,I,J)+TBAR(2,I,J))
      CALL LOCK(TCPMET,CPMET,NCPMET,TEE,CPEE,KK)
      SUMCP=SUMCP+ DMASS*CPEE*(TBAR(2,I,J)-TBAR(1,I,J))
 1300 CONTINUE
      DTAU = ABS(2.0*SUMCP/QNET)
      TAU  = TAU+DTAU
      GO TO 1000
C
  400 CONTINUE
      CALL ERTRAN(6,'@FREE 9  .  ')
      WRITE(KW,600)NSAVE
  600 FORMAT(//10X,'UNIT ',I5,1X,'HAS NOT BEEN FREED'//)
C
  200 CONTINUE
C
      IF(NCKSAV.NE.1 .AND. NCKSAV.NE.2)GO TO 210
      WRITE(KW,600)NCKSTR
      IF(NCKSAV.NE.1)GO TO 210
      NDUM=MAXX*MAXY
      CALL NTRAN(NCKSTR,22,10,22,1,12,TITLE,LL,22,
     X           1,NDUM,THKCK,LL,22,10,22)
      WRITE(KW,610)NCKSTR
  610 FORMAT(/10X,'COKE THICKNESS DATA HAVE BEEN STORED',
     X           1X,'ON UNIT',I5/)
  210 CONTINUE
C
      STOP
      END
```

TABLE A.9 LISTS OF HEAT EXCHANGER INPUT PROGRAM

```
      SUBROUTINE INPUT($,$)
      INCLUDE PROCO, LIST
      DIMENSION  NTEE(10), TYTLE(12)
      DATA  KR,KW/5,6/
      DATA  PI,GC/3.141592, 32.174/
      DATA  ELMASS/0.0/
      DATA  NCPMET,NTYPE,MTCORE,MTSHEL,FACTF,FACTE/0,1,1,1,1.0,2.3/
C
      NAMELIST /INPUT/  NCPMET,CPMET,TCPMET,ELMASS
      NAMELIST /RUNCON/ NI,NJ,NPTHA,NPTHB,NPRNT,NDUMP,KOMPLX,NITER,
     X         NCOST,NTYPE,MTCORE,MTSHEL,FACTF,FACTE,
     X         YLEN,XLEN,ZA,ZB,SWEEP,THKWAL,TOLITR,TURNLA,TURNLE
C
C
C     READ INPUTS - CHECK FOR ERRORS
C
C-----DUMMY PARAMETERS SET FOR USE IN WRITE STATEMENTS
      MAXJ  = MAXX
      MAXI  = MAXY
      MAXP  = MAXPTH
      MAXT  = MAXTAB
      MAXN  = MAXNOD
C
C
      NERR=0
      IF(ISDYN.EQ.1)GO TO 10010
      READ(KR,INPUT,ERR=10000,END=10000)
      ISDYNX=ISDYN-1
      WRITE(KW,10005)ISDYNX
10005 FORMAT(1H1/10X,'**********STARTING DYNAMIC RESPONSE',
     X       1X,'CODE - STEP',I5,1X,'**********'/)
      GO TO 10020
10010 CONTINUE
C-----CARD 1
      READ(KR,500)  (TITLE(I),I=1,12)
  500 FORMAT(12A6,I8)
  510 FORMAT(8I10)
  520 FORMAT(8E10.5)
      READ(5,RUNCON)
10020 CONTINUE
C-----CARDS 10 - 19
      DO 100 N=1,NPTHA
      READ(KR,510) IST,NODE,LSTEP
      ISTART(1,N)= IST
      NODES(1,N) = NODE
      KANSTP(N)=0
      IF(LSTEP.GT.0)KANSTP(N)=1
      READ(KR,520) WDOT(1,N),PZRO(1,N),TZRO(1,N),DHYD(1,N),
     1             DELTAX(N)
      READ(KR,520) FAOFA(N),SAOV(N),FINTHK(N),FINLEN(N),FINSRF(N)
      DO 110 L=1,NODE
      READ(KR,511) I,J, TIN(1,I,J), HASIDE(I,J)
  511 FORMAT(2I10,2E10.5)
  512 FORMAT(3E10.5,I10,2E10.5)
      IARAY(1,N,L)= I
      JARAY(1,N,L)= J
  110 CONTINUE
  100 CONTINUE
C-----CARDS 21 - 29
      DO 200 N=1,NPTHB
      READ(KR,510) IST, NODE
      ISTART(2,N)= IST
      NODES(2,N) = NODE
      READ(KR,512) WDOT(2,N),PZRO(2,N),TZRO(2,N),
     X          NTUBES(N),DHYD(2,N),DELTAY(N)
      DO 210 L=1,NODE
      READ(KR,510) IARAY(2,N,L), JARAY(2,N,L)
  210 CONTINUE
  200 CONTINUE
C
      IF(ISDYN.NE.1)GO TO 10030
C
```

TABLE A.9 Cont'd

```
C-----CARD 32  COKE DATA
      READ(KR,520) XKCOKE
      READ(KR,510) NCOKE
      DO 310 L=1,NCOKE
      READ(KR,520)   TCTAB(L), THKCT(L)
  310 CONTINUE
C
      READ(KR,520) HRSMAX
      READ(KR,510) NHOURS,NCKSAV
      DO 311 L=1,NHOURS
      READ(KR,520)   HOURS(L)
  311 CONTINUE
C
C-----CARD 32
      READ(KR,510) NSAT
      DO 320 L=1,NSAT
      READ(KR,520)   PSATTB(L),TSATTB(L)
  320 CONTINUE
C
C-----CARDS 33-39
C
      LIQCOP=1
      READ(KR,520,ERR=321)   ALAM,BLAM,CLAM,DLAM
      READ(KR,520)   ATURB,BTURB,CTURB
      READ(KR,520)   ASUP,BSUP,CSUP,DSUP
      GO TO 322
  321 CONTINUE
C-----LIQUID J FACTOR USED INSTEAD OF CORRELATIONS
      LIQCOP=2
      READ(KR,510) NLJAY
      DO 323 L=1,NLJAY
      READ(KR,520)RENLIQ(L),STNLIQ(L)
  323 CONTINUE
C
  322 CONTINUE
      READ(KR,510) NSTNTB
      DO 330 L=1,NSTNTB
      READ(KR,520) RENSTB(L),STNTB(L)
  330 CONTINUE
C
C
C-----CARDS 40-49
C
      READ(KR,510) NTABB
      DO 420 L=1,NTABB
      READ(KR,520) TEMBT(L), VISBT(L),XKBT(L),CPBT(L),RHOBT(L)
  420 CONTINUE
      READ(KR,520) PCRITB,TCRITB, AMUB
C-----FUEL VAPOR PROPERTIES
      READ(KR,510) NP,ISPURE
      NPROPS=5
      NTRY  = NPROPS+1
      READ(KR,510)(NTEE(L),L=1,NP)
      TABVAP(1)=NP
      TABVAP(2)=NPROPS
      DO 430 L=1,NP
      TABVAP(2+L)= NTEE(L)
  430 CONTINUE
      LAST= 2+2*NP
      DO 432 N=1,NP
      NT=NTEE(N)
      DO 434 K=1,NT
      READ(KR,520) PEE, (TABVAP(LAST+L),L=1,NTRY)
      IF(K.EQ.1) TABVAP(2+NP+N)=PEE
      LAST=LAST+NTRY
  434 CONTINUE
C
  432 CONTINUE
C-----MIXTURE HEAT CAPACITY
      READ(KR,510)NMIX
      DO 438 L=1,NMIX
      READ(KR,520) PMIXTB(L),CPMIXB(L)
```

TABLE A.9 Cont'd

```
  436 CONTINUF
C
C-----DENSITY ABOVE CRITICAL CONDITIONS
      READ(KR,510)NP
      READ(KR,510) (NTEE(L),L=1,NP)
      NPROPS=1
      NTRY  = NPROPS+1
      TABCRT(1)= NP
      TABCRT(2)= NPPOPS
      DO 440 L=1,NP
      TABCRT(2+L)=  NTEE(L)
  440 CONTINUE
      LAST=2+2*NP
      DO 442 N=1,NP
      NT=NTEE(N)
      DO 444 K=1,NT
      READ(KR,520) PEE,(TABCRT(LAST+L),L=1,NTRY)
      IF(K.EQ.1) TABCRT(2+NP+N)=PEE
      LAST=LAST+NTRY
  444 CONTINUE
C
  442 CONTINUF
C
C
C-----HEAT OF VAPORIZATION
C
      READ(KR,510)  NVAPTB
      DO 480 L=1,NVAPTB
      READ(KR,520) FLAMTB(L),HVAPTB(L)
  480 CONTINUE
C
C-----SURFACE TENSION
C
      READ(KR,510) NSIGMA
      DO 481 L=1,NSIGMA
      READ(KR,520)  TSIGMA(L),SIGTAB(L)
  481 CONTINUF
C
C-----F FUNCTION FOR BOILING
C
      READ(KR,510) NOVXF
      DO 482 L=1,NOVXF
      READ(KR,520) XOVFTB(L),FOVFTB(L)
  482 CONTINUE
C
C-----S FUNCTION FOR BOILING
C
      READ(KR,510) NSTAB
      DO 483 L=1,NSTAB
      READ(KR,520) SRELTB(L),STAB(L)
  483 CONTINUE
C
C-----FRICTION COEFFICIENT
      READ(KR,510) NFRB
      DO 446 L=1,NFRB
      READ(KR,520) PENFB(L),FBTAB(L)
  446 CONTINUE
C
C
C
C
C-----CARDS 50-59
C
      READ(KR,520) AMUA
      READ(KR,510) NTABA
      DO 450 L=1,NTABA
      READ(KR,520) TEMAT(L),VISAT(L),XKAT(L),CPAT(L)
  450 CONTINUE
C
      READ(KR,510) NFRIC
      DO 460 L=1,NFRIC
      READ(KR,520) RENF(L),FTAB(L)
```

TABLE A.9 Cont'd

```
  460 CONTINUE
      READ(KR,510) NSTANT
      DO 470 L=1,NSTANT
      READ(KR,520) RENST(L),STNTAB(L)
  470 CONTINUE
C
C-----CARDS 60-69
C
      READ(KR,510) NWALK
      DO 620 L=1,NWALK
      READ(KR,520)  TWTAB(L), XKWTAB(L)
  620 CONTINUE
C
C      END OF INPUT
C
C
C      WRITE INPUTS
C
      IF(NPRNT .EQ. 0)  GO TO 7471
      WRITE(KW,6000)
 6000 FORMAT(1H1)
      WRITE(KW,6010) (TITLE(I),I=1,12)
 6010 FORMAT(/10X,'INPUT SPECIFICATIONS OF ',12A6/)
      WRITE(KW,6020) NI,NJ,NPTHA,NPTHB,NPRNT,NDUMP,KOMPLX
 6020 FORMAT(
     X/10X,'NO. OF NODES IN Y-DIR.   ',I10,
     X/10X,'NO. OF NODES IN X-DIR.   ',I10,
     X/10X,'NO. OF A - PATHS         ',I10,
     X/10X,'NO. OF B - PATHS         ',I10,
     X/10X,'NPRNT                    ',I10,
     X/10X,'NDUMP                    ',I10,
     X/10X,'KOMPLX                   ',I10,
     X/)
      WRITE(KW,6030) YLEN,XLEN,ZA,ZB,THKWAL,TOLITR,
     X          TURNLA,TURNLB
 6030 FORMAT(
     X/10X,'Y-SIDE LENGTH            ',E12.5,1X,'INCHES',
     X/10X,'X-SIDE LENGTH            ',E12.5,1X,'INCHES',
     X/10X,'A-SIDE DEPTH             ',E12.5,1X,'INCHES',
     X/10X,'B-SIDE DEPTH             ',E12.5,1X,'INCHES',
     X/10X,'WALL THICKNESS           ',E12.5,1X,'INCHES',
     X/10X,'ITERATION TOLERANCE      ',E12.5,1X,'DEG F ',
     X/10X,'SIDE A TURN LOSS FACTOR  ',E12.5,
     X/10X,'SIDE B TURN LOSS FACTOR  ',E12.5,
     X/)
      WRITE(KW,6031) SWEEP
 6031 FORMAT(
     X/10X,'SWEEP ANGLE              ',E12.5,1X,'DEGREES'/)
      WRITE(KW,6049)
 6049 FORMAT(1H1,/10X,'A-SIDE PATH DESCRIPTIONS'/)
C
10030 CONTINUE
      DO 7000 N=1,NPTHA
      WRITE(KW,6050)N,ISTART(1,N),NODES(1,N), KANSTP(N),WDOT(1,N),
     X          PZRO(1,N), TZRO(1,N), DHYD(1,N)
 6050 FORMAT(
     X/10X,'PATH NUMBER              ',I12,
     X/10X,'START INDICATOR          ',I12,
     X/10X,'NUMBER OF NODES          ',I12,
     X/10X,'STEPPING SWITCH          ',I12,
     X/
     X/10X,'FLOWRATE                 ',E12.5,1X,'LBM/SEC',
     X/10X,'INITIAL PRESSURE         ',E12.5,1X,'PSIA   ',
     X/10X,'INITIAL TEMPERATURE      ',E12.5,1X,'DEG F  ',
     X/10X,'HYDRAULIC DIAMETER       ',E12.5,1X,'INCHES ',
     X/)
      WRITE(KW,6060)  FAOFA(N), SAOV(N), FINTHK(N), FINLEN(N),
     X          FINSHF(N)
 6060 FORMAT(
     X 10X,'FLOW AREA/FRONTAL AREA   ',E12.5,
     X/10X,'SURFACE AREA/VOLUME      ',E12.5,    1X,'FT**-1  ',
     X/10X,'FIN THICKNESS            ',E12.5,    1X,'INCHES  ',
```

TABLE A.9 Cont'd

```
     X/10X,'FIN LENGTH                    ',E12.5,     1X,'INCHES  ',
     X/10X,'FIN AREA/SURFACE AREA         ',E12.5,
     X/)
      NODE = NODES(1,N)
      IF(KANSTP(N).GT.-)GO TO 7010
      WRITE(KW,6070)     (IARAY(1,N,L),JARAY(1,N,L),L=1,NODE)
 6070 FORMAT(/10X,'NODE CO-ORDINATES (I,J)=(Y,X)-',
     /        (/10X,10(I3,',',I3,3X)) )
      GO TO 7000
 7010 CONTINUE
      WRITE(KW,6071)
 6071 FORMAT(/10X,  '    I     J',      ' TEMPERATURE          H',
     X        /10X,    8X,              '        DEG F  BTU/HR-SQFT-F'/)
      DO 7020 L=1,NODE
      I = IARAY(1,N,L)
      J = JARAY(1,N,L)
      WRITE(KW,6072)   IARAY(1,N,L),JARAY(1,N,L),TIN(1,I,J),HASIDE(I,J)
 6072 FORMAT(10X,2I4, F12.3, E14.5)
 7020 CONTINUE
      WRITE(KW,6073)
 6073 FORMAT(///)
 7000 CONTINUE
C
C
      WRITE(KW,6100)
 6100 FORMAT(1H1,/10X,'B-SIDE PATH DESCRIPTIONS'/)
      DO 7100 N=1,NPTH3
      WRITE(KW,6053) N,ISTART(2,N), NODES(2,N),NTUBES(N),WDOT(2,N),
     X         PZRO(2,N), TZPO(2,N), DHYD(2,N)
 6053 FORMAT(
     X/10X,'PATH NUMBER                    ',I12,
     X/10X,'START INDICATOR                ',I12,
     X/10X,'NUMBER OF NODES                ',I12,
     X/10X,'NUMBER OF TUBES                ',I12,
     X/
     X/10X,'FLOWRATE                       ',E12.5,1X,'LBM/SEC',
     X/10X,'INITIAL PRESSURE               ',E12.5,1X,'PSIA    ',
     X/10X,'INITIAL TEMPERATURE            ',E12.5,1X,'DEG F   ',
     X/10X,'HYDRAULIC DIAMETER             ',E12.5,1X,'INCHES  ',
     X/10X,'TUBE DENSITY                   ',E12.5,1X,'IN**-2  ',
     X/)
      NODE=NODES(2,N)
      WRITE(KW,6070) (IARAY(2,N,L), JARAY(2,N,L),L=1,NODE)
 7100 CONTINUE
      IF(ISDYN.NE.1)GO TO 10040
C
      WRITE(KW,6110) XKCOKE
 6110 FORMAT(//10X,     'COKE THERMAL COND.        ',E12.5,1X,
     X       'BTU/LBM-FT-HR'/)
      WRITE(KW,6120)
 6120 FORMAT(/10X,'   N     TEMPERATURE  COKE THICK',
     X/15X,'          DEG F          INCHES'/)
      DO 7110 N=1,NCOKE
      WRITE(KW,6130) N, TCTAB(N), THKCT(N)
 6130 FORMAT(10X,I3,2X, 2E12.5 )
 7110 CONTINUE
C
C
      WRITE(KW,6131)HRSMAX
 6131 FORMAT(/10X,'COKE CURVE REPRESENTS CONDITIONS AT',E12.5,1X,
     X        'HOURS'/)
      IF(NCKSAV.EQ.1)WRITE(KW,6121)NCKSTR
      IF(NCKSAV.EQ.2)WRITE(KW,6122)NCKSTR
 6121 FORMAT(/10X,'SAVE COKE THICKNESS DATA ON UNIT',I5/)
 6122 FORMAT(/10X,'READ COKE THICKNESS DATA FROM UNIT',I5/)
C
      WRITE(KW,6132)
 6132 FORMAT(//10X,'    N              TIME'/10X,3X,2X,7X,'HOURS'/)
      DO 7111 N=1,NHOURS
      WRITE(KW,6130) N,HOURS(N)
 7111 CONTINUE
```

TABLE A.9 Cont'd

```
      WRITE(KW,6140)
 6140 FORMAT(/10X,'SATURATION TEMPERATURE TABLE',
     X          /10X,'  N     SAT.-PRESS   SAT.-TEMP',
     X          /10X,'              PSIA        DEG F' /)
      DO 7120 N=1,NSAT
      WRITE(KW,6130) N, PSATTB(N),TSATTB(N)
 7120 CONTINUE
      GO TO (7121,7122), LIQCOR
 7121 CONTINUE
      WRITE(KW,6200) ALAM,BLAM,CLAM,DLAM, ATURB,BTURB,CTURB,
     X          ASUP,BSUP,CSUP,DSUP
 6200 FORMAT(//10X,'HEAT TRANSFER CORRELATION CO-EFFICIENTS',/
     X/10X,'FLOW                A          B          C          D',
     X/10X,'LAMINAR      ', 4E10.5,
     X/10X,'TURBULENT    ', 3E10.5,
     X/10X,'SUPERCRIT.   ', 4E10.5,
     X/)
      GO TO 7129
 7122 CONTINUE
      WRITE(KW,6205)
 6205 FORMAT(/10X,'B-SIDE STANTON NUMBER TABLE (LIQUID)'/
     X/10X,'  N   ','    REYN NO.   ST*PR**2/3'/ )
      DO 7123 N=1,NLIQAY
      WRITE(KW,6310) N, RENLIQ(N), STNLIQ(N)
 7123 CONTINUE
C
 7129 CONTINUE
C
C
      WRITE(KW,6210)
 6210 FORMAT(/10X,'F-SIDE STANTON NUMBER TABLE (VAPOR)'/
     X/10X,'  N   ','    REYN NO.   ST*PR**2/3'/)
      DO 7130 N=1,NSTNTB
      WRITE(KW,6310) N, RENSTB(N),STNTB(N)
 7130 CONTINUE
      WRITE(KW,6300)
 6300 FORMAT(1H1,/10X,'LIQUID THERMAL PROPERTY DATA ',
     X//10X,'  N  TEMPERATURE   VISCOSITY  THERM COND',
     X'       SPEC HEAT     DENSITY',
     X/15X, 7X,'DEG F','  LBM/FT-SEC BTU/FT-F-HR   BTU/LBM-F',
     X'      LBM/CU.FT'/)
      DO 7300 N=1,NTABB
      WRITE(KW,6310)N, TEMPT(N),VISBT(N),XKBT(N),CPBT(N),RHOBT(N)
 6310 FORMAT( 10X,I3,2X,5E12.5)
 7300 CONTINUE
C
      WRITE(KW,6320) PCRITB,TCRITB,AMUB
 6320 FORMAT(
     X/10X,'LIQUID CRIT. PRESSURE   ',E12.5,1X,' PSIA',
     X/10X,'       CRIT. TEMPERATURE',E12.5,1X,' DEG F',
     X/10X,'       MOLECULAR WEIGHT ',E12.5,
     X/)
C
      WRITE(KW,6330)ISPURE
 6330 FORMAT(1H1,/10X,'B-SIDE VAPOR THERMAL PROPERTIES (ISPURE=',
     X          I2,1X,')'/
     X/10X,'  NP  NT     PRESSURE TEMPERATURE     DENSITY',
     X'      VISCOSITY  THERM COND  SPEC. HEAT     QUALITY',
     X/10X,12X, 6X,'PSIA',7X,'DEG F',           '  LBM/CU.FT',
     X'      LBM/FT-SEC BTU/FT-F-HR   BTU/LBM-F     PERCENT'/)
      NP= TABVAP(1)
      NTRY= TABVAP(2)+1
      LAST= 2+2*NP
      DO 7310 N=1,NP
      NT= TABVAP(2+N)
      PEE=TABVAP(2+NP+N)
      DO 7320 K=1,NT
      WRITE(KW,6340)   N,K,PEE,(TABVAP(LAST+L),L=1,NTRY)
 6340 FORMAT(10X,2I5,2X,7E12.5)
      LAST=LAST+NTRY
 7320 CONTINUE
 7310 CONTINUE
```

TABLE A.9 Cont'd

```
      WRITE(KW,6140)
 6140 FORMAT(/10X,'SATURATION TEMPERATURE TABLE',
     X          /10X,'   N      SAT.-PRESS    SAT.-TEMP',
     X          /10X,'                 PSIA          DEG F' /)
      DO 7120 N=1,NSAT
      WRITE(KW,6130) N, PSATTB(N),TSATTB(N)
 7120 CONTINUE
      GO TO (7121,7122), LIQCOR
 7121 CONTINUE
      WRITE(KW,6200) ALAM,BLAM,CLAM,DLAM, ATURB,BTURB,CTURB,
     X          ASUP,BSUP,CSUP,DSUP
 6200 FORMAT(//10X,'HEAT TRANSFER CORRELATION CO-EFFICIENTS',/
     X/10X,'FLOW                A              B            C            D',
     X/10X,'LAMINAR        ', 4E10.5,
     X/10X,'TURBULENT      ', 3E10.5,
     X/10X,'SUPERCRIT.     ', 4E10.5,
     X/)
      GO TO 7129
 7122 CONTINUE
      WRITE(KW,6205)
 6205 FORMAT(/10X,'B-SIDE STANTON NUMBER TABLE (LIQUID)'/
     X/10X,'   N   ','       REYN NO.   ST*PR**2/3'/ )
      DO 7123 N=1,NLIQY
      WRITE(KW,6310) N, RENLIQ(N), STNLIQ(N)
 7123 CONTINUE
C
 7129 CONTINUE
C
C
      WRITE(KW,6210)
 6210 FORMAT(/10X,'B-SIDE STANTON NUMBER TABLE (VAPOR)'/
     X/10X,'   N   ','       REYN NO.   ST*PR**2/3'/)
      DO 7130 N=1,NSTNTB
      WRITE(KW,6310) N, RENSTB(N),STNTB(N)
 7130 CONTINUE
      WRITE(KW,6300)
 6300 FORMAT(1H1,/10X,'LIQUID THERMAL PROPERTY DATA ',
     X//10X,'   N   TEMPERATURE   VISCOSITY  THERM COND',
     X       '     SPEC HEAT       DENSITY',
     X/15X, 7X,'DEG F','  LBM/FT-SEC BTU/FT-F-HR   BTU/LBM-F',
     X    '        LBM/CU.FT'/)
      DO 7300 N=1,NTABB
      WRITE(KW,6310)N, TEMBT(N),VISBT(N),XKBT(N),CPBT(N),RHOBT(N)
 6310 FORMAT(10X,I3,2X,5E12.5)
 7300 CONTINUE
C
      WRITE(KW,6320) PCRITB,TCRITB,AMUB
 6320 FORMAT(
     X/10X,'LIQUID CRIT. PRESSURE    ',E12.5,1X,' PSIA',
     X/10X,'        CRIT. TEMPERATURE',E12.5,1X,' DEG F',
     X/10X,'        MOLECULAR WEIGHT ',E12.5,
     X/)
C
      WRITE(KW,6330)ISPURE
 6330 FORMAT(1H1,/10X,'B-SIDE VAPOR THERMAL PROPERTIES (ISPURE=',
     X          I2,1X,')'/
     X/10X,'   NP    NT       PRESSURE TEMPERATURE       DENSITY',
     X   '     VISCOSITY  THERM COND  SPEC. HEAT      QUALITY',
     X/10X,12X, 6X,'PSIA',7X,'DEG F',             '     LBM/CU.FT',
     X   '     LBM/FT-SEC BTU/FT-F-HR   BTU/LBM-F       PERCENT'/)
      NP= TABVAP(1)
      NTRY= TABVAP(2)+1
      LAST= 2+2*NP
      DO 7310 N=1,NP
      NT= TABVAP(2+N)
      PEE=TABVAP(2+NP+N)
      DO 7320 K=1,NT
      WRITE(KW,6340)   N,K,PEE,(TABVAP(LAST+L),L=1,NTRY)
 6340 FORMAT(10X,2I5,2X,7E12.5)
      LAST=LAST+NTRY
 7320 CONTINUE
 7310 CONTINUE
```

TABLE A.9 Cont'd

```
C
      WRITE(KW,6350)
 6350 FORMAT(//10X,'MIXTURE HEAT CAPACITY TABLE'/
     X/10X,'   N   ',     '      PRESSURE  SPEC. HEAT',
     X/10X, 5X,           '         PSIA    BTU/LBM-F'/)
      DO 7330 N=1,NMIX
      WRITE(KW,6310) N,PMIXTB(N),CPMIXB(N)
 7330 CONTINUE
      WRITE(KW,6360)
 6360 FORMAT(//10X,'DENSITY ABOVE CRITICAL POINT'/
     X/10X,'    NP    NT      PRESSURE TEMPERATURE     DENSITY',
     X/10X, 13X,          '         PSIA       DEG F   LBM/CU.FT'/)
      NP=TABCRT(1)
      NTRY= TABCRT(2)+1
      LAST=2+2*NP
      DO 7340 N=1,NP
      NT= TABCRT(2+N)
      PEE=TABCRT(2+NP+N)
      DO 7345 K=1,NT
      WRITE(KW,6340)N,K,PEE,(TABCRT(LAST+L),L=1,NTRY)
      LAST=LAST+NTRY
 7345 CONTINUE
 7340 CONTINUE
C
      WRITE(KW,6380)
 6380 FORMAT(//10X,'HEAT OF VAPORIZATION TABLE',/
     X/10X,'   N   ',     '      PRESSURE         H-VAP',
     X/10X,   5X,         '         PSIA       BTU/LBM'/)
      DO 7380 N=1,NVAPTB
      WRITE(KW,6310) N, PLAMTB(N),HVAPTB(N)
 7380 CONTINUE
C
      WRITE(KW,6381)
 6381 FORMAT(//10X,'SURFACE TENSION TABLE'/
     X/10X,'   N   ',     ' TEMPERATURE          SIGMA',
     X /10X, 5X,          '        DEG F     DYNES/CM'/)
      DO 7381 N=1,NSIGMA
      WRITE(KW,6310) N, TSIGMA(N),SIGTAB(N)
 7381 CONTINUE
C
      WRITE(KW,6382)
 6382 FORMAT(//10X,'F-FUNCTION FOR BOILING'/
     X/10X,'   N   ',     '         1/BIGX              F' /)
      DO 7382 N=1,NOVXF
      WRITE(KW,6310)N, XOVFTB(N),FOVFTB(N)
 7382 CONTINUE
      WRITE(KW,6383)
 6383 FORMAT(//10X,'S-FUNCTION FOR BOILING'/
     X/10X,'   N   ',     '     RE*F**1.25              S'/)
      DO 7384 N=1,NSTAB
      WRITE(KW,6310) N, SFELTB(N),STAB(N)
 7384 CONTINUE
C
      WRITE(KW,6370)
 6370 FORMAT(//10X,'B-SIDE FRICTION FACTOR TABLE'/
     X/10X,'   N   ',     '      REYN NO.      F-FACTOR'/)
      DO 7350 N=1,NFRB
      WRITE(KW,6310) N, RENFB(N), FBTAB(N)
 7350 CONTINUE
C
C
C
      WRITE(KW,6400)AMUA
 6400 FORMAT(1H1,/10X,'A-SIDE THERMAL PROPERTY DATA',
     X/10X,'MOLECULAR WEIGHT              ',E12.5/
     X/10X,'   N   ',     ' TEMPERATURE    VISCOSITY   THERM COND',
     X     '     SPEC HEAT',
     X/15X,'          DEG F  LBM/FT-SEC BTU/FT-F-HR    BTU/LBM-F'/)
      DO 7400 N=1,NTABA
      WRITE(KW,6310) N, TEMAT(N),VISAT(N),XKAT(N),CPAT(N)
 7400 CONTINUE
C
```

TABLE A.9 Cont'd

```
      WRITE(KW,6450)
 6450 FORMAT(1H1,/10X,'A-SIDE FRICTION FACTOR TABLE'/,
     X/10X,'  N  ','      REYN NO.    F-FACTOR'/)
      DO 7450 N=1,NFRIC
      WRITE(KW,6310) N, RENF(N), FTAB(N)
 7450 CONTINUE
C
      WRITE(KW,6460)
 6460 FORMAT(//10X,'A-SIDE STANTON NUMBER TABLE',
     //10X,'  N  ','      REYN NO.   ST*PR**2/3'/)
      DO 7460 N=1,NSTANT
      WRITE(KW,6310) N, RENST(N), STNTAB(N)
 7460 CONTINUE
C
      WRITE(KW,6470)
 6470 FORMAT(//10X,'WALL THERMAL CONDUCTIVITY TABLE'/,
     X/10X,'  N  ','   TEMPERATURE  THERM COND',
     X/15X,'           DEG F  BTU/FT-F-HR'/)
      DO 7470 N=1,NWALK
      WRITE(KW,6310)N, TWTAB(N), XKWTAB(N)
 7470 CONTINUE
 7471 CONTINUE
 7472 FORMAT(1H1,' P-SIDE FLOW RATES FOR EACH PATH ARE:',//10(1X,
     1      E12.5))
C
C
      IF(ISPURE.LT.1)ISPURE=1
      IF(ISPURE.GT.2)ISPURE=2
      IF(ISPURE.GE.2 .AND. NPRNT.EQ.0)  WRITE(KW,7472)
     1        (WDOT(2,N),N=1,NPTHB)
C
C     CONVERT TO A CONSISTENT SET OF UNITS
C     LENGTH          - FEET
C     MASS            - POUNDS
C     TIME            - SECONDS
C     TEMPERATURE     - RANKINE
C
      XLEN      =  XLEN   /12.0
      YLEN      =  YLEN   /12.0
      ZA        =  ZA     /12.0
      ZB        =  ZB     /12.0
      THKWAL    =  THKWAL/12.0
C
      XKCOKE  = XKCOKE /3600.0
      PCRITB  = PCRITB*144.0
      TCRITB  = TCRITB+460.0
10040 CONTINUE
      DO 8000 N=1,MAXP
      PZRO(1,N)   = PZRO(1,N) * 144.0
      PZRO(2,N)   = PZRO(2,N) * 144.0
      TZRO(1,N)   = TZRO(1,N)+460.0
      TZRO(2,N)   = TZRO(2,N)+460.0
C
      DHYD(1,N)   = DHYD(1,N) /12.0
      DHYD(2,N)   = DHYD(2,N) /12.0
      DELTAX(N)   = DELTAX(N) /12.0
      DELTAY(N)   = DELTAY(N) /12.0
      FINTHK(N)   = FINTHK(N) /12.0
      FINLEN(N)   = FINLEN(N)/ 12.0
C
 8000 CONTINUE
      IF(ISDYN.NE.1)GO TO 10050
      DO 8100 N=1,MAXT
      TCTAB(N) = TCTAB(N)+460.0
      THKCT(N) = THKCT(N)/12.0
C
      PSATTB(N) = PSATTB(N)*144.0
      TSATTB(N) = TSATTB(N)+460.0
C
      TEMBT(N)  = TEMBT(N)+460.0
      XKBT(N)   = XKBT(N)/3600.0
C
```

TABLE A.9 Cont'd

```
      PMIXTB(N) = PMIXTB(N)*144.0
C
      TEMAT(N)  = TEMAT(N)+460.0
      XKAT(N)   = XKAT(N)/3600.0
C
      TWTAB(N)  = TWTAB(N)+460.0
      XKWTAB(N) = XKWTAB(N)/3600.0
C
      PLAMTB(N)   = PLAMTB(N)*144.0
C
      TSIGMA(N)   = TSIGMA(N) + 460.0
C-----DYNE/CM TO LBF/FT
      SIGTAB(N)   = SIGTAB(N) * 2.248E-6* 30.48
C
 8100 CONTINUE
C
      NP= TABVAP(1)
      NTRY = TABVAP(2)+1
      LAST=2+2*NP
      DO 8200 N=1,NP
      NT= TABVAP(2+N)
      TABVAP(2+NP+N)= TABVAP(2+NP+N)*144.0
      DO 8210 K=1,NT
      TABVAP(LAST+ 1) = TABVAP(LAST+1) + 460.0
      TABVAP(LAST+ 4) = TABVAP(LAST+4) / 3600.0
      TABVAP(LAST+ 6) = TABVAP(LAST+6) * 0.01
      LAST=LAST+NTRY
 8210 CONTINUE
 8200 CONTINUE
C
      NP= TABCRT(1)
      NTRY= TABCRT(2)+1
      LAST=2+2*NP
      DO 8220 N=1,NP
      NT= TABCRT(2+N)
      TABCRT(2+NP+N)= TABCRT(2+NP+N) *144.0
      DO 8230 K=1,NT
      TABCRT(LAST+1)= TABCRT(LAST+1)+460.0
      LAST=LAST+NTRY
 8230 CONTINUE
 8220 CONTINUE
C
10050 CONTINUE
      DO 8240 N=1,NPTHA
      IF(KANSTP(N).LE.0)GO TO 8240
      NODE= NODES(1,N)
      DO 8241 L=1,NODE
      I= IARAY(1,N,L)
      J= JARAY(1,N,L)
      TIN(1,I,J)= TIN(1,I,J) + 460.0
      HASIDE(I,J) =  HASIDE(I,J) /3600.0
 8241 CONTINUE
 8240 CONTINUE
C
      IF(ISDYN.NE.1)GO TO 10060
C
C
C
C     INITIALIZATION
C
      DO 5000 I=1,NI
      DO 5100 J=1,NJ
      DO 5200 K=1,2
      IF(K.EQ.2) TIN(K,I,J)=0.0
      TOUT(K,I,J)    = 0.0
      TWALL(K,I,J)   = 0.0
      TMEAN(K,I,J)   = 0.0
      CPMEAN(K,I,J)  = 0.0
 5200 CONTINUE
      QDOT(I,J)      = 0.0
      THKCK(I,J)     = 0.0
      AREE(I,J)      = 0.0
```

TABLE A.9 Cont'd

```
      TERMS(1,I,J)    = 0.0
      TERMS(2,I,J)    = 0.0
      TERMS(3,I,J)    = 0.0
 5100 CONTINUE
 5000 CONTINUE
C
10060 CONTINUE
C
C-----INITIAL TEMPERATURE ASSIGNMENTS
C
      DO 6500 N=1,NPTHA
      NODE= NODES(1,N)
      DO 6510 L=1,NODE
      I=IARAY(1,N,L)
      J=JARAY(1,N,L)
      IF(KANSTP(N).GT.0)GO TO 6520
      TIN(1,I,J)= TZRO(1,N)
      TOUT(1,I,J) = TZRO(1,N)
      TMEAN(1,I,J)= TZRO(1,N)
      GO TO 6510
 6520 CONTINUE
      TOUT(1,I,J) = TIN(1,I,J)
      TMEAN(1,I,J)= TIN(1,I,J)
 6510 CONTINUE
 6500 CONTINUE
      IF(ISDYN.NE.1)GO TO 10070
      DO 6600 N=1,NPTHB
      NODE= NODES(2,N)
      DO 6610 L=1,NODE
      I = IARAY(2,N,L)
      J = JARAY(2,N,L)
      TIN( 2,I,J)     =   TZRO(2,N)
      TOUT(2,I,J)     =   TZRO(2,N)
      TWALL(1,I,J)    =   TZRO(2,N)
      TWALL(2,I,J)    =   TZRO(2,N)
      TCOKE(I,J)      =   TZRO(2,N)
      TMEAN(2,I,J)    =   TZRO(2,N)
      THKCK(I,J)      =   0.0
 6610 CONTINUE
 6600 CONTINUE
C
      IF(NCKSAV.NE.2)GO TO 6700
C
C     RECALL COKE THICKNESS DATA
C
      NDUM=MAXX*MAXY
      CALL NTRAN(NCKSTR,22,10,22,2,12,TYTLE,LL,22,
     X                2,NDUM,THKCK,LL,22,10,22)
      WRITE(KW,6710)(TYTLE(I),I=1,12)
 6710 FORMAT(/10X,'COKE THICKNESS DATA HAVE BEEN RECALLED ',
     X/10X,   'FROM CASE',1X,12A6/)
 6700 CONTINUE
C
C     END OF INITIALIZATION
C
C
C
      IF(NERR .LE.0) RETURN 1
10070 CONTINUE
      IF(ISDYN.GT.2)RETURN 1
C
C-----RESET PRINT OPTION
C
      NPRNT=0
C
C-----COKE THICKNESS CANNOT CHANGE DURING TRANSIENT
C
      HOURS(1)= HOURS(NHOURS)
      NHOURS= 1
```

TABLE A.9 Cont'd

```
      WRITE(KW,10072) ELMASS
10072 FORMAT(//10X,'ELMASS       = ',E12.5,1X,'LBM'/)
      WRITE(KW,10074)
10074 FORMAT(//10X,'METAL HEAT CAPACITY TABLE'/
     X/10X,' N',          ' TEMPERATURE              CP',
     X/10X,2X,            '        DEG F    BTU/LBM-F'/)
      DO 10076 N=1,NCPMET
      WRITE(KW,10078)N, TCPMET(N),CPMET(N)
10078 FORMAT(10X,I2,2E12.5)
      TCPMET(N)=TCPMET(N)+460.0
10076 CONTINUE
      WRITE(KW,10080)
10080 FORMAT(///)
      RETURN 1
10000 CONTINUE
C
C     ERROR SUMMARY
C
      RETURN 2
      END
```

TABLE A.10 LIST OF HEAT EXCHANGER CALCULATION PROGRAM

```
      SUBROUTINE CALC(LOTTA)
      INCLUDE PROCO,LIST
      DIMENSION ZTAB(10),TERROR(2,MAXPTH),QPATH(2,MAXPTH)
      DIMENSION FILDAT(10),INVRSA(MAXY,MAXX),INVRSB(MAXY,MAXX),
     X        QSAT(MAXPTH),UA(MAXY,MAXX),MATEPL(10),TRATE(MAXY,MAXX)
      DATA (MATERL(N),N=1,10)/ 6HCARBON, 6H STEEL, 6HMOLYBD, 6HENUM  ,
     X     6HSTNLS , 6HSTEEL , 6HMONEL , 6H      , 6HSUPER , 6HALLOYS/
      DATA  RZERO /1545.0/
      REAL NEWMOM
C
      COSB=COS(SWEEP*PI/180.)
C
C
C-----SET UP INVERSE ARRAY
C
C
      DO 20 N=1,NPTHA
      NODE=NODES(1,N)
      DO 20 L=1,NODE
      I=IARAY(1,N,L)
      J=JARAY(1,N,L)
      INVRSA(I,J)=N
   20 CONTINUE
      DO 21 N=1,NPTHB
      NODE=NODES(2,N)
      DO 21 L=1,NODE
      I=IARAY(2,N,L)
      J=JARAY(2,N,L)
      INVRSB(I,J)=N
   21 CONTINUE
C
C
C     OUTER LOOP CONTROLS AGING OF HEAT EXCHANGER
C
      DO 50000 ISHOUR=1,NHOURS
C
C     TIME
C
      THEHR = HOURS(ISHOUR)
C
C     SET COKE THICKNESS
C
      IF(ISHOUR.LE.1)GO TO 50100
      DHOURS = THEHR - HOURS(ISHOUR-1)
      IF(ISHOUR.GT.2)GO TO 50050
C
C     GET RATE OF COKE THICKNESS FORMATION BASED
C     UPON FIRST SOLUTION
C
      DO 50010 I=1,NI
      DO 50010 J=1,NJ
      CALL LOCK(TCTAB,THKCT,NCOKE,TWALL(2,I,J),THICK,KK)
      TRATE(I,J)=THICK/HRSMAX
50010 CONTINUE
C
50050 CONTINUE
C
C     UPDATE COKE THICKNESSES
      DO 50060 I=1,NI
      DO 50060 J=1,NJ
      THKCK(I,J)= THKCK(I,J)+  TRATE(I,J) * DHOURS
50060 CONTINUE
C
50100 CONTINUE
C
      IF(NITER .LT. 1)  NITER=25
      QNET=0.0
      THTA=0.0
      DO 10000  ITER=1,NITER
C
C     SAVE PREVIOUS PASS'S OUTLET TEMPERATURES
C
```

TABLE A.10 Cont'd

```
      DO 100 N=1,NPTHA
      NODE= NODES(1,N)
      ILAST= IARAY(1,N,NODE)
      JLAST= JARAY(1,N,NODE)
      TOUTSV(1,N)= TOUT(1,ILAST,JLAST)
  100 CONTINUE
      DO 110 N=1,NPTHB
      NODE = NODES(2,N)
      ILAST = IARAY(2,N,NODE)
      JLAST = JARAY(2,N,NODE)
      TOUTSV(2,N)= TOUT(2,ILAST,JLAST)
  110 CONTINUE
C
C     A-PATH CONDITIONS
C
      DO 200 N=1,NPTHA
      NODE = NODES(1,N)
      DO 210 L=1,NODE
      I = IARAY(1,N,L)
      J = JARAY(1,N,L)
      NB=INVRSE(I,J)
      EL = DELTAX(N)
      IF(ISTART(1,N).EQ.1) EL = DELTAY(NB)
      IF(SWEEP.GT.0.1)  GO TO 111
      FRONAR(N) = ZA*EL
      FLARA(N) = FAOFA(N) * FRONAR(N)
      SRFARA(N)= SAOV(N)*ZA*DELTAX(N)*DELTAY(NB)
      FINAR(N) = FINSRF(N)* SRFARA(N)
      GO TO 112
  111 CONTINUE
      FAOFA(N)  = 1.0
      FRONAR(N) = EL* ZA * COSB
      FLARA(N)  = FRONAR(N)
      SRFARA(N) = DELTAX(N)*DELTAY(NB)
      SAOV(N)   = 1.0/ZA
      FINSRF(N) = 0.0
      FINAR(N)  = 0.0
  112 CONTINUE
      ETAF=0.0
      ETAZRO=1.0
      REN=0.0
      HA = HASIDE(I,J)
      IF(KANSTP(N).GT.0)GO TO 205
C-----THERMAL PROPERTIES
      CALL LOOK(TEMAT, VISAT, NTABA, TMEAN(1,I,J), VIS, KK)
      CALL LOOK(TEMAT, XKAT,  NTABA, TMEAN(1,I,J), XK,  KK)
      CALL LOOK(TEMAT, CPAT,  NTABA, TMEAN(1,I,J), CPMEAN(1,I,J),KK)
C-----TRANSPORT COEFFICIENTS
      GEE=   WDOT(1,N)/ FLARA(N)
      REN =  GEE* DHYD(1,N) /VIS
      PRN =  VIS* CPMEAN(1,I,J)/XK
      CALL LOOK( RENST, STNTAB, NSTANT, REN, STANT,KK)
      HA =  STANT / PRN**0.66667 * GEE * CPMEAN(1,I,J)
C-----FIN EFFECTIVENESS
      CALL LOOK(TWTAB,XKWTAB, NWALK, TWALL(1,I,J), XKWA,KK)
      EM= SQRT(2.0*HA / (XKWA* FINTHK(N)))
      ETAF =  TANH(EM*FINLEN(N)) /(EM*FINLEN(N))
      ETAZRO = 1.0 - FINAR(N) / SRFARA(N) *(1.0- ETAF)
  205 CONTINUE
      FILDAT(1) = HA
      FILDAT(2) = ETAF
      FILDAT(3) = ETAZRO
      FILDAT(4) = REN
      TERMS(1,I,J)=1.0/(ETAZRO  *SRFARA(N) * HA)
      LREC =(I-1)*NJ+J
      WRITE(NSAVE'LREC)(FILDAT(KK),KK=1,NUMWRD)
      IF(ITER.GT.1)  GO TO 210
       QNET = QNET +1.0/TERMS(1,I,J) * (TMEAN(1,I,J) -
     X        0.5*(TWALL(1,I,J)+TWALL(2,I,J)) )
      THTA=THTA + SRFARA(N)
  210 CONTINUE
C
  200 CONTINUE
```

TABLE A.10 Cont'd

```
C
C      B-PATH CONDITIONS
C
       QGAIN=0.0
       DO 300 N=1,NPTHB
       NODE = NODES(2,N)
       X=0.0
       XCK=0.0
       HSV=0.0
       QSAT(N)= 0.0
C
C-----MAXIMUM HEAT ADDITION FOR CONSTANT TEMPERATURE VAPORIZATION PROCE
C
       CALL LOOK(PLAMTB,HVAPTB, NVAPTB, PZRO(2,N), HVAP, KK)
       QHVAP=WDOT(2,N)*HVAP
C
       DO 30 I=1,NI
       DO 30 J=1,NJ
       QUAL(I,J)=0.0
   30  CONTINUE
C
C-----SATURATION TEMPERATURE
C
       CALL LOOK(PSATTB,TSATTB, NSAT, PZRO(2,N),TSAT(N), KK)
       DO 310 L=1,NODE
       I = IARAY(2,N,L)
       J = JARAY(2,N,L)
       NA =  INVPSA(I,J)
       EL=DELTAX(NA)
       IF(ISTART(2,N).EQ.2)  EL=DELTAY(N)
       IF(SWFEP.GT.0.1)  GO TO 11
       FLARB(N) = NTUBES(N)*PI/4.0 * DHYD(2,N)**2
       AWALL(1,N) = NTUBES(N)* PI * (DHYD(2,N)+THKWAL)*EL
       AWALL(2,N) = NTUBES(N)* PI * DHYD(2,N)*EL
       GO TO 10
   11  CONTINUE
       EL=DELTAX(NA)
       IF(ISTART(2,N).EQ.1)  EL=DELTAY(N)
       NTUBES(N)=1
       FLARB(N) = EL*ZB*COSB
       DHYD(2,N)=  2.0* EL* ZB *COSB / (EL*COSB+ZB)
       AWALL(1,N) =  DELTAX(NA)*DELTAY(N)
       AWALL(2,N) =  AWALL(1,N)
   10  CONTINUE
C
C
       IF(PZRO(2,N).GT.PCRITB)  GO TO 311
C
C-----GET QUALITY
C
C
       GO TO (331,332),ISPURE
  331  CONTINUE
C
C      DISTILLATE SUBSTANCE
C
       CALL LOCKUP(TABVAP,PZRO(2,N),TMEAN(2,I,J),ZTAB,KK)
       QUAL(I,J)= ZTAB( 5)
       GO TO 333
C
  332  CONTINUE
C
C      PURE SUBSTANCE, QUALITY DETERMINED FROM PREVIOUS NODE.
C
       IF(L.EQ.1)  GO TO 333
       IP=IARAY(2,N,L-1)
       JP=JARAY(2,N,L-1)
       QUAL(I,J)=QUAL(IP,JP)
  333  CONTINUE
C
       IF(QUAL(I,J).LE.0.0)  GO TO 311
       IF(QUAL(I,J).GT.0.0 .AND. QUAL(I,J).LT.1.0)  GO TO 312
C
```

TABLE A.10 Cont'd

```
C-----FLOW IS 100% VAPOR
C
      IFLAG(I,J) = 3
C
C-----THERMAL PROPERTIES
      CALL LOCKUP(TABVAP,PZRO(2,N),TMEAN(2,I,J),ZTAB,KK)
      XK           = ZTAB( 3)
      VIS          = ZTAB( 2)
      RHOB         = ZTAB( 1)
      CPMEAN(2,I,J)= ZTAB( 4)
C-----TRANSPORT COEFFICIENTS
      GEE =   WDOT(2,N)/FLAFB(N)
      REN =   GEE* DHYD(2,N)/VIS
      PRN = VIS*CPMEAN(2,I,J)/ XK
      CALL LOCK(RENSTB,STNTB,NSTNTB,REN,STANT,KK)
      HB= STANT* GEE* CPMEAN(2,I,J) / PRN**0.66667
      HCONV = HB
      HGURG = 0.0
      HBREAL=HB
      GO TO 370
  311 CONTINUE
C
C     FLOW IS 100% LIQUID
C
      IFLAG(I,J)= 1
C-----THERMAL PROPERTIES
      CALL LOCK(TEMBT,  VISBT,   NTABB, TMEAN(2,I,J), VIS, KK)
      CALL LOCK(TEMBT,  XKBT,    NTABB, TMEAN(2,I,J), XK,  KK)
      CALL LOCK(TEMBT,  CPBT,    NTABB, TMEAN(2,I,J), CPMEAN(2,I,J),KK)
      CALL LOCK(TEMBT,  RHOBT, NTABB, TMEAN(2,I,J), RHOB,KK )
      CALL LOCK(TEMBT,  RHOBT, NTABB, TCOKE(I,J),   RHOW, KK)
C-----TRANSPORT  COEFFICIENTS
      GEE = WDOT(2,N)/  FLARB(N)
      REN=  GEE * DHYD(2,N) /VIS
      PRN=  VIS * CPMEAN(2,I,J)/ XK
C
      GO TO (341,342), LICCOR
  341 CONTINUE
C
      IF(PZRO(2,N).GT. PCRITB)GO TO 340
C-----T LESS THAN TSAT  / P LESS THAN PC
      IF(REN.GT.2300.0) GO TO 320
  345 CONTINUE
      CALL LOCK(TEMBT, VISBT,NTABB, TCOKE(I,J),VISW, KK)
      X=X+EL
      ANU=ALAM*(REN*PRN/(X/DHYD(2,N)))**BLAM
     X       /(VISW/VIS)**CLAM
C-----MINIMUM LAMINAR NUSSELT NO. IS FOR FULLY
C-----DEVELOPED FLOW
      IF(ANU.LT.3.66)ANU=3.66
      HB = ANU* XK / DHYD(2,N)
      HCONV = HB
      HGURG = 0.0
      HBREAL=HB
      GO TO 370
  320 CONTINUE
      ANU =   ATURB*REN** BTURB * PRN** CTURB
      HB = ANU* XK / DHYD(2,N)
      HCONV = HB
      HGURG = 0.0
      HBREAL=HB
      GO TO 37
  340 CONTINUE
C-----P GREATER THAN PC
      IF(REN.LT.2300.0)GO TO 345
      CALL LOCK(TEMBT, VISBT,NTABB, TCOKE(I,J),VISW, KK)
      CALL LOCK(TEMBT, XKBT, NTABB, TCOKE(I,J),XKW,  KK)
      CALL LOCK(TEMBT, CPBT, NTABB, TCOKE(I,J),CPW,  KK)
      REN= GEE*DHYD(2,N)/VISW
      PRN= VISW* CPW/XKW
      XK = XKW
      ANU= ASUP* REN**BSUP*PRN**CSUP*(RHOW/RHOB)**DSUP
```

TABLE A.10 Cont'd

```
      HB = ANU* XK / DHYD(2,N)
      HCONV = HB
      HGURG = 0.0
      HBREAL=HB
      GO TO 370
  342 CONTINUE
C-----LIQUID STANTON NUMBER
      CALL LOOK(RENLIQ,STNLIQ,NLJAY,REN,STANT,KK)
      HB = STANT* GEE* CPMEAN(2,I,J) / PRN** 0.66667
      HCONV = HB
      HGURG = 0.0
      HBREAL=HB
      GO TO 370
  312 CONTINUE
C
C-----FLOW IS A MIXTURE
C
      CALL LOOK(PMIXTB,CPMIXB,NMIXB,PZRO(2,N),CPMEAN(2,I,J),KK)
      IF(KOMPLX .GT. 0)  GO TO 375
      HB = 1.0E+20
      HCONV = HB
      HGURG = 0.0
      HBREAL=0.0
      IFLAG(I,J)=2
      GO TO 370
C
C
  375 CONTINUE
C
C-----TWO PHASE BOILING
C
      IF(QUAL(I,J) .GT. 0.7)  GO TO 371
      GEE =  WDOT(2,N)/ FLARB(N)
      CALL LOOK(TEMBT, VISBT,    NTABB,  TMEAN(2,I,J),   VISL,   KK)
      CALL LOOK(TEMBT, XKBT,     NTABB,  TMEAN(2,I,J),   XKL,    KK)
      CALL LOOK(TEMBT, CPBT,     NTABB,  TMEAN(2,I,J),   CPL,    KK)
      CALL LOOK(TEMBT, RHOBT,    NTABB,  TMEAN(2,I,J),   RHOL,   KK)
      CALL LOOK(PLAPTB,HVAPTB, NVAPTB, PZRO(2,N), HVAP, KK)
      CALL LOOK(TSIGMA,SIGTAB, NSIGMA, TMEAN(2,I,J), SIGMA,KK)
      CALL LOOK(TSATTB,PSATTB, NSAT, TMEAN(2,I,J), PSTTB, KK)
      CALL LOOK(TSATTB,PSATTB, NSAT, TCOKE(I,J),    PSTTW, KK)
      CALL LOOKUP(TABVAF, PZRO(2,N), TMEAN(2,I,J), ZTAB,KK)
      RHOV  = ZTAB(1)
      VISV  = ZTAB(2)
      VFG=1./RHOV - 1./RHOL
      REN = GEE*(1.0-QUAL(I,J)) *DHYD(2,N)/  VISL
      PRN =  VISL* CPL/XKL
      XFUNCT =    (QUAL(I,J)/(1.0-QUAL(I,J)))**0.9
     X      *(RHOL/RHOV)**0.5  * (VISV/VISL)**0.1
      CALL LOOK(XOVFTB,FOVFTB, NOVXF, XFUNCT, FVAL, KK)
      HCONV =  0.023*XKL / DHYD(2,N) * REN**0.8 *PRN**0.4 * FVAL
      SARG =  REN* FVAL**1.25
      CALL LOOK(SRELTB, STAB, NSTAB, SARG, ESS, KK)
      HGURG = 0.0
      DT = 0.0
      DP = 0.0
      IF(TCOKE(I,J) .LT. TSAT(N))  GO TO 372
      DT=TCOKE(I,J) - TSAT(N)
      DP=778.16*DT*HVAP/(TSAT(N)*VFG)
      HGURG = 0.00122 *   XKL**0.79   *CPL**0.45   *RHOL**0.49 * GC**0.25
     X       /(SIGMA**0.25 * VISL**0.29 * HVAP**0.24 * RHOV**0.24)
     X       * DT**0.24 * DP**0.75 * ESS
  372 CONTINUE
      HMAC=HCONV
      HMIC=HGURG
      HB = HCONV+HGURG
      HBREAL=HB
      GO TO 370
  371 CONTINUE
C
C-----HIGH QUALITY MIXTURE
C
```

TABLE A.10 Cont'd

```
      IF(HBV .GT. 0.0)  GO TO 373
      CALL LOOKUP(TABVAP,PZRO(2,N),TMEAN(2,I,J),ZTAB,KK)
      XK=ZTAB(3)
      VIS=ZTAB(2)
      RHOB=ZTAB(1)
      CPV=ZTAB(4)
      GEE=WDOT(2,N)/FLARB(N)
      REN=GEE*DHYD(2,N)/VIS
      PRN=VIS*CPV/XK
      CALL LOOK(RENSTB,STNTB,NSTNTB,REN,STANT,KK)
      HBV=STANT*GEE*CPV/PRN**0.66667
  373 CONTINUE
      HCONV=HBV + ((1.-QUAL(I,J))/0.3)**0.5*(HMAC-HBV)
      HSURG=HMIC*((1.0-QUAL(I,J))/0.3)**0.5
      HB=HCONV + HSURG
      HBREAL=HB
C
  370 CONTINUE
      FILDAT(1) = HB
      FILDAT(2) = REN
      FILDAT(4) = HCONV
      FILDAT(5) = HSURG
C
C-----COKE
C
      THKC = THKCK(I,J)
C-----TERMS IN EFFECTIVE HEAT TRANSFER EQUATION
      TERMS(3,I,J) =  THKC /(XKCOKE* AWALL(2,N))
      ABEE(I,J)=NTUBES(N)*PI*EL*(DHYD(2,N)-THKC)
      IF(KANSTP(NA).GT.0) ABEE(I,J)=  SRFARA(NA)
      TERMS(4,I,J) =  1.0 / (HB* ABEE(I,J))
      TBAR=  0.5*(TWALL(1,I,J)+TWALL(2,I,J))
      CALL LOOK(TWTAB,XKWTAB,NWALL,TBAR,XKW, KK)
      TERMS(2,I,J) =  THKWAL /(XKW* AWALL(1,N))
C
C-----HEAT TRANSFER RATE  (BTU/ SEC)
      UA(I,J)=0.0
      DO 380 LQ=1,4
      UA(I,J) = UA(I,J) + TERMS(LQ,I,J)
  380 CONTINUE
      FILDAT(3) = 1.0/ UA(I,J)
      CALL LOOK(TEMAT,  CPAT,  NTABA, TIN(1,I,J), CPAIN,KK)
      CALL LOOK(TEMAT,  CPAT,  NTABA, TOUT(1,I,J), CPAOUT,KK)
      QDOT(I,J)=(TIN(1,I,J)-TIN(2,I,J))/
     X      (UA(I,J) +1.0/(2.0*WDOT(1,NA)*CPMEAN(1,I,J))
     X       +1.0/(2.0*WDOT(2,N)*CPMEAN(2,I,J)) )
      TOUT(2,I,J)=TIN(2,I,J)+QDOT(I,J)/(WDOT(2,N)*CPMEAN(2,I,J))
C
      GO TO (390,392),ISPURE
  392 CONTINUE
      IF(WDOT(1,NA).LE.0.0 .OR. WDOT(2,N).LE.0.0) QDOT(I,J)=0.0
      TOUT(2,I,J)=TIN(2,I,J)+QDOT(I,J)/(WDOT(2,N)*CPMEAN(2,I,J))
      IF(IFLAG(I,J).EQ.1 .AND. TOUT(2,I,J).GT.TSAT(N))
     1      TOUT(2,I,J)=TSAT(N)
      IF(QSAT(N).GT.0.0 .AND. QSAT(N).LT.QHVAP) TOUT(2,I,J)=TSAT(N)
      QGAIN=QGAIN + QDOT(I,J)
C
C-----CONSTANT TEMPERATURE HEAT ADDITION PROCESS
C
      IF(TOUT(2,I,J).LT.TSAT(N) .OR. XCK.GT.2.0)  GO TO 390
      IFLAG(I,J)=2
      TOUT(2,I,J)=TSAT(N)
C-----ACCUMULATED HEAT TRANSFER INCLUDES CORRECTION
C-----FOR FIRST NODE THAT JUST CONTAINS MIXTURE
C-----(AND TOUT JUST EXCEEDS TSAT)
      QSAT(N)=QSAT(N)+QDOT(I,J)-WDOT(2,N)*CPL*(TSAT(N)-TIN(2,I,J))
      IF(QSAT(N).GT.0.0)  GO TO 391
      IFLAG(I,J)=1
      QSAT(N)=0.0
  391 CONTINUE
      QUAL(I,J)=QSAT(N)/QHVAP
      IF(QUAL(I,J).GT.1.0)QUAL(I,J)=1.0
      IF(QUAL(I,J).LT.1.0)GO TO 390
```

TABLE A.10 Cont'd

```
C
C-----FLOW HAS JUST BECOME VAPOR
      TSAT(N)=TSAT(N)+.C1
      CALL LOCKUP(TABVAP,PZPO(2,N),TSAT(N),ZTAB,KK)
      CPMEAN(2,I,J)=ZTAB(4)
      TOUT(2,I,J)=TSAT(N)+(QSAT(N)-QHVAP)/(WDOT(2,N)*CPV)
      QSAT(N)=QHVAP
      IFLAG(I,J)=3
      XCK=3.0
  390 CONTINUE
C
C
      IF(L.EQ.NODE)GO TO 381
      IP = IARAY(2,N,L+1)
      JP = JARAY(2,N,L+1)
      TIN(2,IP,JP)= TOUT(2,I,J)
      TMEAN(2,IP,JP)=TIN(2,IP,JP)
  381 CONTINUE
      LREC  = NI*NJ+ (I-1)*NJ+J
      WRITE(NSAVE'LPEC) (FILDAT(KK),KK=1,NUMWRD)
      IF(ITER.EQ.1)
     X QNET = QNET - HBREAL*ABEE(I,J) *(TBAR-TMEAN(2,I,J))
  310 CONTINUE
  300 CONTINUE
C
C     UPDATE TEMPERATURES
C
      QLOST = 0.0
      DO 400 N=1,NPTHA
      QPATH(1,N)=0.C
      NODE= NODES(1,N)
      DO 410 L=1,NODE
      I = IARAY(1,N,L)
      J = JARAY(1,N,L)
      IF(WDOT(1,N) .LE. 0.0)  TIN(1,I,J)=TIN(2,I,J)
      IF(KANSTP(N).GT.0)  GO TO 301
      CALL LOCK(TEMAT,  CPAT,  NTABA, TIN(1,I,J), CPAIN,KK)
      TOUT(1,I,J)=TIN(1,I,J) - QDOT(I,J)/(WDOT(1,N)*CPAIN)
      I3=0
  302 CONTINUE
      I3=I3+1
      TOTIJ=TOUT(1,I,J)
      CALL LOCK(TEMAT,  CPAT,  NTABA, TOTIJ, CPAOUT,KK)
      TOUT(1,I,J)=(CPAIN*TIN(1,I,J)-QDOT(I,J)/WDOT(1,N))/CPAOUT
      IF(ABS(TOUT(1,I,J)-TOTIJ) .LT. 1.0 .OR. I3.GT.5)  GO TO 301
      GO TO 302
  301 CONTINUE
      QPATH(1,N)=QPATH(1,N) + WDOT(1,N)*(CPAIN*TIN(1,I,J)-CPAOUT*
     X        TOUT(1,I,J))
      TMEAN(1,I,J)= 0.5*(TIN(1,I,J)+ TOUT(1,I,J))
      TWALL(1,I,J)= TMEAN(1,I,J)- QDOT(I,J) * TERMS(1,I,J)
      TWALL(2,I,J)= TWALL(1,I,J)- QDOT(I,J) * TERMS(2,I,J)
      TCOKE(I,J)   = TWALL(2,I,J)- QDOT(I,J) * TERMS(3,I,J)
      IF(L.EQ.NODE.OR.KANSTP(N).EQ.1)GO TO 410
      IP=  IARAY(1,N,L+1)
      JP=  JARAY(1,N,L+1)
      TIN(1,IP,JP)  = TOUT(1,I,J)
  410 CONTINUE
      QLOST=QLOST + QPATH(1,N)
  400 CONTINUE
C
      DO 420 N=1,NPTHB
      QPATH(2,N)=0.0
      NODE = NODES(2,N)
      DO 430 L=1,NODE
      I = IARAY(2,N,L)
      J = JARAY(2,N,L)
      QPATH(2,N)=QPATH(2,N) + QDOT(I,J)
      TMEAN(2,I,J)= 0.5 *(TIN(2,I,J) + TOUT(2,I,J))
  430 CONTINUE
  420 CONTINUE
```

TABLE A.10 Cont'd

```
C
C     CONVERGENCE CHECK
C
      NOGOOD = 0
      DO 500 N=1,NPTHA
      NODE = NODES(1,N)
      I = IARAY(1,N,NODE)
      J = JARAY(1,N,NODE)
      TCHK = TOUT(1,I,J) - TOUTSV(1,N)
      TERROR(1,N)=TCHK
      IF(ABS(TCHK).GT. TOLITR) NOGOOD= NOGOOD+1
  500 CONTINUE
      DO 510 N=1,NPTHB
      NODE = NODES(2,N)
      I = IARAY(2,N,NODE)
      J = JARAY(2,N,NODE)
      TCHK =  TOUT(2,I,J)- TOUTSV(2,N)
      TERROR(2,N)=TCHK
      IF(ABS(TCHK).GT. TOLITR) NOGOOD = NOGOOD+1
  510 CONTINUE
      ITAT= ITER
      IF(NOGOOD.LE.0)GO TO 20000
C
      IF(NDUMP.LE.0)GO TO 10000
C
C     DUMP OF INTERMEDIATE RESULTS
C
      NALL = 0
      DO 2000 ID=1,NI
      DO 2050 JD=1,NJ
      NALL=NALL+1
      IF(MOD(NALL-1,50).NE.0)GO TO 2100
      WRITE(KW,2110) ITAT,NOGOOD
 2110 FORMAT(1H1,/10X,'DUMP FOR ITERATION',I5,1X,'NOGOOD=',I5,/
     X/10X,'     I        J         TA-IN      TA-OUT     TA-MEAN    TWALL-A',
     X    '      TWALL-B      TCOKE      TB-IN      TB-OUT     TB-MEAN',
     X    '          GDOT',
     X/20X,     9(5X,'DEG R'),3X,'BTU/SEC'/)
 2100 CONTINUE
      WRITE(KW,2120) ID,JD, TIN(1,ID,JD), TOUT(1,ID,JD),
     X          TMEAN(1,ID,JD), (TWALL(L,ID,JD),L=1,2),
     X          TCOKE(ID,JD), TIN(2,ID,JD), TOUT(2,ID,JD),
     X          TMEAN(2,ID,JD), GDOT(ID,JD)
 2120 FORMAT(10X,2I5,9F10.3,E10.5)
 2050 CONTINUE
 2000 CONTINUE
      NALL=0
      DO 2002 ID=1,NI
      DO 2002 JD=1,NJ
      NALL=NALL+1
      NA=INVRSA(ID,JD)
      NB=INVRSB(ID,JD)
      IF(MOD(NALL-1,50).NE.0)   GO TO 2003
      WRITE(KW,2004)  ITAT,NOGOOD
 2004 FORMAT(1H1,/1X,'DUMP FOR ITERATION',I5,1X,'NOGOOD=',I5,/
     X  /1X,'    I        J  CPMEAN-A  CPMEAN-B     TERM-1      TERM-2'
     X  '      TERM-3     TERM-4          UA    QUALITY      DELTAX',
     X  '      DELTAY ?     IFLAG'/)
 2003 CONTINUE
      WRITE(KW,2005) ID,JD,(CPMEAN(I1,ID,JD),I1=1,2),
     1       (TERMS(I2,ID,JD),I2=1,4),UA(ID,JD),QUAL(ID,JD),
     2       DELTAX(NA),DELTAY(NB),IFLAG(ID,JD)
 2005 FORMAT(1X,2I5,7E10.5,3F10.4,I10)
 2002 CONTINUE
      WRITE(KW,2001) QLOST,QGAIN
 2001 FORMAT(/////10X,'HEAT LOST FROM A-SIDE = ',E11.5,' BTU/SEC',
     X             /10X,'HEAT GAINED BY B-SIDE = ',E11.5,' BTU/SEC')
      WRITE(KW,2130)
 2130 FORMAT(///)
C
10000 CONTINUE
C
```

TABLE A.10 Cont'd

```
C      NO CONVERGENCE
C
       WRITE(KW,600) ITAT, NOGOOD
  600  FORMAT(///10X,'FAILED TO CONVERGE...AFTER ',I5,' ITERATIONS,',
     X        1X,'NOGOOD = ', I10//)
       GO TO 30000
20000  CONTINUE
C
C      CONVERGENCE
C
       WRITE(KW,610)  ITAT
  610  FORMAT(///10X,'PROGRAM CONVERGED AFTER',I5,1X,'ITERATIONS'//)
30000  CONTINUE
       WRITE(KW,601)
  601  FORMAT(//10X,'SIDE PATH      ERROR-DEG F'/)
       DO 11000 N=1,NPTHA
       LABSD=4H   A
       WRITE(KW,602)LABSD,N,TERROR(1,N)
  602  FORMAT(10X,A4,I5,5X,F10.3)
11000  CONTINUE
       DO 12000 N=1,NPTHB
       LABSD=4H   B
       WRITE(KW,602)LABSD,N,TERROR(2,N)
12000  CONTINUE
C
C
C      PRESSURE DROP CALCULATION
C
C
C
C      A SIDE
C
       DO 31000 N=1,NPTHA
       NODE = NODES(1,N)
       DELP(1,N) = 0.0
       HEADNU=0.0
       DO 31100 L=1,NODE
       HEADOL=HEADNU
       I= IARAY(1,N,L)
       J= JARAY(1,N,L)
C
       ROIN =  PZRO(1,N)*AMUA / (RZERO * TIN(1,I,J))
       ROEX =  PZRO(1,N)*AMUA / (RZERO * TOUT(1,I,J))
       LREC=(I-1)*NJ+J
       READ(NSAVE'LREC)(FILDAT(KK),KK=1,NUMWRD)
       REN=FILDAT(4)
       CALL LOCK(RENF,FTAB, NFRIC,REN, FRIC,KK)
       GEE =  WDOT(1,N)/  FLARA(N)
       DELP(1,N)= DELP(1,N)   +  GEE**2 /(2.0*GC *ROIN)
     X      *(  (1.0+ (FLARA(N)/FRONAR(N))**2) * (ROIN/ROEX-1.0)
     X      +  FRIC *  SRFARA(N)/ FLARA(N)*ROIN / (0.5*(ROIN+ROEX)) )
       HEADNU =  GEE**2/ (2.0* GC * 0.5*(ROIN+ROEX) )
       IF(L.EQ.1)GO TO 31100
C
C-----TURN LOSS
C
       KSCORE=0
       IM1= IARAY(1,N,L-1)
       JM1= JARAY(1,N,L-1)
       IF(ISTART(1,N).EQ.2)GO TO 31120
C-----HORIZONTAL TRAVERSE
       IF(NJ.EQ.2)GO TO 31100
       IF(J.EQ.1 .OR. J.EQ.NJ) KSCORE=1
       IF(JM1.EQ.1 .OR. JM1.EQ.NJ) KSCORE=KSCORE+1
       GO TO 31150
31120  CONTINUE
C-----VERTICAL TRAVERSE
       IF(NI.EQ.2) GO TO 31100
       IF(I .EQ.1 .OR. I.EQ.NI) KSCORE=1
       IF(IM1.EQ.1 .OR. IM1.EQ. NI) KSCORE= KSCORE+1
31150  CONTINUE
       IF(KSCORE.EQ.2) DELP(1,N) = DELP(1,N)+ 0.5*(HEADNU+HEADOL)*TURNLA
31100  CONTINUE
C
```

TABLE A.10 Cont'd

```
31000 CONTINUE
C
C       B SIDE
C
        DO 32000 N=1,NPTHB
        NODE=NODES(2,N)
        DELP(2,N) = 0.0
        HEADNU = 0.0
        NEWMOM = 0.0
        DO 32900 L=1,NODE
        HEADOL = HEADNU
        OLDMOM = NEWMOM
        I= IARAY(2,N,L)
        J= JARAY(2,N,L)
        NA=INVRSA(I,J)
        EL =  DELTAX(NA)
        IF(ISTART(2,N).EQ.2)  EL    = DELTAY(N)
        IF(SWEEP.GT.0.1)  GO TO 32001
        FLARB(N) = NTUBES(N)*PI/4.0 * DHYD(2,N)**2
        AWALL(1,N) = NTUBES(N)* PI * (DHYD(2,N)+THKWAL)*EL
        AWALL(2,N) = NTUBES(N)* PI * DHYD(2,N)*EL
        GO TO 32002
32001 CONTINUE
        EL=DELTAX(NA)
        IF(ISTART(2,N).EQ.1)  EL=DELTAY(N)
        NTUBES(N)=1
        FLARB(N) = EL*ZB*COSB
        DHYD(2,N)=  2.0* EL* ZB *COSB / (EL*COSB+ZB)
        AWALL(1,N) =  DELTAX(NA)*DELTAY(N)
        AWALL(2,N) =  AWALL(1,N)
32002 CONTINUE
        ALPHA(I,J) = 0.0
        KGO = IFLAG(I,J)
        GO TO (32100, 32200, 32300), KGO
32100 CONTINUE
C
C       FLOW IS 100% LIQUID
C
        GEE = WDOT(2,N)/FLARB(N)
        CALL LOOK(TEMBT,VISBT, NTABB, TMEAN(2,I,J), VISB,KK)
        CALL LOOK(TEMBT,VISBT, NTABB, TCOKE(I,J),    VISW,KK)
        IF(PZRO(2,N).GT.PCRITB .AND. TMEAN(2,I,J).GT. TCRITB) GO TO 321(
        CALL LOOK(TEMBT,RHOBT, NTABB, TMEAN(2,I,J), RHOB,KK)
        GO TO 32110
32105 CONTINUE
        CALL LOOKUP(TABCRT,PZRO(2,N),TMEAN(2,I,J),ZTAB,KK)
        RHOB=ZTAB(1)
32110 CONTINUE
        REN = GEE* DHYD(2,N)/ VISB
        CALL LOOK(RENFB,FBTAB, NFRB, REN,FRIC,KK)
        DELTAP(1,I,J)= 4.0* FRIC* EL/ DHYD(2,N)*GEE**2 /(2.0*GC*RHOB)
      X       *   (VISW /VISB) ** 0.14
        NEWMOM = 0.0
        GO TO 32800
32200 CONTINUE
C
C       MIXTURE
C
        GEE= WDOT(2,N)/FLARB(N)
C-----LIQUID
        CALL LOOK(TEMBT,VISBT, NTABB, TIN(2,I,J), VISL,KK)
        CALL LOOK(TEMBT,RHOBT, NTABB, TIN(2,I,J), RHOL,KK)
C-----VAPOR
        CALL LOOKUP(TABVAP,PZRO(2,N),TOUT(2,I,J),ZTAB,KK)
        RHOV = ZTAB(1)
        VISV = ZTAB(2)
       RENL = (1.0 - QUAL(I,J))*GEE* DHYD(2,N)/VISL
       RENV =        QUAL(I,J)* GEE* DHYD(2,N)/VISV
       CALL GETEX(RENV,RENL,RHOV,RHOL,QUAL(I,J),BIGX(I,J),PSIV2,PSIL2,
     X        KW )
C
C-----DETERMINE WHICH PRESSURE DROP IS APPLICABLE
C
```

TABLE A.10 Cont'd

```
      IF(BIGX(I,J).GT.1.0)GO TO 32250
C-----VAPOR DELTA P
      RHOB = RHOV
      VISB= VISV
      VISW=VISB
      GEE=WDOT(2,N)* QUAL(I,J)/ FLARB(N)
      REN= GEE*DHYD(2,N)/VISB
      EX=0.0
      PSIFAK = PSIV2
      GO TO 32255
32250 CONTINUE
C-----LIQUID DELTA P
      VISB= VISL
      RHOB= RHOL
      CALL LOOK(TEMBT,VISBT,NTABB, TCOKE(I,J),VISW,KK)
      GEE= (1.0 - QUAL(I,J))*WDOT(2,N) /FLARB(N)
      REN=  GEE*DHYD(2,N)/ VISB
      EX=0.14
      PSIFAK = PSIL2
32255 CONTINUE
      CALL LOOK(RENFB, FBTAB, NFRB, REN, FRIC,KK)
      DELTAP(1,I,J)= 4.0*FRIC*EL/DHYD(2,N)*GEE**2 / (2.0*GC*RHOB)*
     X      (VISW/VISB)**EX  *PSIFAK
      ALPHA(I,J)= 1.0/(1.0 + (1.0 - QUAL(I,J))/QUAL(I,J)
     X      *(RHOV/RHOL)**0.66667 )
      NEWMOM =  (1.0 - QUAL(I,J))**2 /(1.0-ALPHA(I,J))/RHOL
     X      + QUAL(I,J)*QUAL(I,J)/ ALPHA(I,J)/RHOV
      EXPNLS =  GEE**2 /(2.0*GC*RHOL*(1.0-ALPHA(I,J)))
      GO TO 32800
32300 CONTINUE
C
C     FLOW IS 100% VAPOR
C
      CALL LOOKUP(TABVAP,PZPO(2,N),TMEAN(2,I,J),ZTAB,KK)
      VISB= ZTAB(2)
      RHOB= ZTAB(1)
      GEE=  WDOT(2,N)/ FLARB(N)
      REN=  GEE* DHYD(2,N)/VISB
      CALL LOOK(RENFB, FBTAB,NFRB,REN,FRIC, KK)
      DELTAP(1,I,J)= 4.0*FRIC* EL/ DHYD(2,N)*GEE**2 /(2.0*GC*RHOB)
      NEWMOM = 1.0/ RHOB
C
32800 CONTINUE
      DELTAP(2,I,J) = 0.0
      IF(L.GT.1) DELTAP(2,I,J)= GEE**2/ GC *(NEWMOM -OLDMOM)
      DELP(2,N)=DELP(2,N)+ DELTAP(1,I,J)+ DELTAP(2,I,J)
      HEADNU = GEE**2/(2.0*GC*RHOB)
      IF(L.EQ.1)GO TO 32900
C
C-----TURN LOSS
C
      KSCORE=0
      IM1=  IARAY(2,N,L-1)
      JM1=  JARAY(2,N,L-1)
      IF(ISTART(2,N).EQ.2)GO TO 32810
C-----HORIZONTAL TRAVERSE
      IF(NJ.EQ.2)GO TO 32900
      IF(J  .EQ.1 .OR. J   .EQ.NJ) KSCORE=1
      IF(JM1.EQ.1 .OR. JM1 .EQ.NJ) KSCORE=KSCORE+1
      GO TO 32850
32810 CONTINUE
C-----VERTICAL TRAVERSE
      IF(NI .EQ. 2)GO TO 32900
      IF(I .EQ.1 .OR. I.EQ.NI) KSCORE=1
      IF(IM1.EQ.1 .OR. IM1.EQ.NI) KSCORE=KSCORE+1
32850 CONTINUE
      IF(KSCORE.NE.2) GO TO 32900
      ADDLOS = 0.5*(HEADNU+HEADOL)* TURNLB
      IF(IFLAG(I,J).EQ.2) ADDLOS =  EXPNLS * TURNLB
      DELP(2,N)= DELP(2,N)+ ADDLOS
32900 CONTINUE
C
```

TABLE A.10 Cont'd

```
32000 CONTINUE
C
      IF(NPRNT.LE.0)GO TO 51000
      IF(ISHOUR.GT.1 .AND. ISHOUR .LT. NHOURS)GO TO 50000
51000 CONTINUE
C
C-----WRITE FLOW CONDITIONS FOR THIS HEAT EXCHANGER
C
      NALL=0
      DO 4000 K=1,2
      GO TO (4010,4020),K
 4010 CONTINUE
      NP=NPTHA
      SIDE = 4H    A
      GO TO 4030
 4020 CONTINUE
      NP=NPTHB
      SIDE=  4H    B
 4030 CONTINUE
C
      DO 4100 N=1,NP
      NALL = NALL+1
      IF(MOD(NALL-1,50).NE.0)GO TO 4200
      WRITE(KW,4110) (TITLE(L),L=1,12)
 4110 FORMAT(1H1,/5X,'A. FLOW CONDITIONS FOR ',12A6/
     X/10X,'  SIDE  PATH    START        END        FLOW        T-IN      T-OUT',
     X   6X,'P-IN       P-OU         QDOT',
     X/   40X,'LB/SEC', 2(5X,'DEG F'),2(6X,'PSIA'),3X,'BTU/SEC'/)
 4200 CONTINUE
      NODE= NODES(K,N)
      I1 =   IARAY(K,N,1)
      IL =   IARAY(K,N,NODE)
      J1 =   JARAY(K,N,1)
      JL =   JARAY(K,N,NODE)
      T1=TIN(K,I1,J1) - 460.0
      T2=TOUT(K,IL,JL) - 460.0
      P1=PZRO(K,N)/144.0
      P2=(PZRO(K,N)-DELP(K,N))/144.0
      WRITE(KW,4220) SIDE,N,I1,J1,IL,JL,WDOT(K,N),T1,T2,P1,P2,
     X         QPATH(K,N)
 4220 FORMAT(10X,2X,A4,I6,2(1X,I3,',',I3,), 6F10.2)
 4100 CONTINUE
 4000 CONTINUE
C
C-----WRITE HEAT EXCHANGER SIZE
C
      WRITE(KW,51001) YLEN,XLEN,ZA
51001 FORMAT(////5X,'B. THE CORE SIZE OF THIS HEAT EXCHANGER IS ',
     X       'APPROXIMATELY = ',2(F5.2,' FT.  BY  '),F5.2,' FT.')
C
C-----ESTIMATE HEAT EXCHANGER MANUFACTURING COST
C
      IF(ITER.GE.NITER .OR. NCOST.EQ.0)  GO TO 51005
      PAMAX=0.0
      PBMAX=0.0
      DO 51002 N=1,NPTHA
51002 IF(PAMAX.LT.PZRO(1,N))  PAMAX=PZRO(1,N)
      DO 51003 N=1,NPTHB
51003 IF(PBMAX.LT.PZRO(2,N))  PBMAX=PZRO(2,N)
      PAMAX=PAMAX/144.0
      PBMAX=PBMAX/144.0
      IF(MTCORE.LT.1) MTCORE=1
      IF(MTSHEL.LT.1) MTSHEL=1
      CALL HXCOST(THTA,PBMAX,PAMAX,NTYPE,MTCORE,MTSHEL,COSTB,
     X         FACTD,FACTPB,FACTPA,FACTM,FACTF,FACTE,COSTM)
      MTCORE=2*MTCORE-1
      MTSHEL=2*MTSHEL-1
      MTC2=MTCORE + 1
      MTS2=MTSHEL + 1
      WRITE(KW,51004) THTA,PAMAX,PBMAX,MATERL(MTSHEL),MATERL(MTS2),
     X           MATERL(MTCORE),MATERL(MTC2)
```

TABLE A.10 Cont'd

```
51004 FORMAT(////5X,'C. THE MANUFACTURING COST OF THIS HEAT ',
     X 'EXCHANGER WAS ESTIMATED BASED ON THE FOLLOWING DATA:',
     X //10X,'1. TOTAL HEAT TRANSFER AREA (A-SIDE)  = ',F8.0,' SC-FT
     X /10X,'2. A-SIDE (OR SHELL-SIDE) PRESSURE    = ',F6.2,' PSIA',
     X /10X,'3. B-SIDE (OR TUBES-SIDE) PRESSURE    = ',F8.2,' PSIA',
     X /10X,'4. A-SIDE (OR SHELL) MATERIAL         =    ',2A6,
     X /10X,'5. B-SIDE (OR TUBES) MATERIAL         =    ',2A6)
      WRITE(KW,51005) FACTD,FACTPA,FACTPB,FACTM,FACTF,FACTE,COSTM
51005 FORMAT(10X,'6. AND FOLLOWING ADJUSTMENT FACTORS: ',//13X,
     X 'DESIGN TYPE FACTOR                    =',F5.2,/13X,
     X 'A-SIDE PRESSURE FACTOR                =',F5.2,/13X,
     X 'B-SIDE PRESSURE FACTOR                =',F5.2,/13X,
     X 'MATERIAL COSTING FACTOR               =',F5.2,/13X,
     X 'MAUFACTURING COMPLEXITY FACTOR        =',F5.2,/13X,
     X 'ESCALATION FACTOR FROM MID-7_         =',F5.2,//10X,
     X '7. TOTAL MANUFACTURING COST   =   ',F10.0,' DALLORS')
51006 CONTINUE
C
C       OUTPUT
C
C-----STORE ALL DATA ON DRUM SINCE OUTPUT WILL ALTER UNITS
      CALL OUTPUT(THEHR)
50000 CONTINUE
      RETURN
      END
```

TABLE A.11 LIST OF HEAT EXCHANGER OUTPUT PROGRAM

```
      SUBROUTINE OUTPUT(THEHR)
      INCLUDE PROCO,LIST
C
C     OUTPUT SUBROUTINE FOR HEAT EXCHANGER DECK
C
C     CHANGE TEMPERATURES TO DEGREES F
C     PRESSURES TO PSIA
C     QUALITIES TO PERCENT
C
      DIMENSION RECA(10),RECB(10)
      DO 1000 I=1,NI
      DO 1100 J=1,NJ
      DO 1200 K=1,2
      TIN(K,I,J)= TIN(K,I,J)-460.0
      TOUT(K,I,J)= TOUT(K,I,J)-460.0
      TMEAN(K,I,J)= TMEAN(K,I,J)-460.0
      TWALL(K,I,J)= TWALL(K,I,J)-460.0
      DELTAP(K,I,J) = DELTAP(K,I,J)/144.0
 1200 CONTINUE
      TCOKE(I,J)= TCOKE(I,J)-460.0
      THKCK(I,J)= THKCK(I,J) * 12.0
      QUAL(I,J)= QUAL(I,J)*100.0
 1100 CONTINUE
 1000 CONTINUE
      DO 1300 K=1,NPTHA
      DELP(1,K)= DELP(1,K)/144.0
 1300 CONTINUE
      DO 1310 K=1,NPTHB
      DELP(2,K)= DELP(2,K)/144.0
 1310 CONTINUE
C
C
      NALL=0
      DO 2000 I=1,NI
      DO 2050 J=1,NJ
      NALL=NALL+1
      IF(MOD(NALL-1 ,50).NE.0)GO TO 2100
      WRITE(KW,2110) (TITLE(K),K=1,12),THEHR
 2110 FORMAT(1H1,/10X,'RESULTS OF',1X,12A6,1X,'TIME =',F6.2,1X,
     X       'HRS'/
     X/10X,'     I      J         TA-IN       TA-OUT     TA-MEAN     TWALL-A',
     X'            TWALL-B        TCOKE        TB-IN       TB-OUT      TB-MEAN',
     X'                QDOT',
     X/20X, 9(5X,'DEG F'),3X,'BTU/SEC'/)
 2100 CONTINUE
      WRITE(KW,2120) I,J, TIN(1,I,J),TOUT(1,I,J),TMEAN(1,I,J),
     X       (TWALL(L,I,J),L=1,2), TCOKE(I,J),
     X        TIN(2,I,J), TOUT(2,I,J), THEAN(2,I,J),
     X        QDOT(I,J)
 2120 FORMAT(10X,2I5,19F10.3,E10.5)
C
 2050 CONTINUE
 2000 CONTINUE
      WRITE(KW,2130)
 2130 FORMAT(///)
      ERROR = 100.0*(1.0 - QLOST/QGAIN)
      WRITE(KW,2200) QLOST,QGAIN,ERROR
 2200 FORMAT(
     X/10X,'HEAT LOST BY A-SIDE     (APPROXIMATE)',E12.5,1X,'BTU/SE
     X/10X,'HEAT GAINED BY B-SIDE   (APPROXIMATE)',E12.5,1X,'BTU/SE
     X/
     X/10X,'ERROR                                ',E12.5,1X,'PERCEN
     X//)
C
C
C     SEARCH FOR MAXIMUM TEMPERATURE OF WALL
C
      IX=0
      JX=0
      TMAX=0.0
      DO 2500 K=1,2
      DO 2500 I=1,NI
```

TABLE A.11 Cont'd

```
      DO 2500 J=1,NJ
      IF(TWALL(K,I,J).LT.TMAX)GO TO 2500
      IX= I
      JX= J
      TMAX= TWALL(K,I,J)
 2500 CONTINUE
      WRITE(KW,2510) TMAX, IX,JX
 2510 FORMAT(/10X,'MAXIMUM WALL TEMPERATURE =',F10.3,1X,'F',
             1X,'AT I=',I5,1X,'J=',I5//)
C
      NALL = 0
      DO 3000 I=1,NI
      DO 3050 J=1,NJ
      NALL=NALL+1
      IF(MOD(NALL-1,50).NE.0)GO TO 3100
      WRITE(KW,3110) (TITLE(K),K=1,12)
 3110 FORMAT( 1H1,/10X,'RESULTS OF',1X,12A6/
     X/10X,'  I       J                  H-A', 3X,'ETA-F    ETA-O',
     X      ' REN NO.-A              H-B REN NO.-B              U*A COKE THK,
     X/10X,10X,        ' BTU/HR-SQFT-F',8X,8X,10X,
     X      ' BTU/HR-SQFT-F',10X,   6X,'BTU/HR-F',   4X,'INCHES',
     X/ )
 3100 CONTINUE
      LREC   = (I-1)*NJ+J
      READ(NSAVE'LREC)   (RECA(KK),KK=1,NUMWRD)
      LREC   = NI*NJ   + (I-1)*NJ+J
      READ(NSAVE'LREC)   (RECB(KK),KK=1,NUMWRD)
      RECA(1) = RECA(1) * 3600.0
      RECB(1) = RECB(1) * 3600.0
      RECB(3) = RECB(3) * 3600.0
      WRITE(KW,3120)I,J,(RECA(KK),KK=1,4),(RECB(KK),KK=1,3),
     X          THCK(I,J)
 3120 FORMAT(10X,2I5,E14.5, 2F8.6, E10.5, E14.5, E10.5, E14.5,F10.5)
 3050 CONTINUE
 3000 CONTINUE
C
C     PATH SUMMARY
C
      NALL=0
      DO 4000 K=1,2
      GO TO (4010,4020),K
 4010 CONTINUE
      NP=NPTHA
      SIDE = 4H    A
      GO TO 4030
 4020 CONTINUE
      NP=NPTHB
      SIDE=  4H    B
 4030 CONTINUE
C
      DO 4100 N=1,NP
      NALL = NALL+1
      IF(MOD(NALL-1,50).NE.0)GO TO 4200
      WRITE(KW,4110) (TITLE(L),L=1,12)
 4110 FORMAT( 1H1,/10X,'PATH SUMMARY FOR ',12A6/
     X/10X,'  SIDE  PATH    START      END         T-IN      T-OUT',
     X         3X,'DELTA P',
     X/10X, 6X,6X, 8X,8X, 2(5X,'DEG F'),6X,'PSIA'/)
 4200 CONTINUE
      NODE= NODES(K,N)
      I1 =  IARAY(K,N,1)
      IL =  IARAY(K,N,NODE)
      J1 =  JARAY(K,N,1)
      JL =  JARAY(K,N,NODE)
      WRITE(KW,4220) SIDE, N, I1,J1, IL,JL, TIN(K,I1,J1),TOUT(K,IL,JL
     X        DELP(K,N)
 4220 FORMAT( 10X,2X,A4,I6,2(1X,I3,',',I3,), 3F10.3)
 4100 CONTINUE
 4000 CONTINUE
C
C     B SIDE PRESSURE DROP DATA TABLE
C
```

TABLE A.11 Cont'd

```
      NALL=0
      DO 5000 N=1,NPTHB
      NODE= NODES(2,N)
      DO 5100 L=1,NODE
      NALL=NALL+1
      IF(MOD(NALL-1,50).NE.0) GO TO 5120
      WRITE(KW,5110) (TITLE(K),K=1,12)
 5110 FORMAT(1H1,/5X,'B-SIDE PRESSURE DROP/QUALITY AND OTHER DETAILS',
     X      1X,'FOR ',12A6/
     X/5X,' PATH      I      J',          '  DELTA-P-FR DELTA-P-MOM',
     X     ' DELTA-P-TOT      QUALITY          BIGX',
     X     '          HB-CONV    HB-GURGLING       ALPHA',
     X/20X,3(8X,'PSIA'), 5X,'PERCENT',
     X      2(' BTU/HR-SQFT-F'),
     X/)
 5120 CONTINUE
      I = IARAY(2,N,L)
      J = JARAY(2,N,L)
      DPTOT=  DELTAP(1,I,J)+DELTAP(2,I,J)
      LREC  = NI*NJ +(I-1)*NJ +J
      READ(NSAVE'LREC) (RECB(KK),KK=1,NUMWRD)
      RECB(4) = RECB(4)*3600.0
      RECB(5) = RECB(5)*3600.0
      WRITE(KW,5130)  N,I,J,(DELTAP(K,I,J),K=1,2),DPTOT,QUAL(I,J),
     X         BIGX(I,J),RECB(4),RECB(5),ALPHA(I,J)
 5130 FORMAT(5X,3I5,5F12.5,2E14.5,E10.4)
 5100 CONTINUE
C
 5000 CONTINUE
      RETURN
      END
```

TABLE A.12 LIST OF HEAT EXCHANGER COMMON BLOCKS

```
PROCO PROC
      PARAMETER  MAXX=30, MAXY=30,
      PARAMETER  MAXPTH=10, MAXNOD=200,
      PARAMETER  MAXTAB=30,
      COMMON /ALLVAR/ GC,PI,KF,KW,
     X      MAXI,MAXJ,MAXP,MAXN,MAXT,
     X      TITLE(12),NI,NJ,NPTHA,NPTHB,NPRNT,NDUMP,KOMPLX,NITER,
     X      XLEN,YLEN,ZA,ZB,SWEEP,THKWAL,TOLITR,TURNLA,TURNLB,
     X      NCOST,NTYPE,MTCORE,MTSHEL,FACTF,FACTE,ISTART(2,MAXPTH),
     X      NODES(2,MAXPTH),DELTAX(MAXPTH),DELTAY(MAXPTH),
     X      WDOT(2,MAXPTH),PZRO(2,MAXPTH),TZRO(2,MAXPTH),DHYD(2,MAXPTH)
      COMMON /ALLVAR/   FAOFA(MAXPTH), SAOV(MAXPTH),
     X      FINTHK(MAXPTH), FINLEN(MAXPTH), FINSRF(MAXPTH),
     X      IARAY(2,MAXPTH,MAXNOD),JARAY(2,MAXPTH,MAXNOD),
     X      NTUBES(MAXPTH),TCTAB(MAXTAB),THKCT(MAXTAB),NCOKE,XKCOKE,
     X      TSATTB(MAXTAB),   PSATTB(MAXTAB), NSAT,
     X      TEMBT(MAXTAB), VISBT(MAXTAB), XKBT(MAXTAB),
     X      CPBT(MAXTAB),   RHOBT(MAXTAB), NTABB,AMUB,PCRITB,TCRITB,
     X      TEMAT(MAXTAB), VISAT(MAXTAB), XKAT(MAXTAB),
     X      CPAT(MAXTAB), NTABA, AMUA
      COMMON /ALLVAR/   RENF(MAXTAB), FTAB(MAXTAB), NFRIC,
     X      RENST(MAXTAB), STNTAB(MAXTAB),  NSTANT,
     X      TWTAB(MAXTAB),   XKWTAB(MAXTAB), NWALK
      COMMON /ALLVAR/   FRONAR(MAXPTH), FLARA(MAXPTH), SRFARA(MAXPTH),
     X      FINAR(MAXPTH), FLARB(MAXPTH), AWALL(2,MAXPTH),
     X      TCUTSV(2,MAXPTH),   TSAT(MAXPTH)
      COMMON /ALLVAR/
     X      TIN(2,MAXY,MAXX), TOUT(2,MAXY,MAXX), TWALL(2,MAXY,MAXX),
     X      TCOKE(MAXY,MAXX), CDOT(MAXY,MAXX),
     X      TMEAN(2,MAXY,MAXX), CPMEAN(2,MAXY,MAXX),
     X      AREE(MAXY,MAXX),   THKCK(MAXY,MAXX),
     X      TERMS(4,MAXY,MAXX)
      COMMON /ALLVAR/
     X      ALAM, BLAM, CLAM, DLAM,
     X      ATURB, FTURB, CTURB,
     X      ASUP,BSUP,CSUP,DSUP,
     X      QGAIN, QLOST, ISPURE,
     X      NSAVE, NUMREC, NUMWRD, LREC
      COMMON /ALLVAR/   IFLAG(MAXY,MAXX), QUAL(MAXY,MAXX),
     X      RENSTB(MAXTAB), STNTB(MAXTAB), NSTNTB,
     X      TABVAP(1022), TABCRT(422),
     X      PMIXTB(MAXTAB), CPMIXB(MAXTAB),NMIX,
     X      DELP(2,MAXPTH), DELTAP(2,MAXY,MAXX),
     X      RENFB(MAXTAB), FBTAB(MAXTAB), NFRB,
     X      ALPHA(MAXY,MAXX), BIGX(MAXY,MAXX)
      COMMON /ALLVAR/
     X      PLAMTB(MAXTAB),HVAPTB(MAXTAB),NVAPTB,
     X      TSIGMA(MAXTAB), SIGTAB(MAXTAB), NSIGMA,
     X      XOVFTB(MAXTAB),FOVFTB(MAXTAB),NOVXF,HASIDE(MAXY,MAXX),
     X      SRELTB(MAXTAB), STAB(MAXTAB), NSTAB,KANSTP(MAXPTH)
      COMMON /ALLVAR/  LIQCOR, NLJAY, RENLIQ(MAXTAB),STNLIQ(MAXTAB)
      COMMON /ALLVAR/ HRSMAX,NHOURS,HOURS(MAXTAB),
     X      NCKSAV, NCKSTR
      COMMON /DYNAMC/ QNET,ISDYN,TAU,NCPMET,CPMET(50),TCPMET(50),
     X      NSTORE, ELMASS
   END
```

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