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**EUROPEAN CONTRIBUTION TO HEAT EXCHANGER DESIGN/PERFORMANCE:
HTFS RESEARCH AND COMPUTER PROGRAMS**

Final Report, July 1, 1978—September 30, 1979

By
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MASTER

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U. S. DEPARTMENT OF ENERGY

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FINAL REPORT
European Contribution to
Heat Exchanger Design/
Performance: HTFS Research and
Computer Programs
Contract No. ET-78-C-03-1866
July 1, 1978 - September 30, 1979

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ABSTRACT

The primary purpose of this report is to evaluate the performance of selected HTFS computer programs in solving example heat exchanger design/performance situations. In addition, the specific inputs required by the program are presented to give an idea of the amount of detail the user must supply concerning the heat transfer system. Comments on the versatility of each program and technical details necessary for running each program are also provided. The computer programs examined rate the performance of shell-and-tube type condensers and plate-fin heat exchangers.

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SUMMARY

An evaluation of the contributions of the European scientific community in general and HTFS (Heat Transfer and Fluid Flow Service; Harwell, Oxforshire, OX11 0RA, U.K.) in particular to the areas of process heat exchanger efficiency and design is the objective of this report. This evaluation has been accomplished through a computerized search of heat exchanger literature, first-hand observation of HTFS experimental facilities, and primarily, the assessment and use of HTFS heat exchanger design and performance computer programs.

The computerized literature search was performed on the Engineering Index data base for the years 1977-79. Abstracts of articles dealing with heat exchanger deficiencies and corrective measures, enhancement techniques, and waste heat recovery were sought. The results of this literature search are summarized in Appendix A-8.

The visits of ENSCI consultant, Robert B. Beckmann, to the HTFS facilities at Harwell and the National Engineering Laboratory were discussed in a previous ENSCI report, "Report of Visit to HTFS Facilities at Harwell and the National Engineering Laboratory; and the HTFS Sponsors Meeting, 24-30 March 1979" (Appendix A-7). The purpose of this on-site visit to Harwell and the NEL was to view the experimental facilities and the status of current experimental investigations related to industrial equipment and systems, including the development of computer design/evaluation programs.

Another previous ENSCI report, "Resume of Computer

Programs" (Appendix A-6), presented the following aspects of the computer programs:

- Inventory of available programs and, briefly, their functions and capabilities.
- Theoretical background and the correlations employed in these programs.

In the current report, the selection of a sampling of the available programs and the use of these programs to solve example heat exchanger design/performance problems, has provided information for evaluating the selected programs in the following areas:

- Structure of the computer programs and the effect of this structure on the ease of possible user modifications to the programs.
- Size of the programs, running times, and the cost of preparing the programs for execution on a user system.
- Adequacy and accuracy of the documentation provided by HTFS.
- Flexibility of the programs and the alternative processing modes possible.
- Computability of the source programs provided by HTFS with a user system (i.e. Computer Sciences Corporation's INFONET system).

- Amount and detail required of input data used by the programs.
- Quantity and type of output, as well as a limited assessment of its usefulness and accuracy.

INTRODUCTION

Two of the computer programs offered by HTFS (to sponsors) which evaluate the performance of heat exchangers are SCON4 and CEMPL. SCON4 rates shell-and-tube condensers, while CEMPL deals with plate-fin type heat exchangers. Sponsors are provided with detailed instructions in the use of these programs in the form of users manuals. The specific correlations and theory behind the programs' logic are included in HTFS design reports. (These correlations were briefly reviewed in a prior ENSCI report, "Resume of HTFS Computer Programs", Appendix A-6).

The HTFS programs are developed for the IBM 370 computer. They are written in ANSI Standard Fortran IV, but require some alteration to run on the UNIVAC 1108.

The first alteration was the conversion of the EBCDIC character code of the HTFS program tapes to the ACSII format used by the Computer Sciences Corporation (CSC) INFONET system. A CSC utility program performs the conversion and stores the ASCII programs on disks.

To minimize storage costs, it is desireable to store programs on tape rather than disk. The Fortran compiler at CSC reads the program file as one Fortran subroutine. In order to successfully compile the program the subroutines have to be separated using an editing utility program. After separation the subroutines can be stored on tape.

Following this procedure, the compilation of the programs

was successful, with only warning messages issued by the compiler, but due to the limit on core size imposed by the CSC account, SCON4 had to be overlaid. The overlay structure was provided in the HTFS users manual. Unfortunately, it was discovered that the overlay structure given for a third program, ACOL3 (Performance of Air-Cooled Heat Exchangers), was not correct and the execution of this program was abandoned.

In Table 1, the time required to prepare the programs, compile, map and execute them is presented. The costs of these steps are presented as ranges, since the CSC charges are based on the priority assigned to the job at submittal by the user. In actual practice, a middle priority was always selected so that the cost was an average of the two ends of each range.

Example problems were solved using SCON4 and CEMPL. The results for these sample runs are summarized in Table 2. More detailed outputs from the programs are included in Appendix 2 (SCON4) and Appendix 4 (CEMPL).

In the following sections a complete description of the programs SCON4 and CEMPL is provided. The capability of the programs, their solution techniques and the specific inputs required are discussed.

Table 1. Cost of Program Preparation and Execution

STEP	SCON4	CEMPl
BIND		
SRU-sec	27	10
COST (\$)	1.30-8.10	.48-3.00
UNBIND		
SRU-sec	41	13
COST (\$)	1.97-12.30	3.14-3.90
SEPARATION		
SRU-sec	176	108
COST (\$)	8.45-52.80	5.18-32.40
COMPILATION		
SRU-sec	245	76
COST (\$)	11.76-73.50	3.65-22.80
MAP		
SRU-sec	27.5	9
COST (\$)	1.32-8.25	.43-2.70
EXECUTION		
SRU-sec	165	108
CPU-sec (UNIVAC)	46	54
COST (\$)	7.92-49.50	5.18-32.40

Table 2. Summary of Example Problem Results

I. SCON4 - SHELL-SIDE CONDENSATION PERFORMANCE, SINGLE VAPOR & GAS

	Example 1	Example 2	Example 3
INPUTS			
Shell type	E	J	J
Shell-side components	Steam + CO ₂	Same	Same
Inlet vapor flowrate	2,100 kg/hr (Cocurrent to coolant stream)	2,100 kg/hr (Counter- current)	Not specified
Shell-side inlet temp. (°C)	130.5 (sat.)	160 (super heat.)	130.5 (sat.)
Shell-side outlet temp. (°C)	Not specified	Not specified	34
Tube-side component	Water	Same	Same
Coolant flowrate (kg/s)	17.222	Same	Not specified
Coolant inlet temp. (°C)	26	Same	Same
Coolant outlet temp.	Not specified	Not specified	45
OUTPUTS			
Total heat load (J/s)	1.510×10^6	1.468×10^9	7.412×10^5
O/A heat transfer coeff. (J/s·m ² ·°C)	518.1	413.2	224.7
Shell area (m ²)	54	44.8	46.5
Shell-side outlet temp. (°C)	34.9	26.2	Specified as input
Coolant outlet temp. (°C)	46.9	46.3	Specified as input
Vapor flowrate (kg/s)	Specified as input	Specified as input	1109.2
Coolant flowrate (kg/s)	Specified as input	Specified as input	9.29828

Table 2. Summary of Example Problem Results (cont'd)

II. CEMPl - PLATE-FIN HEAT EXCHANGER PERFORMANCE PROGRAM

	Example 1	Example 2	Example 3
PROCESS AND GEOMETRIC DATA INPUTS			
# of streams	1	2	3
Stream comp.	1) Nitrogen	1) Ethylene 2) Propylene	1) Natural gas 2) Refrigerant A* 3) Refrigerant B*
# of exchangers	1	3	1
Exchanger effective length (m)	3.430	1.727	3.500
Exchanger effective width (m)	0.0762	0.0233	0.500
# of fin sections per stream	1) 1	1) 1 2) 1	1) 2 2) 2 3) 1
Section fin type	1) 5% perforated	1) Serrated 2) Plain	1) Serrated, 2% perf. 2) Serrated, 2% perf. 3) Serrated
PROGRAM CALCULATED CHANGES IN PROCESS CONDITIONS OVER EXCHANGER LENGTH-START FINISH START FINISH START FINISH			
Temperature (k)	1) 77.3 1) 87.69	1) 225.81 1) 219.98 2) 240.00 2) 225.96	1) 294.27 1) 159.70 2) 305.38 2) 172.10 3) 299.83 3) 171.12
Pressure (bar)	1) 3.130 1) 2.924	1) 11.600 1) 11.887 2) 1.880 2) 1.758	1) 3.45 1) 3.62 2) 5.17 2) 5.03 3) 6.89 3) 6.90
Vapor mass frac.	1) 0 1) 0.6673	1) 0.4750 1) 0 2) 1.000 2) 0	1) 1.0000 1) 0.1472 2) 0.7330 2) 0.0401 3) 1.0000 3) 0
Heat Transfer (J/s)	1) 5.357 x 10 ³	1) -1.624 x 10 ⁷ 2) -1.624 x 10 ⁷	1) -7.646 x 10 ⁵ 2) -6.614 x 10 ⁵ 3) -1.031 x 10 ⁵

* Unspecified multicomponent hydrocarbons

SHELL-SIDE CONDENSATION PERFORMANCE,
SINGLE VAPOR AND GAS (SCON4)

1. Solution Capability

SCON4 evaluates the performance of one or more baffled shell-and-tube condensers. The program allows for condensation of a vapor on the shell side with or without a non-condensing gas also present. The condensate may be subcooled by flooding some of the tubes. At the shell entrance the vapor can be saturated or superheated, but the shell-side fluid cannot fall below the saturation temperature when all the superheat has been removed. The tube-side fluid consists of a single-phase coolant.

There are eight possible modes of operation for SCON4 determined by the system parameters the user chooses to specify.

For coolant in the tubes the user specifies either the
the flowrate

or the exit temperature.

For the shell-side fluid the user specifies either the
the vapor mass flowrate at inlet

or the temperature of the mixture at exit

or the vapor mass flowrate at exit

or the inert mass fraction at exit.

This flexibility in the specification of process data makes SCON4 useful for design purposes.

SCON4 can handle the following condenser geometries:

Shell type: TEMA E-type, TEMA G-type, TEMA J-type (twin inlet or twin outlets)

No. of Shells

in series: up to 4 with any number of identical shells in parallel

No. of tube-

side passes: TEMA E and J (1,2,4,6,8,10,12,14,16)
TEMA G (2,4,6,8,10,12,14)

Type of baffle

plate: Single or double segmental

Baffle cut: Single --- 10% - 45% of shell diameter (cut is vertical to give side-to-side flow)

Double --- Inner and outer windows are assumed to have equal areas before the tubes are fitted.

Max no. of

baffles: E-type - 39
J-type - 39 (per half shell)
G-type - 38 (per half shell)

Shell Orientation: E-type - vertical or horizontal

G-type - horizontal only

J-type - horizontal only

Nozzles: Conventional nozzles with or without an impingement plate. No vapor belts.

Flow Direction: E-type shell - vapor path can be cocurrent or countercurrent to first tube-side pass.

Tube Layouts: Triangular ($\rightarrow 30^\circ$), rotated triangular ($\rightarrow 60^\circ$), square ($\rightarrow 90^\circ$) and rotated square ($\rightarrow 45^\circ$). These are defined with respect to the direction of the vapor flow across the bundle.

Baffle Pitch: Uniform or non-uniform.

Max. no. of baffle pitches:

E-type - 40

J-type - 40 (per half shell)

G-type - 40 (per half shell)

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Clearances: Specified by user or selected by program using TEMA standards.

Baffle Thickness: Specified by user or selected by program using TEMA standards.

2. Input

Input to the program is in card format using only the first 64 columns to allow data to be input from a teletype terminal. Units can be SI, metric or British Imperial Units. The user must include as input a description of the condenser and its dimensions. Also, the physical properties of the shell-side and tube-side streams as well as the state of these streams at entry must be stipulated. Process data is also supplied by the user. A complete list of the inputs required for SCON4 is included in Appendix A-1. The actual inputs used in the example runs are printed as part of the program output. These example inputs are included in Appendix A-2.

The input file channel numbers used in the Fortran 'READ' statements are easily changed by the user to meet specific system requirements. HTFS provides data sheets in the program users manual as an aid in preparing inputs. Geometric and process data inputs can be varied in a single run in order to consider a range of design possibilities.

3. Output

Output can be received in an abbreviated form at the teletype, while the majority of the output is printed at a line printer. Optionally, all the output can be directed to the line printer.

The program is equipped with a number of error messages explaining why the performance of the condenser(s) cannot be rated. There are also 'non-fatal' error messages which are issued when design information outside normal conditions is specified. The processing continues in these cases, however.

The final output consists of a full account of the input data and values calculated within the program which describe the performance of the condenser. The outputs produced by the three example problems considered are included in Appendix A-2.

4. Solution Technique

The general logic of the program is as follows:

- a) Input data is read and checked for completeness and reasonableness. Appropriate error messages, if any, are printed. Fatal errors result in program termination.
- b) The estimated heat load input by the user is employed in the estimation of the vapor flowrate at the inlet and the coolant outlet temperature or flowrate.
- c) The coolant temperature at the vapor inlet plane is estimated. Proceeding baffle space by baffle space towards the vapor outlet, the amount of condensation and the change in the stream temperatures and pressures are calculated for each pass. Discontinuities in the outlet coolant temperature due to the inaccuracy of the initial inlet cooling temperature estimate cause a new estimate to be made and Step (c) is repeated.
- d) Subsequent shells, if any, are rated in the same manner.
- e) When all the shells have been considered, the calculated outlet conditions are checked against those specified by the user. If there is a discrepancy, the values for the outlet conditions initially assumed are revised

and processing returns to step (b).

- f) Finally, the changes in condensate level are calculated and the results are printed.

5. Technical Information on Program

SCON4 is a structured program consisting of 70 subroutines. The source listing is heavily documented. Of the 17,437 cards comprising the program, 8,256 are comments. At the beginning of each subroutine, HTFS includes a list and brief description of each subroutine called. A listing of the tags used for common areas accessed by the subroutine and a definition of each tag are also provided.

The program size is 202 kbytes on the IBM 370 and 42 kword on the Univac 1108 when the overlay structure supplied in the users manual is employed. The overlay structure halves the program size.

The running time of the program is affected by the type of shell specified, the initial conditions which the user chooses to specify and the accuracy of the heat load estimate. For the three examples supplied by HTFS, they give the following running times:

IBM 370	UNIVAC 1108
(s)	(s)
22.84	40.52

SCON4 is written in ANSI Standard Fortran IV.

6. Description of Examples

- a) In the first example problem, the condenser is specified

as a TEMA E-type shell. The shell side carries a mixture of steam and carbon dioxide. The condenser is designed to subcool the condensate by flooding the shell to a depth of 22% of the shell diameter. Inlet conditions for the shell are specified as a vapor flowrate of 0.5833 kg/s with an inert mass fraction of .255. Cooling water enters the tubes at 26°C and a flowrate of 1.222 kg/s. The system heat load is estimated to be 1.400×10^6 J/sec.

- b) The second example is similar to the first, but a J-type shell is specified. The process conditions are the same, except the shell-side vapor mixture is superheated by 30°C. The vapor flow, rather than being cocurrent to the first tube pass, as in the first example, is countercurrent. All clearances are given the default value. The specified tube-side fouling resistance is slightly lower than example one. The tube-side inlet pressure is lower than in the first example. The effect of vapor shear on the shell-side heat transfer coefficient was ignored in the first example, but is considered in this second example.
- c) The same components are used in Example 3 as in the first two examples. A J-type shell is designated with uniformly cut double segmental baffles and non-uniform baffle pitching. For this example, the inlet vapor flowrate and coolant flowrate are not specified. These parameters are replaced by the coolant and shell-side outlet temperatures.

The detailed inputs and outputs for these examples are found in Appendix A-2.

7. Results of Example Problems

The performance of the specified condensers in the three examples is summarized in the following Table 3 which cites some of the output parameters calculated by SCON4.

Table 3. SCON4 Example Problems Results

	Example		
	1	2	3
Heat load (J/sec)	1.510×10^6	1.473×10^6	7.337×10^5
Heat transfer coefficient (J/sec m ² °C)	298.5	265.8	166.7
Area/shell (m ²)	54.03	44.87	46.50
Coolant flowrate (kg/s)	17.222	17.222	9.203
Vapor inlet flowrate (kg/s)	0.5833	0.5833	0.3044
Coolant temp. rise (°C)	20.9	20.4	19.0

As expected, the 30° of superheat added to the inlet vapor in Example 2 improves the efficiency of the condenser by increasing the temperature gradient. It is interesting to note that specifying the outlet stream temperatures in the third example, rather than flowrates, results in a shell of comparable size, but with half the heat load and throughput.

Since all three examples used a mixture of CO₂ and steam on the shell side, the significance of the presence of a noncondensable gas on the shell side is not apparent. However, experimental work by HTFS indicates that a 7% concentration of nitrogen in the input vapor stream can reduce the overall heat transfer coefficient by a factor of two. Thus, the program's ability to consider a noncondensable component is an important feature.

The capability of SCON4 as a design tool has been reviewed by Semeria and Hewitt*. Two arrangements for the condensation

* R. Semeria and G.F. Hewitt, "Aspects of Heat Transfer in Two-Phase Gas-Liquid Flow," in Heat Exchangers: Design and Theory Sourcebook, N.H. Afgan and E.U. Schlunder, eds., McGraw-Hill, N.Y., 1974.

of butane with 0.5% methane are considered by the program.

In the first arrangement, four shells in parallel are each divided into 10 equally divided baffled sections. The second arrangement utilizes non-uniform baffle spacing. The program rates this second system as 36% smaller in shell area with essentially no difference in performance.

PLATE-FIN HEAT EXCHANGER PERFORMANCE PROGRAM (CEMPl)

1. Solution Capability

CEMPl evaluates the performance of plate-fin type heat exchangers. The program is capable of considering up to three streams and these streams may be single-component or multi-component; evaporating, condensing or single-phase. The assumption is made that streams losing heat are flowing counter-current to streams gaining heat.

There are three possible calculation modes in CEMPl.

These modes are:

Mode 1 - Single-stream

Mode 2 - Two-stream

Mode 3 - Three-stream

Figure 1 shows a typical three-stream plate-fin heat exchanger. The shaded area is the exchanger core. It is this section only that is considered by CEMPl.

2. Input

Inputs to CEMPl can be in the form of cards or teletype-keyed entries, fixed or free format. The user has the option of selecting SI, British or metric units.

The input data required by the program are of three basic types:

- a) Geometric data - Dimensions and configuration of the exchanger and the fins. (Figure 2 illustrates some of the key exchanger core dimensions that the user must supply to the program. Figure 3 shows the three types of fins which are used in the example runs of CEMPl.)

- b) Fin data-specific data points giving Reynolds number, Fanning friction factor and Colburn j-factor for each exchanger fin type.
- c) Data points at a number of temperatures for each stream.
 - i) Process data
 - ii) Thermal data
 - iii) Liquid data
 - iv) Vapor data

The specific inputs used by CEMPL are listed in Appendix A-3. The inputs used for the three example runs are presented in Appendix A-4.

Figure 1. Plate-Fin Heat Exchanger Showing Core Section

Figure 2. Plate-Fin Heat Exchanger Core Dimensions

Figure 3. Three Types of Fins

HTFS provides input data sheets to aid in preparing inputs to the program. The input channels in the program's Fortran "read" statements are easily modified to fit the user's system through the use of control cards.

3. Output

Output from CEMPL can be received via the teletype, line printer, or a combination of the two. The output consists of a format listing of the inputs and the results of the program calculations.

In the primary results section of the output, the local values of temperature and pressure for each stream and the local wall (i.e. separating plate) temperatures are presented. Also, the cumulative heat transfer between streams is printed for specific increments along the length of the exchanger.

For each stream, the equilibrium vapor mass fraction, total specific enthalpy of the stream, average fin efficiency, average heat transfer coefficient, average heat flux, friction and gravity pressure changes, and the total pressure stream for each increment are reported in the local results section. A summary of results citing values at the start and finish of calculations appears at the end of the program output.

Output from the example runs of CEMPL is included in Appendix A-4. In addition, error messages are printed when any of the following conditions occur:

- a) Input data format error
- b) Inconsistent input data
- c) Calculation errors (i.e. non-convergent iteration)

4. Solution Technique

The processing proceeds along the length of the exchanger. The user specifies the number of increments for the calculations. In the following descriptions, the end of each element where the conditions are known will be called the "near-end", and the end where the conditions are being calculated will be called the "far-end".

4.1. Mode 1

In the first mode, a single fin layer of a single stream is considered. The calculation procedure for the mode is as follows:

- a) The conditions at one end of the exchanger are known. These are used as the conditions for the "near-end" of the first stream element: temperature, pressure, specific enthalpy, vapor mass fraction and mass flow-rate.
- b) Using the "near-end" conditions, the pressure change for the element is calculated.
- c) Next the elemental heat flux and rate of heat transfer are calculated.
- d) The "far-end" conditions of the stream element are determined: pressure, specific enthalpy, temperature and vapor mass fraction.
- e) The average elemental conditions are calculated based on the "near-end" and "far-end" values.
- f) The effective elemental heat transfer coefficient is found from the average elemental conditions.
- g) The mean elemental (wall-stream) temperature is calculated and used to determine the "far-end" wall temperature.

- h) The "far-end" conditions from step d now become the "near-end" conditions for the next element.
- i) Processing returns to step b.

4.2 Modes 2 and 3

- a) The conditions at the "near-end" of the first element (starting conditions) are known: temperature, pressure, specific enthalpy, vapor mass fraction, and mass flow-rate for each stream.
- b) The pressure change for each stream over the element is calculated.
- c) Next the elemental rate of heat transfer is estimated for each stream.
- d) The elemental "far-end" conditions are calculated, then the average conditions for the element are found.
- e) Using the average conditions, the effective elemental mean heat-transfer coefficient is calculated for each stream.
- f) The elemental mean wall temperature is calculated and used to solve for the elemental mean (wall-stream) temperature.
- g) The mean temperature difference is assumed to be constant over the element.
- h) The elemental "far-end" wall temperature and then the effective elemental heat flux are calculated.
- i) The estimate of the elemental rate of heat transfer is revised.
- j) Steps d-i are repeated until values for the rate of heat transfer converge.
- k) When convergence is achieved, the "far-end" conditions become the "near-end" conditions for the next element and processing returns to Step b.

5. Technical Information on Program

The size of CEMPL is 100 kbytes (25 kwords) without overlay, 164 kbytes (41 kwords) with overlay. (The users manual
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provided by HTFS gives a suggested overlay structure.) There are 26 routines and a total of 18 common areas.

The source program is structured and all routines are in alphabetical order to simplify any modification to the program. The exception to this alphabetical order is the main routine of the program, which appears first.

At the beginning of each routine is a 'dictionary' of routines called in the particular routine and common areas accessed by the routine. Comments are liberally placed among the executable statements. Of the 4,064 cards comprising the program, 2,169 are comments.

The running time of the program is dependent on four factors:

- 1) Program mode (i.e. number of streams).
- 2) Number of elements chosen for step integration.
- 3) Number of data points supplied for fin, thermal, liquid and vapor data.
- 4) Number of iterations required for convergence.

The following table gives comparative running times for each of the three examples on the HTFS IBM 370 computer.

Table 4. Running Time for CEMPL Example Problems.
CPU time (sec)

Data	No. of Elements	With Overlay	Without Overlay
Example 1	200	3.0	1.4
Mode 1	300	3.5	1.8
Example 2	200	4.4	3.1
Mode 2	300	5.6	4.1
Example 3	200	7.7	6.4
Mode 3	300	9.4	8.3

6. Description of Examples

6.1. Example 1, Mode 1

This example estimates the pressure change in a stream of evaporating nitrogen through a plate-fin exchanger. A vertical aluminum exchanger 3.430 m high with a single perforated fin layer between two 6.4×10^{-3} m thick separating plates is specified.

The fin layer is 6.4×10^{-3} m high and the flow channel between the side bars is 7.62×10^{-2} m wide. The fins themselves are 2.0×10^{-3} m thick, 5% perforated and occur at a frequency of 591 fins/m.

The nitrogen stream is heated by passing an electric current through the separating plates. The subcooled nitrogen enters the exchanger at 77.3K and 3.13 bar at a mass flowrate of 0.037 kg/s.

6.2. Example 2, Mode 2

Three two-stream vertical exchangers evaporate ethylene and condense propylene. Each of these exchangers is 1.7 m long with an effective width of 0.592 m. Forty fin layers carry the ethylene; forty-one carry the propylene. The separating plates are 1.27×10^{-3} m thick.

The ethylene layers are comprised of serrated fins, each 8.89×10^{-3} m high and 2.54×10^{-4} m thick. The fins are distributed 472 fins/m.

The propylene layers use plain fins that are 6.35×10^{-3} m high and 2.54×10^{-4} m thick. There are 591 fins/m.

Ethylene enters the base of each exchanger as a subcooled

liquid and is partially evaporated as it flows upward through the exchangers. The mass flowrate of the ethylene is 8.19 kg/s through all three exchangers.

Propylene enters the top of the exchangers as dry saturated vapor and is condensed and subcooled as it flows downward. The flowrate is 35.8 kg/s.

Calculations for the second example begin at the warm end of the three exchangers (top).

6.3. Example 3, Mode 3

A three-stream plate-fin heat exchanger liquefies natural gas. The natural gas becomes totally condensed while a high pressure refrigerant is almost totally condensed by exchanging heat with a countercurrent evaporating low pressure refrigerant stream. All three streams are multicomponent hydrocarbons. The vertical aluminum exchanger is 3.500 m long and 0.500 m wide.

Stream 1 (the low pressure refrigerant) flows through 15 fin layers each 0.010 m high and composed of 2 fin sections. The warm-end section is 2.000 m long with serrated fins that are 4×10^{-4} m thick and distributed 591 fins/m. The cold-end section has 709 fins/m, is 1.500 m long and consists of perforated fins that are 4×10^{-4} m thick and 2% perforated.

Stream 2 (the high pressure refrigerant) passes through 10 layers that are each 7×10^{-3} m high. Each layer has two fin sections. The first is a 2.000 m long section at the warm end of the exchanger. There are 591 fins/m, each being 6×10^{-4} m thick and serrated. At the cold end, a 1.500 m section of perforated fins with 2% perforation is situated.

Each fin is 6×10^{-4} m thick and the fins occur at 709 fins/m.

Stream 3 (the natural gas) flows through 5 layers. Each layer is a single fin section with 591 fins/m. The fins are serrated, 7×10^{-3} m high and 6×10^{-4} m thick. The separating plates are 2×10^{-3} m thick.

Stream 1 enters the base of the exchanger as a two-phase mixture with a mass flowrate of 0.126 kg/s. It exits superheated at 21°C, 3.4 bar.

Stream 2 is a two-phase mixture at 32°C, 5.17 bar when it enters the top of the exchanger. Passing downward at 1.26 kg/s, the stream exits almost totally condensed.

Stream 3 is a superheated vapor when it enters the exchanger at the top. It flows at a rate of 0.1638 kg/s from 27°C, 6.89 bar at entry conditions to a subcooled state at exit.

7. Results of Example Problems

A portion of the example problem output is included in Appendices A-4-1 through A-4-3. The output included in the Appendices summarizes changes in the primary system parameters over the length of the exchanger. The program also provides a recording of a large number of parameters at each increment along the exchanger. This incremental data output has been omitted from this report due to its excessive length.

Because the three example problems each treat very different plate-fin exchanger geometries and stream compositions, a comparison of the results would not be useful. However, the results for the first example can be compared with experimental

results obtained by HTFS. (See Appendix A-4-1.) The calculated pressure drop is 0.2062 bar and the experimental result is very close: 0.186 bar.

Since the number of data points supplied by the user influences the accuracy of the calculations, it is best to obtain as many points as possible in cases where conditions vary greatly along the exchanger. As indicated in Appendix A-3, a maximum of 20 thermal data points and 10 liquid and vapor data points can be specified by the user. In the Example 1 inputs HTFS has elected to use a small number of points, two or three at each of two pressures, corresponding to small changes in temperature and pressure along the exchanger. (See Table 2.) By contrast, the third example problem uses up to 20 thermal data points and 7 liquid and vapor data points to accomodate the relatively large temperature changes in the three streams of the heat exchanger. Temperature changes are recorded in Table 2 and Appendix A-4-3.

The fin data required by the program may be somewhat difficult for many of the users of CEMPl to obtain. Fin data is dependent on fin type. The fin data for the example problems comes from an HTFS report. As noted in Appendix A-3, fin data consists of a friction factor and a Colburn j factor for 2 to 10 Reynolds numbers for each fin type. In the example problems, 8 to 10 fin data points are specified by HTFS for each fin type.

CONCLUSIONS AND RECOMMENDATIONS

European activities in the areas of process heat exchanger efficiency and design improvement were generally reviewed through a computerized literature search in these subject areas (Appendix A-8). The contributions of HTFS in particular were examined through personal visits to their experimental facilities (Appendix A-7) and through the examination and testing of heat exchanger computer programs (Appendix A-6, current report).

The computerized literature search of the Engineering Index data base for articles dealing with heat exchanger deficiencies and corrective measures, enhancement techniques, and waste heat recovery revealed that the majority of this literature is concentrated in heat exchanger deficiencies: fouling, corrosion and flow-induced tube vibration. Of those articles which focus on enhancement techniques, most concern the use of fins in heat exchanger design. Few entries were found on waste heat recovery, but this could be due to the indexing system employed by Engineering Index. It was found that 15% of all articles selected were published in European countries.

Sample runs of HTFS computer programs which rated the performance of shell-and-tube and plate-fin-type heat exchangers supplied results leading to the following conclusions about the HTFS computer programs:

- The programs are structured, organized and documented within the source listing in order to make program

modifications as simple and straightforward as possible.

- The programs are so large that an "average" computer core partition is too small to contain one of the programs for execution without overlaying the subroutines.
- The documentation provided by HTFS is generally adequate for running the programs. However, it was found, in one case at least, that the HTFS suggested overlay structure was incorrect. No other incidence of inaccurate documentation was found.
- The programs allow a variety of geometric configurations and processing modes. For example, in the case of shell-and-tube heat exchanger design, the user has the option of specifying either stream flowrates or stream outlet temperatures.
- In order to use the HTFS Fortran computer programs (written on tapes by an IBM 370 system) on the Computer Sciences Corporation INFONET system (UNIVAC 1108), time-consuming, expensive conversion is required.
- The programs require considerable input data and generally, the more input data supplied, the more accurate the results.
- Detailed output is provided by the programs, both in summary form and for each increment used in the program for calculations. (For example, for shell-and-tube heat exchangers each baffle space constitutes one increment.)
- The shell-and-tube condenser program, SCON4, is useful for design purposes since geometric configurations, number of shells in series, outlet temperatures and flowrates can be varied and the resultant heat loads and condenser areas can be compared.
- The plate-fin heat exchanger program, CEMPl, has been validated for accuracy using HTFS experimental data.

On the basis of the results of the current study of European activity in the process heat exchanger area, it is recommended that the Department of Energy continue to be cognizant of European contributions. However, the current evidence does not indicate that the European research to improve heat exchanger efficiency is significantly different from research being pursued in the United States.

APPENDICES

APPENDIX A-1. SCON4 INPUTS

Following is a list of the inputs required by the SCON4 program including options and default values.

<u>Input Description</u>	<u>Default Value</u>
<u>GEOMETRIC DATA</u>	
Level number - For a number of shells in series, this is the number of the shell counting from the entry point of the vapor.	1
Unit identifier - British, metric or SI units (can have different units for GEOMETRIC, PROCESS and COMPONENT PROPERTIES.)	SI units
Shell type - TEMA E-type, TEMA G-type, TEMA J-type or I-type.	None
Orientation - Vertical or horizontal.	Horizontal
Cocurrent to first tube pass- yes or no?	Yes
Number of consecutive identical levels.	1
Number of parallel shells.	1
Shell inside diameter.	None
Bundle-shell diametric clearance - If -1 is specified clearance is calculated with changing diameter.	$1.27 \times 10^{-2} \text{ m}$ (Units are as specified)
Baffle-shell diametric clearance.	TEMA value
Baffle-tube diametric clearance.	TEMA value
Percent baffle cut on diameter.	25%
Baffle pitch (uniform only).	Variable
Baffle type-single or double segmental.	Single segmental
Baffle thickness.	TEMA value
Number of baffles.	None
Number of pairs of sealing strips.	0

<u>Input Description</u>	<u>Default Value</u>
<u>GEOMETRIC DATA</u>	
Impingement plate-impingement plate fitted or no impingement plate.	Plate is fitted
Shell-side inlet nozzle inside diameter	None
Shell-side outlet nozzle inside diameter	None
Number of tube-side passes.	None
Tube outside diameter	None
Tube pitch (Only square or equilateral triangular patterns allowed).	None
Tube-pitch angle.	None
Tube-side inlet nozzle inside diameter	None
Tube-side outlet nozzle inside diameter	None
Depth of condensate.	0
Height of baffle weir.	0
Number of tubes in baffle window (Program can calculate number of tubes if desired).	Non-uniform specifications follow
Baffle pitches (non-uniform).	None
Percent baffle cuts on diameter (non-uniform).	None
Number of tubes in baffle window (non-uniform).	None
<u>PROCESS DATA</u>	
Coolant mass flow at inlet.	Calc. by program
Liquid mass flow fraction at inlet (shell).	0
Vapor mass flow at inlet (shell).	Calc. by program
Inlet temperature of coolant.	None
Outlet temperature of coolant.	Calc. by program
Fouling resistance (tube-side).	0
Inlet pressure.	0

<u>Input Description</u>	<u>Default Value</u>
<u>COMPONENT PROPERTIES</u>	
Liquid phase viscosity.	None
Liquid phase thermal conductivity.	None
Liquid phase latent heat.	None
Liquid phase saturated vapor pressure.	None

Appendix A-2-1. Detailed Output from SCON4 - Example 1

		Hot Shell Side		Cold Tube Side				
		Inlet	Outlet	Inlet	Outlet	Heat Load Etc.		
Flowrates	Units	Steam - Carbondioxide		Water		Total Heat Load	(KW)	1509.73
Total Fluid Flowing	(KG/H)	2818.8		62000.0		Effective M.T.D.	(C)	53.937
Total Vapour + Gas	(KG/H)	2818.8	724.1			Surface Area	(M2)	54.026
Total Liquid	(KG/H)	0.	2094.7	62000.0	62000.0	Overall Coeff	(W/M2 K)	518.10
Non-Condensables	(KG/H)	718.8						
Condensed	(KG/H)	2094.7						
Non-Cond. Mass Fraction		.255	.993					
Liquid Props						Nozzle Pressure-Drop	Shell	Tube
Density	(KG/M3)	931.9850	989.1222	997.3739	984.2972	Inlet(s)	(BAR)	0.
Viscosity	(Centipoise)	.2191	.6911	.8645	.6115			.0029
Specific Heat	(KJ/KG K)	4.2814	4.1995	4.1877	4.2064	Outlet(s)	(BAR)	.0050
Conductivity	(W/M K)	.6783	.6149	.6057	.6202			0.
Molecular Weight		18.00	18.00			Dimensionless Nos.	Shell	Tube
Vapour-Gas Props						Reynolds In Gas/Vapour	14030.	
Density	(KG/M3)	1.9490	5.1566	0.	0.	Out Gas/Vapour	3917.	
Viscosity	(Centipoise)	.0145	.0131	0.	0.	In Liquid		26271.
Specific Heat	(KJ/KG K)	1.9420	.8614	0.	0.	Out Liquid		26271.
Conductivity	(W/M K)	.0270	.0173	0.	0.	Prandtl In Gas/Vapour	1.044	0.
Molecular Weight		21.19	43.54	0.	0.	Out Gas/Vapour	.652	0.
Molecular Diff.						In Liquid	1.383	5.977
Coeff.	(CM2/S)	.118	.074			Out Liquid	4.720	4.147
2-Phase Props						Lewis In Gas/Vapour	.606	
Latent Heat	(KJ/KG)	2169.53	2416.54			Out Gas/Vapour	.524	
Vapour Pressure	(BAR ABS)	2.707	.055			Submergence Details		
Temperatures and Pressures						Number of Tubes Submerged		56
Stream (Vapour + Gas)	(C)	130.500	34.858	0.	0.	Number of Rows Submerged		5
Stream (Liquid)	(C)	130.441	39.180	26.000	46.886			
Dew Point (Vapour + Gas)	(C)	130.441	34.509					
Wall (Max/Min)	(C)	93.17	30.39					
Inlet Pressure	(BAR ABS)	3.080		5.000				
Dp Calculated	(BAR)	.034		.356				

Appendix A-2-2. Detailed Output from SCON4 - Example 2

Condensation was Assumed to Cease in the 9-th Baffle Space in the 1-th Level as the Mixture Saturation Temperature was Within 0.5K of the Coldest Coolant Temperature at Entry to that Baffle Space

		Hot Shell Side		Cold Tube Side			
		Inlet	Outlet	Inlet	Outlet		
Flowrates		Steam - Carbondioxide		Water		Heat Load Etc.	
Total Fluid Flowing	(KG/H)	2818.8		62000.0		Total Heat Load	(KW) 1468.02
Total Vapour + Gas	(KG/H)	2818.8	722.1			Effective M.T.D.	(C) 79.167
Total Liquid	(KG/H)	0.	2096.7	62000.0	62000.0	Surface Area	(M2) 44.874
Non-Condensables	(KG/H)		718.8			Overall Coeff	(W/M2 K) 413.23
Condensed	(KG/H)		2096.7				
Non-Cond. Mass Fraction			.255				
			.995				
Liquid Props						Nozzle Pressure Drop	
Density	(KG/M3)	931.9850	964.2159	997.3739	984.6577	Inlet(s)	(BAR) 0. .0011
Viscosity	(Centipoise)	.2191	.3892	.8645	.6170	Outlet(s)	(BAR) 0. .0057
Specific Heat	(KJ/KG K)	4.2814	4.2352	4.1877	4.2059		
Conductivity	(W/M K)	.6783	.6425	.6057	.6198		
Molecular Weight		18.00	18.00			Dimensionless Nos.	
Vapour-Gas Props						Reynolds In Gas/Vapour	Shell Tube 12961.
Density	(KG/M3)	1.8163	5.3776	0.	0.	Out Gas/Vapour	3868.
Viscosity	(Centipoise)	.0154	.0130	0.	0.	In Liquid	26191.
Specific Heat	(KJ/JG K)	2.0310	.8504	0.	0.	Out Liquid	26191.
Conductivity	(W/M K)	.0296	.0165	0.	0.	Prandtl In Gas/Vapour	1.056 0.
Molecular Weight		21.19	43.71	0.	0.	Out Gas/Vapour	.671 0.
Molecular Diff. Coeff.	(CM2/S)	.133	.070			In Liquid	1.383 5.977
2-Phase Props						Out Liquid	2.566 4.187
Latent Heat	(KJ/KG)	2093.35	2438.93			Lewis In Gas/Vapour	
Vapour Pressure	(BAR ABS)	6.372	.034			Out Gas/Vapour	.602 .517
Temperatures and Pressures						Submergence Details	
Stream (Vapour + Gas)	(C)	160.000	26.187	0.	0.	Number of Tubes Submerged	0
Stream (Liquid)	(C)	130.441	78.961	26.000	46.311	Number of Rows Submerged	0
Dew Point (Vapour + Gas)	(C)	130.441	26.161				
Wall (Max/Min)	(C)	87.85	/ 25.96				
Inlet Pressure	(BAR ABS)	3.080		2.000			
Dp Calculated	(BAR)	.005		.300			

Vapour Shear Enhancement is Included

Appendix A-2-3. Detailed Output from SCON4 - Example 3

		Hot Shell Side		Cold Tube Side		Heat Load Etc.		
		Inlet	Outlet	Inlet	Outlet			
Flowrates	Units	Steam - Carbon dioxide		Water		Total Heat Load	(KW)	741.20
Total Fluid Flowing	(KG/H)	1488.9		33473.8		Effective M.T.D.	(C)	70.933
Total Vapour + Gas	(KG/H)	1488.9	382.2			Surface Area	(M2)	46.497
Total Liquid	(KG/H)	0.	1106.6	33473.8	33473.8	Overall Coeff	(W/M2 K)	224.73
Non-Condensables	(KG/H)		379.7					
Condensed	(KG/H)		1106.6					
Non-Cond. Mass Fraction		.255	.993					
Liquid Props						Nozzle Pressure-Drop	Shell	Tube
Density	(KG/M3)	931.9850	963.4542	997.3465	985.4531	Inlet(s) (Bar)	0.	.0008
Viscosity	(Centipoise)	.2191	.3833	.8638	.6294		0.	
Specific Heat	(KJ/KG K)	4.2814	4.2363	4.1877	4.2048	Outlet(s) (Bar)	0.	.0043
Conductivity	(W/M K)	.6783	.6434	.6057	.6189		0.	
Molecular Weight		18.00	18.00					
Vapour-Gas Props						Dimensionless Nos.	Shell	Tube
Density	(KG/M3)	1.9490	5.2338	0.	0.	Reynolds In Gas/Vapour	1883.	
Viscosity	(Centipoise)	.0145	.0131	0.	0.	Out Gas/Vapour	1043.	
Specific Heat	(KJ/KG K)	1.9420	.8599	0.	0.	In Liquid		14844.
Conductivity	(W/M K)	.0270	.0172	0.	0.	Out Liquid		14844.
Molecular Weight		21.19	43.58	0.	0.	Prandtl In Gas/Vapour	1.044	0.
Molecular Diff. Coeff.	(CM2/S)	.118	.073			Out Gas/Vapour	.654	0.
2-Phase Props						In Liquid	1.383	5.972
Latent Heat	(KJ/KG)	2169.53	2419.09			Out Liquid	2.524	4.276
Vapour Pressure	(BAR ABS)	2.707	.052			Lewis In Gas/Vapour	.606	
Temperature and Pressures								
Stream (Vapour + Gas)	(C)	130.500	33.871	0.	0.	Submergence Details		
Stream (Liquid)	(C)	130.441	80.177	26.044	45.040	Number of Tubes Submerged		0
Dew Point (Vapour + Gas)	(C)	130.441	33.310			Number of Rows Submerged		0
Wall (Max/Min)	(C)	90.04 /	26.31					
Inlet Pressure	(BAR ABS)	3.080		5.000				
Dp Calculated	(BAR)	.000		.103				

Vapour Shear Enhancement is Excluded

APPENDIX A-3. CEMPL INPUTS

Following is a list of the inputs required by the CEMPL program including options and default values.

<u>Input Description</u>	<u>Default Value</u>
Format for data input - Free or fixed.	None
Program mode - Single, double or triple-stream.	None
Number of elemental lengths - Insert no. of elements into which program is to divide length of exchanger in order to perform step-integration. Range: 100 - 999.	200
<u>GEOMETRIC DATA</u>	
Units code - SI, British or metric.	None
Number of exchangers in parallel.	0
Exchanger effective length.	0
Exchanger effective width.	0
Exchanger orientation - Angle with respect to horizontal.	0
Number of different fin types.	0
Fin height (Fin type 1) - Distance between separating plates.	0
Fin thickness (Fin type 1) - Thickness of fin material.	0
Fin frequency (Fin type 1) - Number of fins per unit width of fin layer.	0
Fin porosity (Fin type 1) - Fraction of surface area cut away.	0
Fin thermal conductivity (Fin type 1).	0
ETC. FOR ALL OTHER FIN TYPES	
Separating plate thickness.	0
Separating plate thermal conductivity.	0

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<u>Input Description</u>	<u>Default Value</u>
--------------------------	----------------------

GEOMETRIC DATA

Number of layers (Stream 1) - Modes 1,2,3.	0
Number of layers (Stream 2) - Modes 2,3.	0
Number of layers (Stream 3) - Mode 3.	0
Number of fin sections (Stream 1).	0
Fin type for 1st fin section (Stream 1).	0
Length of 1st fin section (Stream 1).	0
Fin type for 2nd fin section (Stream 1)	0
Length of 2nd fin section (Stream 1).	0
Fin type for 3rd fin section (Stream 1).	0
ETC. FOR OTHER STREAMS (IF ANY)	

FIN DATA

Points for each fin type - 2-10 points for each of three parameters: Reynolds number, Fanning friction factor, Colburn j-factor.	0
--	---

PROCESS DATA

Units code - SI, British or metric.	0
Starting end of exchanger - End where calculations are to start (Cold or warm end).	0
Heat transfer process in Stream 3 (heating or cooling) - Not required in Modes 1 and 2.	0
Number of Heat-Flux Points - Used to define heat-flux profile in Mode 1.	0
Number of components (Stream 1).	0
Number of components (Stream 2).	0
Number of components (Stream 3).	0
Starting temperature (Stream 1) (At starting end).	0
Starting pressure (Stream 1).	0

<u>Input Description</u>	<u>Default Value</u>
Starting specific enthalpy (Stream 1).	0
Mass flowrate (Stream 1).	0
Fouling resistance (Stream 1).	0
Z-factor multiplier from Bell and Ghaly (1973) method (One for each stream).	0
Heat flux at three different points along the exchanger (Additional points may be specified).	0

THERMAL DATA

Units code - SI, British or metric.	None
Thermal data points - Specify 2-20 points at one or two pressures for each stream. The following information is to be supplied at each point: pressure, temperature, enthalpy and vapor mass fraction.	0

LIQUID DATA

Units code - SI, British or metric.	None
Liquid data points - Specify 2-10 points at one or two pressures for each stream. The following information is required at each point: pressure, temperature, liquid density, liquid specific heat capacity, liquid dynamic viscosity and liquid thermal conductivity.	0

VAPOR DATA

Units code - SI, British or metric.	None
Vapor data points - Specify 2-10 points at one or two pressures for each stream. The following information is required at each point: pressure, temperature, vapor density, vapor specific heat capacity, vapor dynamic viscosity and vapor thermal conductivity.	0

<u>Input Description</u>	<u>Default Value</u>
<u>PROCESS DATA</u>	
Inlet temperature.	None
Outlet temperature	Calc. by program
Fouling resistance.	0
Inlet pressure.	None
Tube-side heat transfer coefficient.	Calc. by program
Tube-side coefficient factor (if modification- of calculated coefficient is desired).	1
Estimated heat load of system.	None
Tube wall thermal conductivity.	None
Inert mass fraction at inlet.	None
Vapor flowrate at outlet.	Calc. by program
Inert mass fraction at outlet.	Calc. by program
Vapor shear effect.	Not included

COMPONENT PROPERTIES

Stream identification-shell-side or tube-side?	None
Fluid (shell-side) - Non-condensing gas or condensing component?	None
Molecular weight (shell-side fluid).	None
Molecular diffusion volume (shell-side fluid) -Use Fuller, Schettler and Gidding's method.	None
Stored component properties (Sat. Water-Steam (280-485K, .01 - 20 bar); Air (200 - 1000K, 0 - 20 bar)).	Input properties

THE FOLLOWING COMPONENT PROPERTIES MUST BE SPECIFIED AT TWO TEMPERATURES, T_1 AND T_2 ($T_1 \neq T_2$). THE TWO TEMPERATURES MUST ALSO BE SUPPLIED FOR EACH PROPERTY.

Liquid phase density.	None
Liquid phase specific heat.	None

Appendix A-4-1. Detailed Output from CEMPl - Example 1.

Example 1 for the CEMPl Users Manual
 1 Vertical 1-Stream Exchanger
 Experimental Data at Harwell (Sep 75) Run 1099
 Stream 1 - Nitrogen
 Measured Pressure Change = 0.186 BAR

SUMMARY DATA OUTPUT

	Stream 1		Stream 2		Stream 3	
	Start	Finish	Start	Finish	Start	Finish
Temperature (K)	77.30	87.69	0.	0.	0.	0.
Pressure (BAR)	3.130	2.924				
Vapour Mass Fraction (-)	0.	.6673	0.	0.	0.	0..
Mass Flow Rate (KG/S)						
Liquid	.037	.012	0.	0.	0.	0..
Vapour	0.	.025	0.	0.	0.	0..
Total	.037		0.		0..	
Mass Flux (KG/M2 S)						
Liquid	88.81	29.55	0.	0.	0.	0.
Vapour	0.	59.27	0.	0.	0.	0.
Total	88.81	88.81	0.	0.	0.	0.
Reynolds Number (-)						
Liquid	1297.	571.	0.	0.	0.	0.
Vapour	0.	24285.	0.	0.	0.	0.
Pressure Change (BAR)						
Friction	-.11751		0.		0..	
Gravity	-.08870		0.		0..	
Total	-.20621		0.		0..	
Heat Transfer (W)	5.357E+03		0.		0.	
Volume of Fabrication Material Per Exchanger (Excluding Side Bars) (M3)				.00366		
	Fin Type 1	Fin Type 2	Fin Type 3	Fin Type 4	Fin Type 5	Fin Type 6
Sub-channel Flow Area (MM2)	9.251	0.	0.	0.	0.	0..
Sub-channel Hydraulic Diameter (MM)	2.405	0.	0.	0.	0.	0..
Sub-channel Perimeter -						
Primary (MM)	2.984	0.	0.	0.	0.	0..
Secondary (MM)	12.400	0.	0.	0.	0.	0..
Total (MM)	15.384	0.	0.	0.	0.	0..

Appendix A-4-2. Detailed Output from CEMPl - Example 2

Example 2 for the CEMPl Users Manual
 3 Vertical 2-Stream Exchangers
 Stream 1 - Ethene, Stream 2 - Propene

SUMMARY DATA OUTPUT

	Stream 1		Stream 2		Stream 3	
	Start	Finish	Start	Finish	Start	Finish
Temperature (K)	225.81	219.98	240.00	225.96	0.	0.
Pressure (BAR)	11.600	11.887	1.880	1.758	0.	0..
Vapour Mass Fraction (-)	.4750	0.	1.0000	0.	0.	0.
Mass Flow Rate (KG/S)						
Liquid	42.994	81.900	0.	35.800	0.	0..
Vapour	38.906	0.	35.800	0.	0.	0..
Total		81.900		35.800		0..
Mass Flux (KG/M2 S)						
Liquid	79.66	151.75	0.	94.91	0.	0.
Vapour	72.09	0.	94.91	0.	0.	0.
Total	151.75	151.75	94.91	94.91	0.	0.
Reynolds Number (-)						
Liquid	3008.	5456.	0.	1192.	0.	0.
Vapour	27136.	0.	31531.	0.	0.	0.
Pressure Change (BAR)						
Friction		.23981		-.14790	0..	
Gravity		.04675		.02604	0..	
Total		.28657		-.12185	0..	
Heat Transfer (W)	-1.624E+07		-1.624E+07		0.	
Volume of Fabrication Material Per Exchanger (Excluding Side Bars) (FT3) 7.3522						
	Fin Type 1	Fin Type 2	Fin Type 3	Fin Type 4	Fin Type 5	Fin Type 6
Sub-channel Flow Area (IN2)	.02493	.01360	0.	0.	0.	0..
Sub-channel Hydraulic Diameter (IN)	.12065	.09169	0.	0.	0.	0..
Sub-channel Perimeter - Primary (IN)	.14667	.11333	0.	0.	0.	0..
Secondary (IN)	.68000	.48000	0.	0.	0.	0..
Total (IN)	.82667	.59333	0.	0.	0.	0..

Appendix A-4-3. Detailed Output from CEMPl - Example 3.

Example 3 for the CEMPl Users Manual

1 Vertical 3-Stream Exchanger

All 3 Streams are Multi-component Hydrocarbons

SUMMARY DATA OUTPUT

		Stream 1		Stream 2		Stream 3	
		Start	Finish	Start	Finish	Start	Finish
Temperature	(F)	70.00	-172.23	90.00	-149.90	80.00	-151.68
Pressure	(PSIA)	50.00	52.49	75.00	72.98	100.00	100.12
Vapour Mass Fraction	(-)	1.0000	.1472	.7330	.0401	1.0000	0.
Mass Flow Rate	(LB/H)						
Liquid		0.	8528.	2670.	9599.	0.	1300.
Vapour		10000.	1472.	7330.	401.	1300.	0.
Total		10000.		10000.		1300.	
Mass Flux	(LB/FT2 H)						
Liquid		0.	15360.	10012.	48499.	0.	11696.
Vapour		14086.	2651.	27485.	2027.	11696.	0.
Total		14086.	18011.	37497.	50526.	11696.	11696.
Reynolds Number	(-)						
Liquid		0.	87.	196.	346.	0.	447.
Vapour		4646.	990.	6911.	557.	2589.	0.
Pressure Change	(PSI)						
Friction		1.95568		-2.16656		-.17520	
Gravity		.53516		.14465		.29882	
Total		2.49084		-2.02190		.12362	
Heat Transfer	(BTU/H)	-2.609E+06		-2.257E+06		-3.517E+055	
Volume of Fabrication Material Per Exchanger (Excluding Side Bars) (M3) .26122							
		Fin Type 1	Fin Type 2	Fin Type 3	Fin Type 4	Fin Type 5	Fin Type 6
Sub-channel Flow Area	(MM2)	9.700	5.187	6.989	12.404	0.	0..
Sub-channel Hydraulic Diameter	(MM)	1.828	1.439	1.866	2.278	0.	0..

APPENDIX A-5. UNIT CONVERSIONS

SI	BRITISH
m^3	35.31 ft^3
kg	2.2 lb
m	3.2808 ft
J/s (watt)	9.478×10^{-4} BTU/s, 0.7376 ft-lb/s
bar	0.0872 atm, 14.51 psi

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Resume of HTFS

Computer Programs

Prepared for:

Energy Technology Fossil Fuel
Division
Department of Energy

by

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February 15, 1979

Under Contract - ET-78-C-03-1866

ENSCI, INC.

RESUME OF HTFS COMPUTER PROGRAMS

HTFS (Heat Transfer and Fluid Flow Service) is an international organization providing design and research information in the fields of applied heat transfer and related fluid flow areas. HTFS is jointly operated by the United Kingdom Atomic Energy Authority [UKAEA], located at Harwell, Oxfordshire, and the National Engineering Laboratory at East Kilbride, Scotland. The organization and operation of HTFS centers around three basic services to its Industry "Sponsors":

(1) The HTFS Subscription Information Service.

In return for their annual fee each industry sponsor receives design reports, a design handbook, computer programs, consulting services, information office services and research information. Some of these items (i.e. specific computer programs) are available at an added unit/item cost not included with the annual "Sponsor" fee.

(2) The HTFS Research Program.

The basic HTFS research program, supported by the British government is particularly oriented to the fundamentals of heat transfer and fluid flow in relation to the design and/or analysis of industrial heat transfer equipment.

(3) HTFS Contract Research.

The HTFS staff and facilities are available on a contract basis to industrial organizations and other outside agencies for the conduct of proprietary research and development.

As of October, 1978, a total of 151 industrial organizations were participating "Sponsors" in HTFS.

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While the majority of Sponsors are industrial organizations located in the United Kingdom, Western Europe and the United States are also well represented. The work of HTFS is considered proprietary in that information distribution to its "Sponsors" is for their sole, in-house use and not for general publication.

The HTFS programs on research and information service are organized in relation to seven industrial heat transfer equipment areas, as follows:

1. Condensers
2. Boilers and Pipeline Systems
3. Cryogenic Heat Transfer Equipment
4. Refrigeration, Air Conditioning and Proprietary Heat Exchange Equipment
5. Furnaces
6. Air-Cooled Heat Exchangers
7. Single Phase Heat Transfer Equipment

The primary purpose of this report is to summarize the available computer programs, developed by the HTFS, for the design/evaluation of industrial heat transfer equipment and/or systems. The HTFS programs may be used on the following computer systems:

Multi CDC 6600
IBM 370 and Multi IBM 370
Multi UNIVAC 1106
UNIVAC 1108 and Multi UNIVAC 1108

TABLE I and the following sections of the report briefly summarize each computer program from the standpoints of objective, range of cases covered, data requirements, the computer program output, and a brief presentation of the theoretical or experimental background relevant to the program development.

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TABLE I
SUMMARY OF HTFS COMPUTER PROGRAMS FOR THE DESIGN/EVALUATION
OF INDUSTRIAL HEAT TRANSFER EQUIPMENT

CODE NAME	PROGRAM TITLE	OBJECTIVE
TREB	Thermosyphon Reboiler Performance and Design	Design and/or evaluation
TASC	Shell-and-Tube Exchanger, Design and Performance program with Condensing, Single Phase and Boiling Options	Design, evaluation or simulation
SCON	Performance of Shell-and-Tube Condensers of Vapors Containing Non-condensing Gases	Performance prediction
OPTU	Optimization of Heat Exchanger Tube Counts	Tube sheet layout design and optimiaztion
ACOL	Performance of Air-Cooled Heat Exchangers	Performance evaluation
COTE	Cryogenic Once-Through Evaporator Performance	Performance prediction
LOOP	Instability Prediction in Two-Phase Systems	Prediction of oscillatory instabilities
ASPE1	Cost Optimized Design of an Air-Cooled Heat Exchanger (Single Phase Fluids)	Design optimization for lowest cost
ADCS1	Cost Optimized Design of an Air-Cooled Heat Exchanger (Condensation of Pure Vapor)	Design optimization for lowest cost
IMIS	Condensation Curve Calculations for Immiscible Liquid Phases	Input data calculation for phase change conditions

TABLE I, CONT'D

CODE NAME	PROGRAM TITLE	OBJECTIVE
CRYO	Design and Performance of Cryogenic, Plate-fin Type Reboilers	Reboiler performance evaluation and design aid
HANA	Critical Heat Flux and Pressure Drop for Single Component flow in a Vertical Tube	Critical heat flux calculation, vaporizing liquid
ZONE2	Two Dimensional Radiant Heat Transfer Calculations, Zone Analysis Method (*)	Radiant heat transfer prediction for a cylindrical furnace
FCON	Condensation Curve Calculation for Multiple Component Mixtures	Phase equilibria, dew pt., bubble pt., and fractional condensation curve calculation
WILP1 WILP2	Calculation of Wilson Binary Energy Parameters	Calculation of Wilson parameters.

(*) The ZONE program is used for axially fired cylindrical furnaces and the ZORT program for rectangular (Box Type) furnaces. Both use the ZONE2 method of analysis.

TREB: Thermosyphon Reboiler Performance and Design

Objective: The design and/or rating of vertical thermosyphon reboilers.

Range of Cases Covered: The typical vertical thermosyphon reboiler with four types of possible outlet geometries. Four operational modes are possible: (1) design to calculate the number and length of tubes for requisite heat duty, pressure drop and recirculation ratio; (2) design to calculate the number of tubes and recirculation ratio for specified tube length, total flow rate and heat duty; (3) performance evaluation to calculate the heat transfer and pressure drop in a reboiler of specified dimensions and total flow rate; (4) a performance evaluation to calculate the total flow rate and heat duty for a specific reboiler with a known available liquid head in the downcomer.

Input Data: Input data requirements relate to the usual geometrical details, flow rates, operating pressures and temperatures, fouling resistances, and physico-chemical properties of the fluids involved.

Computer Results: The computer output restates the input data and provides (optionally) a step-by-step printout of temperatures, pressures, quality, and heat flux along the tubes. By adjustment of the input results, the program can incorporate the LOOP computer program for stability assessment.

Program Background: The program is based on a stepwise calculation and integration procedure relating the local pressure gradient and the local heat transfer coefficient. The physical properties are evaluated at the local conditions for temperature

and pressure. Flashing is accounted for as well as inlet and outlet losses. The work of Sellars et al. (1) and the work of the Engineering Sciences Data Unit (ESDU) (2) serve as background for single phase convective heat transfer in laminar and turbulent flows. The work of Chen (3), modified, is used in the sub-cooled boiling heat transfer regime. Convective boiling heat transfer similarly relies on the work of Chen (3) in the turbulent regime and calculations in laminar flow rely on a film thickness-void fraction model. Void fraction and frictional pressure drop calculations are based on in-house HTFS correlations (4).

- (1) Sellars, J.R., Tribus, M.; and Klein, J.S.: "Heat Transfer to Laminar Flow in a Round Tube or Flat Conduit - The Gravity Problem Extended."; Trans. A.S.M.E., Vol. 78, pp. 441-448, (1956).
- (2) ESDU: "Forced Convection Heat Transfer in Circular Tubes. Part I - Correlations for Fully Developed Turbulent Flow.": Item No. 67016, (1967); 4 Hamilton Place, London, W1, Great Britain.
- (3) Chen, J.C.; "A Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow."; A.S.M.E. Paper No. 63-HT-34, (1966).
- (4) Collier, J.G., Claxton, K.T., and Ward, J.A.; "Correlations for Two Phase Pressure Drop and Void Fraction." HTFS Design Reports 15(AERE-R6454 and 28(AERE-R7162), (1972).

TASC: Shell-and-Tube Exchanger Design and Performance Program
With Condensing, Single Phase and Boiling Options

Objectives: The optimized design of shell and tube heat exchangers or the performance evaluation of heat exchangers of specified geometry.

Range of Cases Covered: The program can be operated in three modes: (1) optimized design for specified system constraints; (2) the performance evaluation of a specified shell and tube heat exchanger; and (3) the operational simulation of a specified heat exchanger for varying operational situations. The program incorporates a wide range of fluid systems and exchanger geometries. Fluid systems may be single or multicomponent compositions, and operating in a single or two phase (evaporating or condensing) mode in the heat transfer process. The exchanger geometry is directed to the TEMA (Tubular Exchanger Manufacturers Association) classes E and J (the latter with either dividing or combining flow) incorporating a wide variety of geometric variables relating to the number of shells (series/parallel), tube side passes, shell diameters, tube lengths and tube layouts, baffles and baffle cuts, shell orientation (vertical or horizontal) and clearance values.

Input Data: The input data are specified in groups: (1) geometric data relating to performance specifications; (2) geometric data relating to design limitations; (3) process data relating to each stream, including allowable pressure drops and fluid velocities; and (4) physical properties for both shell and tube side fluids. It should be noted that different groups of data may be in different unit systems.

Computer Results: The computer output format depends upon whether the objective is design or performance evaluation. In design, the output details the selected design and also gives a brief summary of alternate designs of reasonable cost (or heat transfer areas). In performance evaluation cases, the alternate design tabulations are omitted and replaced by a detailed presentation of local conditions throughout the exchanger. In both instances, the input data utilized is reproduced.

Program Background: The program design logic utilizes a systematic search for different pass arrangements. For each arrangement the program attempts to find suitable shell diameters and lengths, and baffle layouts to satisfy design constraints. If the exchanger is to be optimized for minimum cost or minimum area, the program search continuously seeks the minimum cost or lowest area option. Correlations used for local heat transfer coefficients and temperature differences are:

I. Single Phase Coefficients

Tube Side coefficients: ESDU (2) and (5); a modification of Dittus-Boelter equation for the turbulent flow regime and ESDU (6) for laminar flow conditions.

Shell Side transfer coefficients rely on the work of Bell (7) as modified by Butterworth, et al. (8). In some cases, the work of Weisman (9) and Bergelin, et al. (10) are incorporated into the procedure.

II. Condensing Heat Transfer Coefficients

The evaluation of condensing film coefficients rely on the work of Nusselt (11) with HTFS in-house modifications (12,13,14). The evaluation of gas phase resistance follows the work of Silver (15) or Bell and Ghaly (16).

III. Boiling heat transfer situations follow the previous outlined procedures for TREB.

- (5) E.S.D.U.: "Forced Convection Heat Transfer in Circular Tubes: Part III - Additional Turbulent Flow Data: Item 68007, (1968); 251-259 Regent Str. London, W1R 7AD, Great Britain.
- (6) E.S.D.U.: "Forced Convection Heat Transfer in Circular Tubes; Part II - Laminar and Transitional Flows; Item 68006 (1968); 4 Hamilton Place, London, W1, Great Britain.
- (7) Bell, K.J.; "Final Report of the Cooperative Research Program on Shell and Tube Heat Exchangers"; Univ. of Delaware Engr. Expt. Station, Bull. No. 5, January (1963).
- (8) Butterworth, D., Hewitt, G.F., and Moore, M.J.C.; "Shell and Tube Heat Exchangers with Single Phase Flow", HTFS Design Report AERE-R6185 (2nd Revision) (1972).
- (9) Weisman, J. "Effect of Void Volume and Prandtl Number on Heat Transfer in Tube Banks and Packed Tubes"; A.I.Ch.E. Jr., 1, No. 5, pp. 342-348 (1955).
- (10) Bergelin, O.P., Brown, G.A., and Doberstein, S.C.: "Heat Transfer and Fluid Friction During Flow Across Tube Banks"; Trans. ASME, 74, pp. 953-960, (1952).
- (11) Nusselt, W.: "Surface Condensation of Water Vapor"; Zeit. D. Ver. Devt. Ing., 60, No. 28, pp. 569-575, (1916).
- (12) Butterworth, D., and Pulling D.J.: "Condensation of n-Propyl Alcohol in a Horizontal Tube"; AERE-M-2560 (1972).
- (13) Butterworth, D., Owen, R.G., and Pulling, D.J.: "Condensation of n-Propyl Alcohol in a Horizontal Tube; Final Report HTFS Research Symposium Paper RS-128 (1974).
- (14) Ibid _____ "Condensation of Propyl Alcohol and Propyl Alcohol - Nitrogen Mixtures in a Horizontal Tube; AERE-R-7647, (1974).
- (15) Silver, L.: "Gas Cooling with Aqueous Condensation." Trans. Inst. Chem. Engrs. 25, pg. 30, (1947).
- (16) Bell, K.J. and Ghaly, M.A.: "An Approximate Generalized Design Method for Multicomponent Partial Condensers." A.I.Ch.E. Sym. Series, 49, No. 131, pg. 72, (1973).

SCON: Performance of Shell-and-Tube Condensers of Vapors
Mixed with Non-Condensing Gases

Objective: To provide the user, and designer, of shell-and-tube condensers with a procedure for predicting the performance of a specific unit. This program complements the TASC design program, or other design procedure of the user, to more accurately evaluate a given design.

Range of Cases Covered: The program treats the case of a single component vapor condensing on the shell side in the presence of a single component non-condensing gas. Multicomponent condensing vapors can be handled if pseudo-single-component physical properties of the mixture are representative. Performance predictions can be made for a single shell or up to four shells in series. Series arranged shells may be dissimilar types and sizes and each may have any number of similar shells in parallel. Shell features, variable within the program, include: type (TEMA, types E, G and J), shell orientation (vertical or horizontal), baffle configurations, and condensate subcooling (shell flooding to any desired depth).

Input Data: Although the program is designed for maximum flexibility for performance evaluation, there are constraints on the form and format of input data; i.e. certain parameter items, singly or in combination must be specified. There are eight possible input parameter combinations with the program executing for the missing parameters. The input data is classified in three general categories: (1) a geometrical description of the system; (2) process data relating to the two fluid streams; and (3) physical property data for the condensing vapor, the non-condensing gas and the tube side

coolant. Either British or SI units may be used.

Computer Results: The program output data contains details of vapor flows, temperatures and pressures, and inert concentrations at the inlet and outlet of each shell along with statements of heat loads, overall coefficients and condensate temperatures. Additional baffle-space-to-baffle-space information may be retrieved.

Program Background: In as much as SCON is a predictive program to complement the design work of TASC, the SCON program utilizes additional reference works for improved performance calculation in as much as the design situation is specified. For example, Nusselt's work (11) is modified for horizontal tubes by the work of Grant and Osment (17), and Shekriladze and Gomelaury (18). For vertical tubes the work of Labuntsov (19) is utilized. Additional correlations utilized in addition to those reported for TASC and TREB are: Ishigai, et al. (20), Pearce (21), Jakob (22) and Butterworth, et al. (23) for frictional pressure drop evaluation. The work of Diehl and Unruh (24) is used to calculate a two phase correction factor. A variety of methods are used to evaluate shell side conditions: Perry and Chilton (25), Sparrow, Loeffler and Hubbard (26), Deissler and Taylor (27), and McAdams (28).

(17) Grant, I.D.R., and Osment, B.D.J. "The Effect of Condensate Drainage on Condenser Performance"; Nat'l. Engr. Laboratory (Kilbride, Scotland) Report No. 350 (1968).

(18) Shekriladze, I.G., and Gomelaury, V.I.: "Theoretical Study of Laminar Film Condensation; Int. Jr. Heat and Mass Transfer, 9, (6), 584-591, (1966).

- (19) Labuntsov, D.A.: "Heat Transfer in Film Condensation of Pure Steam on Vertical Surfaces and Horizontal Tubes": Teploenergetika, 4, (7), 72-80, (1957).
- (20) Ishigai, S., Nishikawa, Y. et al.: "Shell Side-Pressure Drop in Multi-baffled Shell and Tube Heat Exchangers."; Bull. J.S.M.E., 8, (32), 644-651, (1965).
- (21) Pearce, H.R.: "Crossflow Pressure Drop in Tube Banks"; AERE-R7589 (1974).
- (22) Jakob, M. "Discussion of Heat Transfer and Flow Resistance in Cross Flow of Gases Over Tube Banks."; Trans. ASME, 60, 384-386, (1938).
- (23) Butterworth, D., Hewitt, G.F., and Moore, M.J.C.: "Shell and Tube Heat Exchangers with Single Phase Flow"; HTFS Design Report No. 2, Part. 1, (1972).
- (24) Diehl, J.E., and Unruh, C.H.; "Two-Phase Pressure Drop for Horizontal Cross Flow Through Tube Banks."; ASME, Paper No. 58-HT-20, (1958).
- (25) Perry, R.H., and Chilton, C.H.: "Chemical Engineers Handbook"; McGraw-Hill Book Co., N.Y., N.Y. (1973 Edition).
- (26) Sparrow, E.M., Loeffler, A.L. Jr., and Hubbard, H.A." "Heat Transfer to Longitudinal Flow between Cylinders."; Jr. Heat Transfer, 83, 415-422, (1961).
- (27) Deissler, R.G. and Taylor, J.M.: "Analysis of Axial Turbulent Flow and Heat Transfer through Banks of Rods or Tubes."; Reactor Heat Transfer Conference, US-AEC, TID 7529 (Pt. 1, Bk. 2, 416-61), (1956).
- (28) McAdams, W.H.: "Heat Transmission"; Third Edition, pg. 258, McGraw-Hill Book Company, New York, N.Y.

OPTU: Optimization of Heat Exchanger Tube Counts

Objective: Tube sheet layout design and optimization for shell-and-tube heat exchangers.

Range of Cases Covered: The design optimization program gives the position and number of tubes for each pass, subject to the following constraints:

- (1) up to eight tube passes; (2) square, rotated square, triangular, or rotated triangular pitches; (3) alternate pass arrangements are available only for 4, 6, or 8 passes; (4) can handle need for inlet and escape areas subject to certain restrictions; and (5) tube alignment between passes (if desired) lowers the total tube count.

Input Data: Only five input data cards are required. These relate to the shell and tube dimensional details, control parameters governing the extensiveness of optimization, clearance information, type of pitch, the need for entrance and escape areas, and the configuration and number of passes and alignment desires.

Computer Results: The printout reproduces the input specifications and the optimum total tube count and tube count for each pass. A graphical output can also be obtained.

Program Background: The basic principle involved is to minimize an objective function which balances the requirements for maximum tube counts and equalizes the number of tubes per pass. The specific procedure systematically adjusts the position of tube centers within the allocated pass areas.

ACOL: Performance of Air Cooled Heat Exchangers

Objective: A generalized method of performance evaluation for air cooled heat exchangers.

Range of Cases Covered: The hot fluid may be a single phase liquid, a single phase gas, or a condensing vapor with or without non-condensable gases present. Subcooling and desuperheating can be handled with some sacrifice of accuracy of prediction.

Input Data: Four types of input data are required: (1) geometric data relating to the exchanger details; (2) process data defining process operating conditions, resistances and heat loads; (3) air-side flow data (including Fan information if appropriate); and (4) physical properties relating to the hot side fluid system. The program can accomodate mixed unit (by datagroups) systems and user correlations for air-side heat transfer coefficients and pressure drops can be incorporated into the program.

There are a number of constraints on the geometric considerations possible with the ACOL program; however the program accomodates most conventional air-cooled heat exchangers including U-tube and finned tube types.

Computer Results: In addition to reproducing the specific input data, the program output yields an overall summary of the unit performance and a tabulated presentation of the stepwise calculation results internal to the program.

Program Background: The ACOL program permits the user to specify preferred correlations in lieu of built-in program correlations for the calculation of air-side heat transfer correlations. The program is particularly useful for those cases where

process-side or air-side heat transfer coefficients vary significantly through the exchanger.

Reference background material for the program is as follows:

1. Tube-side Condensing Coefficient: The work of Butterworth (29) in the two phase region and the work of Silver (15) on the gas-phase side.
 2. Single Phase Regions (including superheated vapor): ESDU reports (2) (5) and (6) and the work of Cowen, Hale, and Stinchcombe (29).
 3. The Pressure Drop (Two phase) on the Tube-side: uses the correlations of Collier, Claxton, and Ward (4).
 4. The Air-side Heat Transfer Coefficient: uses a user specified correlation or, if none is specified, the work of Briggs and Young (30) for staggered tube arrays or that of Schmidt (31) for in-line arrays.
 5. The Air-side Pressure Drop: for staggered tube arrays, the work of Robinson and Briggs (32) is used and for in-line arrays, that of Vampola (33). Based on experimental work of HTFS (34), the pressure drop predictions of Robinson and Briggs are increased by 10%.
- (29) Cowan, G.H., Hale, A.B., and Stinchcombe, R.A.: "Further Comparison Between Predictions from ACOL-1 Program and Single Phase Heat Transfer Data." AERE-R-7606 (1974).
- (30) Briggs, D.E., and Young, E.N." "Convection Heat Transfer and Pressure Drop of Air Flowing Across Triangular Pitch Banks of Finned Tubes."; Chem. Engr. Progr. Symposium Series, 59, No. 41, pp. 1-10, (1963).
- (31) Schmidt, E." "Heat Transfer at Finned Tubes and Computation of Tube Bank Heat Exchangers."; Kältetechnik, Vol. 15, pg. 98; also Vol. 15, pg. 370, (1963).
- (32) Robinson, K.K., and Briggs, D.E.: "Pressure Drop of Air Flowing Across Triangular Pitch Banks of Finned Tubes."; Chem. Engr. Progr. Sym. Series, Vol. 62, pp. 177-184, (1966).

- (33) Vampola, J.: "Generalization of Heat Transfer and Pressure Drop Relationships for Gas Flow Across a Finned Tube Bundle"; Proc. of the 2nd All-Soviet Union Conference on Heat and Mass Transfer, Vol. 1. (1964).
- (34) Cowan, G.H.: "Axial Flow Fans and Plenum Chambers Associated with Air Cooled Heat Exchangers"; AERE-R-7950, HTFS Design Report 39, (1975).

COTE: Cryogenic Once-Through Evaporator Performance

Objective: The prediction of the overall performance of a two-stream tubular, or plate-fin, heat exchanger where partial or complete evaporation occurs during once-through flow.

Range of Cases Covered: The heat exchanger may be tubular or a plate (fin) type. There are certain restrictions on the possible geometric considerations. The evaporating stream may enter as a subcooled liquid, a two-phase mixture, or a superheated vapor. The second stream specification may be a uniform heat flux, a linear variation of temperature and heat transfer coefficient (or hA value), or an equivalent single phase flow with specified conditions.

Input Data: The input data requirements relate to the geometric specifications of the heat exchanger, process data for the evaporating stream and the second stream, fin characteristics, and physical and transport property data of the evaporating stream at two pressures.

Computer Results: The computer output restates the input data and follows with an incremental specification of the change in conditions along the exchanger. The final output is an overall summary of the exchanger performance.

Program Background: The performance calculation is for a heat exchanger of specific design and with inlet conditions specified for each process stream. The length of the exchanger is divided into a selected number of equal size elements. The local pressure gradient, local heat transfer coefficient, and the local heat transfer rate are evaluated for each element. The program takes into account the onset of subcooled boiling and bulk boiling, the suppression of nucleate boiling, dryout and the disappearance of liquid droplets.

LOOP: Instability Prediction in Two Phase Systems

Objective: The prediction of oscillatory instabilities in two phase flow systems.

Range of Cases Covered: The program is developed to consider evaporative heat transfer systems containing the three regions of (1) single phase heat transfer, (2) boiling, and (3) superheat. The program responds to input velocity fluctuations and handles once-through boiler operations, parallel channel situations, and thermosyphon reboilers.

Input Data: Input data are required for each of the aforementioned three regions and relate to: (1) the steady state friction pressure drop, (2) the inlet momentum flux for each section, (3) the enthalpy rise (single phase region) or the inlet-outlet velocity ratio for sections in the two-phase mode, and (4) the gravitational pressure drop in the two-phase region.

Computer Results: The principle outputs are an "open loop response" and a "closed loop response" using the Nyquist diagram for instability criterion. The output is both tabular and graphical, in the latter case in the form of Bode and Nyquist diagrams.

Program Background: The models for the onset of instability are based on the solution of the fundamental equations of the conservation of mass, energy and momentum. The equations are linearized for small perturbations and Laplace transformed for each boiler section. The major perturbations considered are inlet velocity and the overall pressure drop. Flow is assumed to be one-dimensional with no variations across a section.

FCON: Condensation Curve Calculation for Multicomponent Mixtures

Objective: The calculation of phase equilibria and the determination of dew point, bubble point, and fractional condensation curves for multicomponent mixtures.

Range of Cases Covered: Complete vapor-liquid equilibrium is assumed, with total miscibility in the liquid phase. Another program (IMIS) deals with the case of non-condensable vapors and immiscible condensate systems. The program is applicable up to moderate pressures; typically vapor densities up to half the critical density. Mixtures containing up to five components are readily handled.

Input Data: The input data required relate to (1) system variables such as pressure, temperature, feed vapor composition and flow rate; (2) physical and thermodynamic data for each component of the mixture; (3) the Wilson energy parameters for each binary pair of the mixture; and (4) molecular weight and enthalpy correlation constants for each component. Item (4) is required only if heat loads are to be calculated. Programs WILP-1 and WILP-2 are available for calculating Wilson parameters.

Computer Results: In addition to recanting the input data, the program yields the following: dew points and bubble points with associated vapor and liquid compositions; vapor-liquid splits in relation to a condensation curve; and a tabulation of liquid-vapor splits as a function of heat removed and total enthalpy.

Program Background: The methods employed take into account vapor non-idealities using a virial equation and liquid phase deviations using activity coefficients calculated from the Wilson equation (see WILP-1 and WILP-2).

Calculations establish the dew point and bubble point to define the condensing temperature range. The special techniques employed are iterative, developed to ensure rapid convergence for the desired solution.

ASPE1: Cost Optimized Design of Air-Cooled Heat Exchanger
for the Cooling of Single Phase Fluids

Objective: The design of an air-cooled heat exchanger, with a specified heat duty and a single-phase fluid on the tube side, for minimum cost.

Range of Cases Covered: The design is performed within constraints of minimum/maximum unit width, minimum/maximum tube bundle width, minimum/maximum pressure drop on the air side, maximum pressure drop on the tube side, and minimum/maximum unit length.

The program optimizes tube diameter, length, pitch, fin height and number of fins per unit length. Any fin or tube material may be specified and eleven standard tube-side pass arrangements are incorporated into the program. The use of fans (number, size and power rating) may be incorporated into the program.

Input Data: The design input data requirements includes the usual physical and thermodynamic properties of the process fluid, the specification of any minimum/maximum constraints, and such factors as inlet/outlet temperatures, process fluid flow rate, the fouling factor (tube side), the type and character of tube fins desired, and the ambient air temperature and pressure. To minimize cost, the input data includes the annual charge on investment capital, operating time, power costs, etc. It is possible to specify an exchanger type and fan characteristics and control. The design can be optimized to give minimal annual or capital cost.

Computer Results: The computer results are in tabulated form within the given constraints. Minimum cost designs and design alternates are possible by variation of constraints.

Program Background: The ASPE program uses a factorial search optimization of the fin tip clearance and extended area. The performance calculation is based on selected overall heat transfer coefficient correlations with a temperature correction to account for cross-flow conditions.

Calculations of the exchanger cost, on both a capital cost and an annual cost basis, use budget costing methods.

ADCS1: Cost Optimized Design of Air-Cooled Heat Exchangers
for Condensation of a Pure Vapor

Objective: The optimized (lowest cost) design of an air-cooled condenser for a specified heat duty with de-superheating, isothermal condensation and subcooling of a pure component vapor on the tube side.

Range of Cases Covered:

The design is performed within the following constraints: minimum/maximum unit width, minimum/maximum tube bundle width, minimum/maximum shell side air stream pressure drop, maximum tubeside pressure drop and minimum tubeside velocity.

The program optimizes tube row and pass arrangements; tube length, diameter, pitch, and fin height and frequency for either lowest annual or capital cost. Up to 54 different heat exchanger geometries may be considered and de-superheating may be specified as "dry wall" or "wet wall".

If permitted by geometrical constraints, and the limitations of air flow and pressure drop, the program will specify the number, size, and power requirements of required fans.

Input Data: The program requires the usual process operating data, physical property data, geometrical design considerations, cost data and system constraints. There are a wide range of default options including a budget cost curve and cases may be run with a minimum of process and physical property data. There is opportunity for incorporating individual costing methods.

Computer Results: The computer output tabulates input data, important geometrical and process data, lists

viable design alternates and a more detailed presentation of the lowest cost design.

Program Background: The ADCS program utilizes appropriate single-phase turbulent flow correlations for the desuperheating and subcooling zones, and for the condensing zones, design methods proposed by Kern (35). The air-side heat transfer coefficients are based on HTFS data (36) and overall coefficients are calculated for each zone. Utilizing the specified temperatures and areas, heat transfer rates are calculated and checked against the required heat duty.

The program has an option to use either a factorial search or "heuristic" method to obtain the lowest cost design.

(35) Kern, D.A.: "Process Heat Transfer",

(36) Cowan, G.H.: "Heat Exchangers with Extended Surfaces";
HTFS Design Report, in two parts, AERE-R-6186,
(1970).

IMIS: Condensation Curve Calculations for an Immiscible
Liquid Phase

Objective: The calculation of phase equilibria and the determination of dew point, bubble point, and fractional condensation curves for multicomponent mixtures containing non-condensable gases and which form immiscible liquid phases.

Range of Cases Covered: The feed vapor can consist of a maximum of seven components containing a non-condensable gas, up to five components which form a multicomponent non-ideal miscible liquid phase, and a single component which forms a separate immiscible liquid phase.

Input Data: The requisite input data is summarized as follows:

- (1) System variables of feed temperature, pressure, composition and flow rate; the feed can be two-phase.
- (2) Individual component Antoine constants, and the molar liquid volumes for components of the miscible liquid phase.
- (3) The Wilson energy parameters for each binary pair of the miscible liquid phase.
- (4) The molecular weights and enthalpy correlation constants for each component if the heat load is to be calculated.

Computer Results: The program printout yields the following information: bubble point, dew point, transition point, the heat load along the condensation path, and the temperature, number of liquid phases, and the compositions in relation to the condensation curve and specified vapor-liquid ratios.

Program Background: The IMIS program calculates the dew and bubble points to define the condensing temperature

range for a particular situation. In addition, it establishes the transition point where a change in the number of liquid phases occurs.

Pure component vapor pressures are based on the Antoine equation and vapor phase non-idealities are accounted for by a Virial equation. Pure component molar volumes are expressed, in terms of temperature, in quadratic equation form. Non-ideal liquid phase conditions are predicted using the Wilson equation for liquid phase activity coefficient behavior (See VILP-1 and WILP-2). Vapor phase fugacity coefficients and saturated vapor fugacity coefficient calculations are based on the works of Prausnitz, et al. (37) and Lyckmann, et al. (38).

(37) Prausnitz, J.M., Eckert, C.A., Oyre, R.V., and O'Connell, J.P.: "Computer Calculations for Multicomponent Vapor-Liquid Equilibria", Prentice Hall, Englewood Cliffs, N.J. (1967).

(38) Lyckmann, E.W., Eckert, C.A., and Prausnitz, J.M.: "Generalized Fugacities for Phase Equilibrium Thermodynamics.", Chem. Engr. Sci. Vol. 20, p. 685, (1965).

CRYO: Design and Performance of Cryogenic Plate-Fin Type
Reboilers

Objective: The performance prediction of vertical plate-fin (matrix) type thermosyphon cryogenic reboilers.

Range of Cases Covered: Performance prediction for a specified cryogenic reboiler. Although the program can serve as a design aid particularly for deciding submergence levels it is not adapted to geometrical changes; the standard reboiler is a matrix block mounted in a pool of cryogenic fluid with condensing in alternate blocks channels of another fluid.

Four program modes are possible

1. Calculation of the total vapor flow and pressure drop based on the total stream flow.
2. The determination of the requisite submergence for a specified vapor flow.
3. A evaluation case of constant heat flux to the evaporating channels. (Primarily of use for comparison to data from experimental units operating in this mode.)
4. The vapor flow rate and recycle ratio for a given submergence.

Input Data: The requisite input data are: (1) the control parameters (including the program mode above); (2) physical details of the boiling and condensing sections; (3) physical property and thermodynamic information at two reference temperatures, including fouling factor; and (4)---optional ---personal data for friction factor and the heat transfer "j" factor for single phase flow in the plate-and-fin channel.

Computer Results: A tabular presentation of the data input and the resultant calculations, according to the

program mode of operation, for differential increments of the channel. A final summary tabulates overall parameters, including submergence, mass velocities, surface areas, pressure drops, etc.

Program Background: CRYO is a performance prediction method for a specified cryogenic reboiler and utilizes a wide variety of heat transfer and pressure drop correlation and/or predictive methods. For pressure drop in the single phase region the program is adaptable to a specific user correlation or, in the absence of a user specified correlation, the program uses the correlation of Kays and Clark (39) for laminar flow, that of Langhaar (40) for entrance effects and the data of Kern (35) for rough tube effects. In the bulk boiling region, the program uses the correlations of Barocay (41) and C.I.S.E. (42) for pressure drop and void fraction predictions.

The heat transfer calculations are based on the work of Kays and Clark (39), Sellars (1), and ESDU (2) in the single phase region, and the correlations of Chen (3) in the subcooled and bulk boiling regions.

- (39) Kays, W.M., and Clark, S.H.: T.R. No. 17, Dept. of Mechanical Engineering, Stanford University, California (1967).
- (40) Langhaar, H.L., Trans. ASME, A64, 55 (1942).
- (41) Baroczy, C.J.: "A Systematic Correlation for Two Phase Pressure Drop", Chem. Eng. Progr. Sym. Series, Vol. 62, No. 64, pp. 232-249, (1966).
- (42) C.I.S.E.: "An Empirical Correlation for Evaluating Two-Phase Mixture Density Under Adiabatic Conditions."; European Two-Phase Flow Group Meeting, Milan, Italy, 8-10 June (1970).

HANA: Critical Heat Flux and Pressure Drop for Single
Component Flow in a Vertical Tube

Objective: The calculation of the critical heat flux for a vaporizing liquid flowing in a channel; or, alternately, to determine if a specified heat flux exceeds the critical heat flux.

Range of Cases Covered: The program is restricted to upward flow in a vertical tube. Any vaporizing fluid stream can be handled providing appropriate physical/thermodynamic data are available; steam-water data are stored in the program. The heat flux variation may be in any one of three modes: independent of axial position, a sine curve distribution with the maximum occurring at the tube midpoint, or a user specified distribution with the tube divided into a maximum of 19 sections with a linear axial distribution in each section.

Input Data: The input data relate to the geometry of the system, physical/thermodynamic properties of the fluid (data for steam-water is stored in the program) and heat flux distribution specifications.

Computer Results: In addition to statements regarding the critical heat flux situation, the results detail (by position along the tube) quality, film flow rate, interfacial shear stress, average liquid film thickness, entrainment and deposition rates.

Program Background: The HANA program assumes that the two-phase, vapor-liquid, mixture forms an annular flow system with a liquid film on the tube walls and the vapor flowing in the central channel. Liquid droplets are continually being torn off the liquid film (particularly in the regions of liquid wave formation), carried along with the vapor, and

deposited onto the film. Using generalized correlations for entrainment and deposition rates, and a boundary condition for the film flow rate, the film flow rate is calculated at each axial position. When the film flow rate becomes equal to zero, dry-out is presumed to have occurred.

ZONE2: Two-Dimensional Radiant Heat Transfer Calculations
Using the Zone Method of Analysis

Objective: The calculation of the two-dimensional radiant heat transfer in a cylindrical furnace using the zone method of analysis. The ZORT program is available for box-type furnaces.

Range of Cases Covered: The furnace is an axisymmetric cylinder with the burner and exit flue centrally positioned. There may be cooling tubes lining the furnace wall, positioned parallel to the furnace axis or placed circumferentially. Oil or natural gas fuels are considered.

Input Data: The input data required are:

- (1) Furnace geometry and zoning, also information relating to refractory emissivities and the cooling tube situations.
- (2) Gas/Soot factors. These are stored for natural gas and oil, but others may be incorporated.
- (3) Partial pressures of absorbing gases for each zone. Also, if gas is used, the partial pressure of methane and, for oil-fired furnaces, the soot concentration.
- (4) Heat release and flow patterns throughout the furnace.
- (5) Physical property and thermodynamic information as well as certain operating parameters.

Computer Results: The output produced consists of two parts: the result of directed flux area calculations and the results of total energy balance considerations.

The final overall result yields the wall, tube and gas temperature distributions, surface heat flows, heat fluxes and an overall picture of zone distributions.

Program Background: The ZONE model for predicting radiant heat transfer is based on the work of Hottel and Cohen (43), Hottel and Sarofin (44) and the subsequent work of Johnson and Beer (45). The ZONE2 program provides certain enhancements over the original ZONE program. The basic differences between ZONE and ZORT are in the numerical procedures for calculating direct exchange areas and in allowing for the spatial variation of absorption coefficients.

- (43) Hottel, H.C. and Cohen, E.S.: "Radiant Heat Exchange in a Gas-Filled Enclosure"; A.I.Ch.E. Journal, Vol. 4, pp. 3-14, (1958).
- (44) Hottel, H.C. and Sarofin, A.F.: "Radiative Heat Transfer", McGraw-Hill Book Company, New York, N.Y. (1967).
- (45) Johnson, T.R. and Beer, J.M.: "Radiative Heat Transfer in Furnaces-Zone Method of Analysis"; 14th International Symposium on Combustion, pp. 639-649, (1972).

WILP1 & WILP2: Calculation of Wilson Binary Energy Parameters
for Use in Condensation Calculations

Objective: To provide a calculation of the Wilson binary energy parameters from known binary mixture data.

Range of Cases Covered: The use of WILP1 or WILP2 depends upon the form and format of the available binary mixture data. WILP1 uses boiling point data as a function of composition and phase equilibrium data as a function of temperature, all at a constant pressure. WILP2 uses activity coefficient and solubility parameter information.

Input Data: In addition to the information defining the use of WILP1 or WILP2, both programs require molar liquid volume constants for a three constant equation, the Antoine (vapor pressure) equation coefficients, and critical properties for each component.

Computer Results: The final result of either WILP1 or WILP2 is a tabular printout of the Wilson binary energy parameters as a function of temperature and the composition of liquid and vapor phases.

Program Background: In WILP-1, the program searches for a system of Wilson parameters to minimize the error in the prediction of total system pressure; this involves a non-linear least squares fit of system total pressure and the binary form of the Wilson equation. The specific method used in WILP-2 depends on the input data but the final result is the calculation of the log activity coefficient end values and the relation of these to the Wilson binary energy parameters.

The principle function of the WILP programs is a subroutine service within other design performance evaluation programs for multicomponent systems.

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APPENDIX A-7

REPORT OF VISIT TO HTFS FACILITIES AT HARWELL AND THE NATIONAL
ENGINEERING LABORATORY; AND THE HTFS SPONSORS MEETING,
24-30 MARCH 1979

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15 April 1979

REPORT OF VISIT TO HTFS FACILITIES AT HARWELL AND THE NATIONAL
ENGINEERING LABORATORY; AND THE HTFS SPONSORS MEETING,
24-30 MARCH 1979

The Annual Meeting of HTFS Sponsors was held in London, England, 30 March 1979. This author utilized this opportunity to visit the staff and research facilities associated with the HTFS program at Harwell (Atomic Energy Research Establishment--AERE--in Oxfordshire, England) and at the National Engineering Laboratory (NEL--in East Kilbride, Scotland) during the week immediately preceding the Sponsor Meeting in London. Approximately two days was spent visiting with the HTFS staff and viewing facilities at each location.

THE GENERAL ORGANIZATION OF THE HTFS PROGRAM EFFORT

A brief review of the HTFS organization is in order to better understand the overall program and the working relationships between Harwell and the NEL. The basic HTFS program centers around two functions: an applied general research program, and a subscription information service (SIS) which distributes HTFS publications and reports, computer programs, and a variety of information services to HTFS Sponsors.

The General Manager of the HTFS program is Dr. Geoffrey F. Hewitt, and he is assisted by two Technical Managers: Dr. Ian D. R. Grant for the general research activities, and Mr. D. Butterworth for the SIS program. Each Technical Manager is responsible for the overall activities of his area

regardless of whether the work is being carried out at Harwell or NEL. Mr. Lionel B. Cousins (Manager-Sponsor Services) serves for coordination and liaison activities with the industrial Sponsors of HTFS. The number of world-wide industrial Sponsor members of HTFS has grown from 20 in 1968 to the present complement of 158 as of March 1979.

The current level of operating income for HTFS activities is approximately 1.50 million Pounds-Sterling, the majority of which comes from the Sponsors and the UK-CMRB--in roughly equal amounts--and the remaining funds from research, development or evaluation contracts with private industry (worldwide) and from contractual services to other agencies (i.e. Department of Energy) of the U.K. The CMRB (Chemical and Materials Review Board) of the U.K. serves a budgetary function, for the U.K. government, to allocate research and development funds to the various government agencies and laboratories.

The ability and freedom for HTFS to undertake contractual research, development or evaluation activities on behalf of private industry is a rather unique feature of the HTFS--as a government supported entity--that is not possible for U.S. government agencies or laboratories. The net effect of this appears to be a very close awareness of the HTFS personnel with the needs and problems of industry and a generally strong support of their activities on the part of industry. The National Engineering Laboratory (NEL) at East Kilbridge, Scotland has a particularly strong and active program of R&D activities for

industrial contractors in a wide spectrum of engineering areas, most of which are not related to the HTFS.

THE GENERAL RESEARCH PROGRAM

As pointed out earlier, the General Research program of HTFS, apart from contractual services, is funded by the UK-CMRB and through Sponsor fees, in roughly equal amounts. The selection and scheduling of specific projects accordingly requires a careful blend of CMRB and Sponsor priorities and desires.

At the present time, all R&D efforts of HTFS fall into seven major categories; these are:

1. Condensers
2. Single Phase Heat Transfer Equipment
3. Furnaces
4. Cryogenic Heat Transfer Equipment
5. Air Cooled Heat Exchangers
6. Boilers & Pipeline Systems
7. Refrigeration, Air Conditioning and Proprietary Heat Exchange Equipment. (RACPHEE)

In addition, there is a small R&D effort on Physical Properties which is primarily directed to specific information in support of the major R&D programs.

Dr. Ian D. R. Grant (NEL) is the Technical Manager for the total research program and each research area is headed by a Project Coordinator whose resident base may be either NEL or Harwell. It should be noted that the Project Coordinator also has the responsibility for SIS work in his area, and, in essence, he is coordinator of all activities in a given topical area.

Specific research activities are delegated to a Project Engineer who will have the day-to-day responsibility for one or more projects (including SIS) which may be in more than one general topical area. Projects are assigned to Harwell or NEL on the basis of experimental capability and personnel resource capability and availability. In general, there appeared no discernible research assignment basis to either NEL or Harwell other than these factors; each laboratory had active programs in each of the aforementioned topical areas.

THE SUBSCRIPTION INFORMATION SERVICES (SIS)

The SIS program of the HTFS is almost totally funded from Sponsor fees and service charges with no UK-CMRB funds allocated to this area.

The SIS program is under the general direction of Technical Manager David Butterworth and involves such activities as:

1. Design Reports and the continuing update of the HTFS Design Handbook.
2. Computer Programs directed to the design/evaluation of specific heat exchange equipment types.
3. Information Services which includes the preparation of requested literature searches and the monthly "Heat Transfer and Fluid Flow Digest".
4. Proprietary Advice and Research Services which includes contractual arrangements for proprietary research and confidential consulting services (two free days/year, additional on a fee basis).
5. Validation of Design/Evaluation Methods and Programs through liaison and cooperation with Sponsor information and activities in a given area.

Inasmuch as much of the SIS activities--particularly in areas 1, 2, and 5 above--is carried out by the NEL and Harwell personnel (Project Coordinators and Project Engineers) having a dual role relating to Research and SIS in a given area, there is a close collaboration and coordination by the Technical Managers Grant and Butterworth to effect a smooth working relationship.

SPONSOR INPUT TO THE RESEARCH AND SIS PROGRAMS

The primary Sponsor input to the planning, execution and evaluation of the HTFS Research and SIS programs is through the seven Sponsor Review Panels; one for each of the topical areas listed under "The General Research Program". Each Review Panel meets at least three times each year and has the following functions:

1. To advise HTFS on a continuing basis on the on-going and future programs in the specific technical area.
2. To ensure that the products produced by HTFS (e.g. Design Reports, Computer Programs, technical reports, etc.) are in a form to meet the needs of the various industrial sectors which HTFS serves and in line with the wishes of Sponsors as expressed at the Special Meetings.
3. To represent the interests of all Sponsors in the particular technical area to make sure that HTFS is made fully aware of Sponsor needs.

Membership on the Review Panels is governed by the following, and the Chairman is normally the HTFS Project Coordinator for the specific area:

Two members from User companies (e.g. Chemical Manufacturers, Petroleum companies, utilities).

Two members from heat exchanger manufacturing companies.

Two members from contracting companies.

In addition to the full members, there may be up to three Corresponding Advisers (normally one each from a user, a manufacturer and a contractor company respectively) whose function would be to provide written comment on documents being considered by the Review Panel.

The Panel and/or Chairman have the right to invite technical specialists to any meeting where they and/or he feel that their contribution would be valuable to the work of the Panel.

Membership on a Review Panel is normally four years with nomination and election (or re-election) by all the Sponsor organizations. The terms of Panel members are staggered so that no more than 50% of a Panel is up for election at each two year interval.

There are two other vehicles for general Sponsor input to HTFS. There are: (1) the Spring (1 day) general Sponsor meeting and the Fall (1 week) Research Symposium and Sponsor meeting held each year; and (2) a general work planning Questionnaire sent to each Sponsor each Spring for indicating work priorities in general and work intensity (funding level) preferences--based on Panel recommendations--for budgetary planning. For example, the Spring '79 Questionnaire related to proposed work for Fiscal 1980-81. These results are then coordinated with the UK-CMRB preferences to prepare the final work schedule and budget. Based on experiences to date, the finalized work schedule and budget very strongly reflect the Sponsor (cumulative) preferences.

TABLES I-1 through I-7 illustrate the SIS and Research topics covered in the Questionnaire for Fiscal 1980-81. In reviewing these topics, it should be kept in mind that some of the topics presented, particularly in the SIS area (i.e. updating

TABLE I-1

PROPOSED SIS & RESEARCH STUDY AREAS, FISCAL 1980-81

CONDENSERSSIS PROGRAM

1. Updating the HTFS Handbook Section on Condensation.
2. Restructure TASC computer program to handle additional structural options and fluid considerations.
3. Development of the general purpose advanced computer program, APEX, for the performance prediction of shell and tube exchangers. A more rigorous program than TASC with additional options relating to structural considerations and baffling modes.
4. Incorporate plugged tube consideration in TASC.
5. Modify TASC to permit outlet temperature calculation from inlet temperature, overall enthalpy balances, and flow-rate information.
6. Provide a variety of independent heat transfer subroutine packages.
7. Prepare design report for feed effluent heat exchangers with simultaneous boiling and condensation.
8. Prepare design report on heat transfer in baffled and packed columns.

RESEARCH PROGRAM

1. Performance testing in the Harwell and NEL test rigs (ITR). The purpose is to obtain data under a variety of load conditions for comparison with program predictions; i.e. TASC, SCON, APEX.
2. Performance testing of enhanced heat transfer tubing for condensers; i.e. roped and finned tubes.
3. Effect of vapor velocity on shell side condensation coefficients.
4. Reflux condensation in tubes and on tube bundles.
5. Condensation (in tubes) of vapor mixtures that form immiscible liquids.
6. Experimental study of spray type direct condensers.
7. Flow modelling of annular flows in horizontal and inclined tubes; important to the HANA program.
8. Development of flow models for the performance prediction of turbine exhaust condensers.
9. Experimental study of condensation near the critical region.
10. Condensation on low-finned tubes.
11. Gas phase mass transfer on falling liquid films for the improvement of mass transfer models used in computer programs and derived from single phase heat transfer analogies.
12. Saturated gas cooling (containing condensable vapors) in plate type heat exchangers.
13. Study of glycol injection to prevent hydrate formation during condensation.

TABLE I-2

PROPOSED SIS & RESEARCH STUDY AREAS, FISCAL 1980-81

SINGLE PHASE HEAT TRANSFER EQUIPMENTSIS PROGRAM

1. Extension of design/evaluation methods to axial flow exchangers; i.e. rod baffles, disc-donut baffles, unbaffled, etc.
2. Continuing development of TASC and APEX programs for vibration analysis, inside tube heat transfer and pressure drop, low-fin tube performance, and laminar flow bypass effects.
3. Improved design optimization techniques.
4. Design report on corrosion effects.
5. Design report on process plant thermal integration.
6. Synthesis of heat exchanger networks for energy recovery.
7. Preparation of some specific, independent subroutines such as: in-tube heat transfer, Div-Flo method for shell-side pressure drop and heat transfer, vibration analysis, LMTD corrections, tubeside pressure drop.
8. Fluidized bed heat transfer.
9. Enhancement techniques for convective heat transfer; a state-of-the-art type review.
10. General review of current turbulence theories and relationship (impact) on heat and mass transfer theories.
11. Use and effects of artificial roughness.

RESEARCH PROGRAM

1. Tube bundle vibration studies.
2. Experimental study of heat exchanger fouling.
3. Tube erosion in heat exchanger environments.
4. Plate heat exchangers model studies using electrochemical techniques for evaluation of plate geometries.
5. Thermal mixing in tube bundles; effect on shell side heat transfer and pressure drop.
6. End-zone performance studies on shell and tube exchangers.
7. Heat transfer in jacketed and agitated vessels.

TABLE I-3

PROPOSED SIS & RESEARCH STUDY AREAS, FISCAL 1980-81

FURNACESSIS PROGRAM

1. Continuing Handbook update.
2. Further modification of ZONE for process side calculations in cylindrical furnaces.
3. Further development of ZORT (three dimensional furnace code) for rectangular furnaces.
4. Extensions of furnace flow modelling and finite difference methods of TUFC for gas flames to handle oil spray flames.
5. Literature survey on burner vibrations and instabilities.
6. State-of-the-art review on use of Raman light scattering as a technique for combustion measurements.
7. State-of-the-art review on three dimensional furnace combustion chamber flow and heat transfer modelling.
8. Literature survey on pulverized fuel combustion.

RESEARCH PROGRAM

1. Theoretical models for the prediction of heat transfer from gaseous flames.
2. Simple jet mixing models for flow and combustion studies as adjunct to ZONE computer code.
3. Application of finite element methods for flow modelling.
4. Burner studies on NEL vertical cylindrical furnace.
5. Convective heat transfer in radiant section of fired heaters.
6. Characterization of exit flows for various classes of industrial burners.
7. Fuel spray studies; droplet size distributions in burning and non-burning sprays.
8. Development of water cooled probes for velocity measurements.
9. Development and evaluation of "Standard Experiments" for burner and furnace research (experimental and theoretical).
10. Development of Laser anemometry to measure Reynolds shear stresses.
11. Use of data from Harwell model furnace to validate/improve turbulence models for furnaces.

TABLE I-4

PROPOSED SIS & RESEARCH STUDY AREAS, FISCAL 1980-81

CRYOGENIC HEAT TRANSFER EQUIPMENTSIS PROGRAM

1. Continuing development of CEMP computer program series.
2. Development of computer program for countercurrent flow of liquid and vapor in specified streams.
3. Use of coiled tube heat exchangers in cryogenic service; an inquiry to determine Sponsor interest and specific suggestions.

RESEARCH PROGRAM

1. Continuation of work on boiling and condensing in plate-fin type passages, including flow mal-distribution and flow instability effects.
2. Countercurrent flow (boiling and condensing) in plate-fin type passages.
3. Boiling outside tube coils.

TABLE I-5

PROPOSED SIS & RESEARCH STUDY AREAS, FISCAL 1980-81

AIR-COOLED HEAT EXCHANGERSSIS PROGRAM

1. Design report on noise and performance testing.
2. HTFS Handbook section on wet, dry, and hybrid cooling towers.
3. Reliability improvements and maintenance related to the ACOL computer program.
4. Extension of ACOL program to side by side tube pass configuration.
5. Continuing development of DACE computer design program.

RESEARCH PROGRAM

1. Continuing general research work on fans and plena. a) Full-scale; b) 1/4-scale; c) Model work using 1/18 scale configuration; and d) a new, full scale facility.
2. New industrial test rig (ITR) heat exchanger; overall performance evaluation.
3. Headers and manifold distribution studies.
4. Inclined forced flow convection and pressure drop over extended surfaces.
5. Natural convection-extended surface heat transfer over tube bundles.

TABLE I-6

PROPOSED SIS. & RESEARCH STUDY AREAS, FISCAL 1980-81

BOILERS AND PIPELINE SYSTEMSSIS PROGRAM

1. Continuing update of Handbook section and further additions.
2. Completion of Design report on two phase pressure drop in pipes.
3. Transition flow regimes between specific two phase flow patterns; i.e. slug and annular flows (vertical and horizontal), stratified flow and slug flow (horizontal). Design report.
4. New Design report on high velocity two phase flow; i.e. choked flow, relief valve systems.
5. Design report on instrumentation techniques (pressure, Δp , and flow rate) in single and two phase flows.
6. Design report and Handbook sheets on pressure drop in single phase pipework components.
7. Design report on feed-effluent heat exchangers with simultaneous boiling and condensation.
8. Establishment of boiling data bank for correlation and computer program validation.
9. Participate in APEX program development.
10. Design general purpose computer program for design of reboilers (kettle and thermosyphon types).

RESEARCH PROGRAM

1. Collect experimental data on transition regions in two phase flow.
2. Two phase pressure drop in rough tubes and pipeline components.
3. Two phase pressure drop and void fraction for shell-side type geometries.
4. Experimental study on deposition, entrainment, shear stress and other variables for non-vertical annular two phase flow.
5. Evaluation of turbulent flow modelling techniques, and comparison with experimental data for single phase pressure drops for a wide variety of geometrical configurations (orifice plates, expansions, contractions, roughened pipes, etc).
6. Single phase friction factor correlation for rough tubes.
7. Experimental reboiler studies (kettle and thermosyphon types) on the Harwell industrial test rig (ITR).
8. Experimental boiling studies--cross flow liquid over tube banks, variable tube arrangements.
9. Multicomponent boiling in tubes.
10. Pool boiling studies; surface and mixture effects.

SEE NEXT PAGE

11. Provide computer subroutines to Sponsors for specific well identified calculations (i.e. single and two phase pressure drop in pipe flow; void fraction in two phase pipe flow; chenn forced convection boiling correlation).

TABLE I-7

PROPOSED SIS & RESEARCH STUDY AREAS, FISCAL 1980-81

REFRIGERATION, AIR CONDITIONING AND PROPRIETARY HEAT EXCHANGE EQUIPMENT (RACPHEE)

SIS PROGRAM

1. Development of simplified design methods with high priority reference to AC coolers, small air cooled exchangers with tube-in-plate and other forms of extended surface.
2. Continuing Handbook development.
3. Computer programs for the design of small scale exchangers.
4. Design methods for in-tube evaporation and condensation.
5. Compilation and review of air side corrosion protection. Design report objective.

RESEARCH PROGRAM

1. Horizontal in-tube evaporation and condensation of refrigerants.
2. Experimental studies on finned surfaces.
3. Shell-side boiling of refrigerants.
4. Transport of liquids (i.e. lubricating oils) in refrigerant vapor; effect on evaporation and condensation.
5. Refrigerant distribution and flooding in horizontal air-cooled condensers.
6. Fin bonding studies.
7. Fan performance studies.
8. Distributor tube design-direct expansion air coolers.

of the Handbooks and computer program improvements) are relatively permanent and continuing projects and the point of inclusion in the Questionnaire primarily is to determine the relative priority and importance placed on the project by the Sponsors. In some cases, the work is scheduled to be completed in 1979-80 and the focus of the Questionnaire is to determine whether or not the Sponsors see a need--as indicated by a high priority--for a continuing effort. The Questionnaire topics for relative rating are supplemented by brief notes of elaboration to afford each Sponsor a more complete picture of what is envisioned by the proposed SIS or Research topic and also to provide opportunity for indicating relative priorities or preferences within a given proposed program. The various Review Panels play a major role in assisting HTFS in planning the Questionnaires and evaluating the returns.

Although not indicated in the preceding TABLES, some of the research work--particularly that of a fundamental fluid flow or mass transfer nature--is often contracted out to UK Universities to serve as graduate thesis studies. A number of these were reported at the Fall 1978 Research Symposium held at Oxford.

EXPERIMENTAL FACILITIES

The experimental facilities at Harwell and at the National Engineering Laboratory (NEL) devoted to HTFS activities are particularly impressive. A major factor in the development of these facilities is directly related to the fact that the HTFS

facilities are a subsection of a large comprehensive research establishment at each location: the Atomic Energy Research Establishment (AERE) at Harwell and NEL at East Kilbride, Scotland. This arrangement provides excellent adjunct capability to support the HTFS programs by providing auxiliary services as needed.

There is no apparent attempt to develop an exclusive experimental capability at Harwell or the NEL; each installation had experimental projects ranging from the very fundamental to the applied on industrial scale equipment in each of the seven HTFS areas of interest. At NEL, it was noted that the large majority of heat transfer and flow experimentation related to the flow and heat transfer conditions outside of tubes; however, this seems to be a basic emphasis for most of the HTFS work.

Most of the experimental equipment incorporated a maximum element of versatility to enable it to serve on a variety of projects. Instrumentation is extensive and, generally, each unit is directly tied to the main computer system to provide immediate calculation and display (printout) of the desired information.

Some of the experimental equipment noteworthy for special mention are the following:

1. Vertical tube assembly for multicomponent boiling studies; the role of surface tension, interfacial turbulence and bubble growth.
2. A shell and tube model heat exchanger using diffusion controlled electrolysis for studying shell side heat transfer and pressure drop characteristics.

3. In-tube condensation assemblies for horizontal, vertical, or inclined tube studies.
4. A two phase flow manifold system (4" diam., 16' feet long; 7000 lb/hr air/water flow) for evaluating manifold two phase flow design parameters.
5. A wide variety of liquid nitrogen cooled extended surface assemblies for cryogenic condensation studies.
6. Laboratory furnaces (Harwell and NEL) as part of the furnace design program.
7. A square wind tunnel (3' x 3') housing an 18" square tube bundle for flow and vibration studies across tube bundles.
8. Two industrial test rigs (ITR) at Harwell and NEL for a variety of heat transfer and flow studies on shell and tube exchangers. One is an 18" diameter, 6' long TEMA type E, floating heat unit (288 tubes - 0.78" diameter). The other is a 16' exchanger with a 15" tube bundle (85 tubes per pass, two passes, 0.75" tubes). Each unit is capable of handling a variety of test situations.
9. A vertical thermosyphon reboiler (104 tubes, 8' x 0.75" o.d. in a 15" diameter baffled shell) may be operated with a variety of geometric configurations and handle pure or multicomponent mixtures in forced or natural circulation.
10. A large plenum rig capable of testing air cooler fans up to 12 ft. diameter in forced draft operation over tube bundles.
11. A forced draft air-cooled exchanger with two (6' diameter) variable pitch fans in shaped plenums. The heat exchanger is four layers of Aluminum G finned 1" o.d. tubes in an 8' x 20' bundle.
12. A wide variety of plastic scale models for sections through shell and tube and plate-fin exchanger for flow studies.

Depending upon the plans for future work that materialize, HTFS is currently considering the installation of a new industrial test rig for cryogenic studies, the installation of a facility for jacketed and agitated heat transfer studies, and further enhancement of the NEL furnace installation.

APPENDIX A-8. Survey of Heat Exchanger Literature

A sampling of the contributions of the European scientific community to the improvement of process heat exchanger efficiency and performance was obtained through a computerized literature search of Engineering Index for the period 1977 to March, 1979. (These dates refer to the date of the article's citation, not its publication, so that many articles published in 1976 are included in this literature search.) The computerized search was performed employing keywords which were selected using as a guide topics included in the DOE report, "Origin and Status of the DOE Heat Exchanger Technology Program to Improve Energy Conversion Efficiency". These topics can be categorized into three general areas:

1. Heat exchanger deficiencies and corrective measures
2. Enhancement techniques
3. Waste heat recovery

The results of the literature search is reviewed here both from the standpoint of the extent of the European contribution to the literature and the distribution of the article citations with respect to the three areas listed above. Generally, the search yielded the largest amount of entries for the first subject area, heat exchanger deficiencies and corrective measures. About two-thirds of all citations selected dealt with the problems of corrosion, fouling and flow-induced tube vibration. The other third of the selected citations fell into the second category, enhancement techniques. These entries focused primarily on the use of fins of various

types in heat exchanger design. An insignificant amount of output was received from the computerized literature search for the third area of waste heat recovery.

Table 5 below categorizes the citations according to subject and country of publication.

Table 5. Heat Exchanger Citations from Computerized Literature Search of Engineering Index, 1977-79.

I. HEAT EXCHANGER DEFICIENCIES AND CORRECTIVE MEASURES

A. Fouling - 11 articles

1. Chemical antifoulants - 4
2. Research in fouling (incl. mechanisms, mathematical models and experimental work) - 7
3. Country of publication
 - a. European - 1
 - b. Russian - 0
 - c. U.S. - 7
 - d. Other - 3

B. Corrosion - 36 articles

1. General mechanisms - 6
2. Corrosion inhibitors - 9
3. Specific materials - 9
4. Specific items of equipment - 9
5. Monitoring - 3
6. Country of publication
 - a. European - 9
 - b. Russian - 3
 - c. U.S. - 19
 - d. Other - 5

C. Vibration - 34 articles

1. Mechanisms of flow-induced vibration - 16

2. Wear of materials due to vibration - 3
3. Mathematical models - 9
4. Research in vibration (control, measurement, design) - 6
5. Country of publication
 - a. European - 6
 - b. Russian - 3
 - c. U.S. - 16
 - d. Other - 9

II. ENHANCEMENT

- A. Surface roughness - 6 articles
- B. Fins - 20 articles
- C. Extended surfaces (other than fins) - 8 articles
- D. Country of publication
 1. European - 1
 2. Russian - 18
 3. U.S. - 9
 4. Other - 6

****European contribuion $\approx$ 15% of citations****