NOV 29 1965

GENERAL ATOMIC DIVISION
GENERAL DYNAMICS CORPORATION

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Informal AEC Research
And Development Report

GAMD-6675
Supplement
Copy No.

STMGEN

This report is a supplement to GAMD-6675,
"A Computer Code for the Design of a Steam Generator"

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IN NUCLEAR SCIENCE ABSTRACTS

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Project 317
U.S. Atomic Energy Commission
AT(04-3)-167
Project Agreement No. 17

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The STMGEN computer code is described herein as it existed on September 1, 1965 . The code has been in continuous development for 1 years and in its presented form has been applied successfully by General Atomic to the kind of problems discussed later in this report. However, the development and improvement of the code are being continued, so that duplication of results (or even close agreement) between problems run with the code as published and the code as it existed either before or after this time is not necessarily to be expected.

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1. SUMMARY

This report is a supplement to GAMD-6675, entitled "A Computer Code for the Design of a Steam Generator". The purpose of the report is to discuss the design and cost additions that have been made to facilitate the use of the code as a sub-program in the optimization code currently under development at General Atomic.

2. INTRODUCTION

This report is a supplement to the Steam Generator Design Code Report GAMD-6675, "A Computer Code for the Design of a Steam Generator". The original report discusses the general design capabilities of the program without reference to a specific steam generator configuration. The supplement describes the additions to the code that are required to design and compute the cost of the steam generator selected for the first version of the optimization program currently under development at General Atomic. The selected steam generator consists of a two-pass U-tube superheater/reheater (see Fig. 1) composed of alternate superheater and reheater tubes arranged in a circular pattern, and an economizer-evaporator (see Fig. 2) formed by a bank of spirally wound equilaterally spaced tubes.

Additional subroutines have been added to the code to compute the size of the headers and risers that are needed to complete the steam generator design. The required cost subroutines have also been written.

A brief discussion of the optimization code (of which STMGEN forms a part) should be useful in understanding the problems associated with the formulation of the design method used to design the complete steam generator, and is therefore presented below. The optimization program may be divided into three basic categories as follows:

1. Power Plant Performance Analysis (OPUS)
2. Design and Cost
3. Optimization

The Power Plant Performance Analysis Section of the code specifies how the various components are interconnected and performs a mass energy balance on the complete system to determine the boundary conditions for each component. A detailed mass energy balance cannot be made unless the various helium and steam pressure drops are available. The flow channel details are unknown at this point in the analysis, therefore, a pressure drop must be selected for each component. As a result, the steam and helium pressure drops are "design" constraint functions.*

*A constraint function is a dependent variable that is forced to assume a specified value by proper adjustment of the independent variables. A "design" constraint function may be treated as an independent variable for optimization purposes.

The Design and Cost Section of the code is composed of various sub-programs that are used to design and compute the cost of each component as a function of its boundary conditions (computed by the flow network analysis) and its independent variables. In addition, certain "material" constraints may also be imposed on the design. The maximum fuel and tube metal temperatures are examples of "material" constraints.

The Optimization portion of the code determines that set of values of the independent variables which correspond to a reactor plant with a minimum cost.

The selection of the independent variables for STMGEN was determined on the basis of its use as a sub-program in the optimization code, which requires that the cost be very sensitive to variations of the independent variables. This strong dependence is necessary to enable the optimizer to determine the value of each independent variable associated with the minimum cost. An independent variable of a particular component may be a dependent variable of the reactor plant and is therefore not explicitly optimized. The helium flow rate is an example of this category; it is an independent variable for the steam generator, but it is a function of the primary system design conditions. The more important variables and constraints are as follows:

Independent Variables

1. Outer diameter of the reheater
2. Number of tubes per row
3. Reheat steam flow rate and the inlet and outlet conditions
4. Superheater steam flow rate and the outlet conditions
5. Economizer-evaporator steam flow rate and the inlet conditions
6. Number of tubes per row in the economizer-evaporator

Constraint Functions

1. Reheater steam pressure drop
2. Economizer-evaporator plus the superheater pressure drop
3. The steam generator over-all helium pressure drop
4. Maximum tube temperature in the superheater/reheater

Dependent Variables

I. Superheater/Reheater

1. Tube diameter
2. Number of tube rows per pass
3. Tube length
4. Pitch spacing
5. Inside diameter of tube bank

II. Economizer-Evaporator

1. Tube diameter
2. Number of tube passes (total length)
3. Pitch spacing
4. Outside diameter of the tube bank (the inside diameter is set equal to the inside diameter of the economizer-evaporator)

The dependent variables and the constraint functions are all non-linear; as a result, the problem is solved by an iterative technique. The computer time for the current version of the code (.03 hours) is considered too long for optimization purposes. A gradient (partial derivatives) method of solution is under consideration that should decrease the number of iterations required to find a solution and result in shorter computer time.

The cost of the steam generator is computed as a function of the total heat transfer area, the non-productive tube length (risers) required to connect the heat transfer portion to the headers, plus the cost of the headers. The cost data used by the code is based on the vendor estimates of several steam generators of this general type. This data was expanded to include all tube sizes and tube lengths by modifying the data with manufacturers tube cost data (see section 5.1 for the details).

The following sections give the details of the design and cost methods currently used by the code.

3. HEAT TRANSFER SURFACE DESIGN

The control subroutines (AREA and CONTRL) of the computer code STMGEN have been written to enable the optimization code to specify the design condition for a steam generator with a two-pass U-tube superheater/reheater composed of alternate reheater and superheater tubes arranged in a circular pattern (see Fig. 1). The economizer-evaporator is composed of a bank of spirally wound tubes arranged on an equilateral pitch spacing (see Fig. 2). The details of the design methods are given below.

3.1 REHEATER/SUPERHEATER

The helium side of the reheater/superheater is the same for both sections. The superheater steam pressure is considerably higher than the steam in the reheater, which accounts for the major difference between the sections; the superheater has a thicker tube wall. The design conditions (independent variables and the constraint functions) for both sections are as follows:

Independent Variables

1. Outer diameter of the reheater
2. Number of tubes per row
3. Reheat steam flow rate and the inlet and outlet conditions
4. Superheater steam flow rate and the outlet conditions

Constraint Functions

1. Reheater steam pressure drop
2. Maximum metal temperature

3.1.1 The Reheater

The reheater/superheater is designed by assuming that the entire bundle is a reheater: all of the tubes are assumed to be reheater tubes (instead of alternate reheater and superheater tubes), and double the actual reheat steam flow is used. This assumption is valid for the current version of the steam generator because the thermal duty of the superheater and the reheater are approximately equal. If this were not so, the 1:1 ratio between the number of superheater and reheater tubes would have to be altered.

The sequence of satisfying the design conditions and constraints is very important if convergence problems are to be kept to a minimum. The maximum tube temperature constraint is satisfied first, followed in order by the required heat transfer and reheat steam pressure drop.

(1) Maximum Tube Temperature

The maximum tube temperature is a function of the heat transfer film coefficient and the gas temperatures. For specified helium and steam temperatures the tube temperature may be controlled by varying the helium flow area. (The steam flow area will also cause variations in the tube temperature.) Most film coefficient correlations are based on the minimum flow area. This creates a problem with a triangular pitch spacing produced by tubes arranged in rows on concentric pitch circles (see Figure 1). The average diagonal flow area varies directly with the longitudinal pitch spacing. For a fixed outer diameter the average transverse flow area varies inversely as the longitudinal pitch. This is demonstrated by the graphical representation given below.

For a small longitudinal pitch, the diagonal flow area is smaller than the transverse area; this difference decreases until $SL = SL'$. At this point the average transverse and diagonal flow areas are equal. When SL is increased above SL' , the transverse flow area is the controlling (minimum) area and it is less than the flow area associated with SL' . Therefore, the maximum average helium flow area occurs at $SL = SL'$. If the maximum tube temperature is too high at this point, the tube diameter must be decreased until the required flow area is obtained.

(2) Required Heat Transfer

The amount of heat transferred to the reheated steam is a known quantity since the steam flow rate and the inlet and outlet conditions are known. The heat transferred by the reheater is compared to the desired value after the maximum tube temperature constraint is satisfied. If it is not correct, the tube length is adjusted and the entire computation is repeated.

(3) Reheat Pressure Drop

The reheat steam pressure drop is checked after the maximum tube temperature and heat transfer requirements are satisfied. The steam pressure drop is controlled by changing the flow area. The tube diameter is not used to control the pressure drop because it must be changed periodically to adjust the helium flow area (see 3.1.1(1) above). As a result, the number of tube rows per pass are used to adjust the helium pressure drop.

There is a minimum reheat steam pressure drop for a given set of helium-steam conditions and maximum tube temperature. A typical example will best explain this situation.

Consider a reheater with seven tube rows per pass in which the reheat steam pressure drop is too high. The number of tube rows is increased to eight in an effort to decrease the pressure drop. The value of SL' (see "Maximum Tube Temperature" above) is less for eight rows per pass than it is for seven rows. In this assumed case the maximum metal temperature exceeds the maximum value when the longitudinal pitch SL is reduced to the new value of SL' . As a result, the tube diameter must be decreased. The increase in reheat steam pressure drop associated with the decrease in tube diameter is larger than the decrease in pressure drop produced by increasing the number of tube rows from seven to eight. Therefore, the seven-tube arrangement has the minimum possible reheat steam pressure drop.

3.1.2 The Superheater

The superheater outlet steam conditions and the helium inlet and outlet conditions are known. The geometry, with the exception of the tube thickness, is the same as that computed for the reheater. The inlet steam conditions are computed by a straight-forward performance calculation if the superheater is a countercurrent exchanger; an iterative solution is required if the superheater is a cocurrent heat exchanger.

3.2 THE ECONOMIZER-EVAPORATOR

The independent variables and the constraint functions for the economizer-evaporator are as follows:

Independent Variables

1. Number of tube columns
2. Number of tubes per row
3. Inlet and outlet helium and steam conditions

Constraint Functions

1. Helium pressure drop
2. Steam pressure drop

The computation begins by setting the outlet steam conditions of the economizer-evaporator equal to the computed superheater inlet conditions. The helium and steam pressure drop constraints are then set equal to the total steam generator losses minus the pressure drops computed for the superheater/reheater.

(1) Required Heat Transfer -- The amount of heat to be transferred is determined from the known steam flow and the inlet and outlet conditions. The first step in the iterative solution is to determine the number of spiral coils (tube length) that are needed to transfer the required heat.

(2) Steam Pressure Drop -- After the heat transfer requirements are satisfied, the steam pressure drop is compared to the specified value. If it is not correct, the tube diameter is adjusted and the entire computation is repeated.

(3) Helium Pressure Drop -- The helium pressure drop is now compared with its constraint value. If it does not agree, the equilateral pitch spacing is changed and the entire computation is repeated again.

The design of the heat transfer surfaces is now complete. The header and tube riser design are discussed in Section IV.

ST - TRANSVERSE PITCH
SL - LONGITUDINAL PITCH

FIGURE 1

ECONOMIZER EVAPORATOR

FIGURE 2

4. HEADERS AND RISERS

The steam generator risers are a continuation of the heat transfer surface that is not exposed to the helium flow. The risers form the connecting link between the heat transfer surface and the headers.

The steam flow is distributed to and collected from the various riser tubes by the steam generator headers. There is an inlet and outlet header for each steam generator component (superheater, reheater, and economizer-evaporator).

This section describes the method used to design the risers and headers.

4.1 HEADERS

The steam generator headers are designed to satisfy the requirements of the ASME Pressure Vessel Code, and the cost is assumed to be a function of the material volume. A computer routine has been written which will determine the header dimensions associated with a minimum material volume and satisfy the ASME code and certain physical dimensions of the particular installation.

4.1.1 General Equations

The routine assumes a "medusa" type header, which consists of concentric cylindrical sections telescoped together. The program designs each header section separately. Referring to Fig. 3, four computation options are available which allow both a fixed section length and a fixed number of riser-tube holes per longitudinal row, one of these, or neither to be specified as restraints on the header section design. The routine may also be used to compute the wall thicknesses of pressure vessels without holes.

The ASME Pressure Vessel Code, Section VIII, gives equations 1a, 1b and 2 for the header wall thickness and longitudinal ligament efficiency.

$$t_{SL} = \frac{P D_i}{2(SE_L - .6P)} \quad P \leq .385 SE_L \quad (1a)$$

$$t_{SL} = \frac{D_i}{2} \left[\left(\frac{SE_L + P}{SE_L - P} \right)^{1/2} - 1 \right] \quad P > .385 SE_L \quad (1b)$$

$$E_L = \frac{P_L - d}{P_L} = 1 - \frac{d}{P_L} \quad (2)$$

According to the ASME code requirements, when the circumferential ligament efficiency is less than one-half the longitudinal ligament efficiency, the shell thickness is given by equations 3a and 3b.

$$t_{SC} = \frac{P D_i}{4(SE_C + .2P)} \quad P \leq 1.25 SE_C \quad (3a)$$
$$E_C < 1/2 E_L$$

FIGURE 3

$$t_{SC} = \frac{D_i}{2} \left[\left(\frac{P}{SE_C} + 1 \right)^{1/2} - 1 \right] \quad \begin{array}{l} P > 1.25 SE_C \\ E_C < 1/2 E_L \end{array} \quad (3b)$$

Define E_C as

$$E_C = \frac{P_C - d}{P_C} = 1 - \frac{d}{P_C} \quad (4)$$

The thickness is then given as

$$t_S = \text{maximum} (t_{SL}, t_{SC}, 3/32) \quad (5)$$

Furthermore, if $t_S < .25$, then the thickness must be multiplied by 7/6 to allow for corrosion.

Certain basic geometric relationships may also be derived for the header section. The hole pattern shown in Fig. 3 leads to the following dimensional equations:

$$W = \frac{\theta}{360} \pi (D_i + t_S) \quad (6)$$

$$P_L = \frac{L + d}{n_h + 1} \quad (7)$$

$$n_R = \frac{n_T}{n_h} \quad (8)$$

$$P_C = \frac{W}{n_R} \quad (9)$$

A minimum allowable value of the diameter exists such that the riser-tube holes do not overlap at the inner wall. Referring to Fig. 4 and equation 6 with $t_S = 0$ at the inner wall,

$$W = \frac{\theta}{360} \pi D_i \quad (10)$$

Combining equations 9, 10, and 8,

$$P_C = \frac{\theta \pi D_i n_h}{360 n_T} = d \quad (11)$$

FIGURE 4

FIGURE 5

Solving for D_i ,

$$D_{i(\min)} = \frac{360 n_T d}{\theta \pi n_h} \quad (12)$$

4.1.2 Options

The following header design options are available:

Option 1

If both the header section length and the number of holes per longitudinal row are specified, the computation of the shell thickness and hole pattern pitches is straight forward using equations 1 through 12.

Option 2

When only the header section length is fixed and the number of holes per longitudinal row is to be optimized for minimum material volume (option 2), the design requires an iterative solution. As seen in Fig. 5 t_{SL} increases and t_{SC} decreases with n_h for a fixed section length. The minimum thickness (and optimum number of holes per longitudinal row) is at the point where $E_C = 1/2 E_L$.

By substituting for E_C from equation 4 and E_L from equation 2, and using equations 6 through 9 with $t_S = t_{SL}$, the following relationship may be found for the number of riser-tube holes per longitudinal row:

$$n_h = \frac{B - 1 + \sqrt{(1 - B)^2 + 4\alpha\gamma}}{2\gamma} \quad (13)$$

where

$$\alpha = \frac{360 n_T d}{\pi \theta (D_i + t_{SL})} \quad (14)$$

$$B = \frac{L}{2(L + d)} \quad (15)$$

$$\gamma = \frac{d}{2(L + d)} \quad (16)$$

Note that the negative root term would yield a meaningless, negative value for n_h in equation 13.

An iteration is thus required on n_h , P_L , E_L , and t_{SL} with checks on D_i vs. $D_{i(\min)}$ and E_C vs. $1/2 E_L$ until two successive values are found for n_h which are within a desired percent tolerance (i.e., .001%).

Option 3

If the number of holes per longitudinal row is defined as an input constant, the material volume must be minimized by solving for the optimum header section length by setting

$$\left. \frac{dv}{dL} \right|_{n_h} = 0 \quad (17)$$

For the shell section (neglecting drilled-out holes),

$$v = \frac{\theta}{2\pi} \cdot \frac{\pi}{4} L (D_i + 2 t_s)^2 - D_i^2 \quad (18)$$

Therefore,

$$\frac{\partial}{\partial \theta} \left. \frac{dv}{dL} \right|_{n_h} = (D_i + 2t_s)L \frac{dt_s}{dL} + Lt_s \frac{dD_i}{dL} + (D_i + t_s)t_s \quad (19)$$

By equation 1a

$$\frac{dt_s}{dL} = - \frac{P D_i S \frac{dE_L}{dL}}{2(SE_L - .6P)^2} + \frac{P \frac{dD_i}{dL}}{2(SE_L - .6P)} \quad P \leq .385 SE_L \quad (20)$$

and by equation 1b

$$\frac{dt_s}{dL} = - \frac{PD_i S \frac{dE_L}{dL}}{2(SE_L - P) \sqrt{(SE_L)^2 - P^2}} + \frac{1}{2} \left[\left(\frac{SE_L + P}{SE_L - P} \right)^{1/2} - 1 \right] \frac{dD_i}{dL} \quad (21)$$

$P > .385 SE_L$

Substituting equation 7 into 2 and differentiating

$$\frac{dE_L}{dL} = - \frac{d}{(L+d)^2} \left[(L+d) \frac{dn_h}{dL} - (n_h + 1) \right] \quad (22)$$

But since n_h is constant for option 3, $dn_h/dL = 0$; therefore

$$\frac{dE_L}{dL} = \frac{n_h + 1}{(L+d)^2} \quad (23)$$

The diameter, D_i , is usually a constant, hence $dD_i/dL = 0$ in equations 19, 20 and 21. However, when the limiting condition of equation 12 is encountered, then by differentiation of equation 12,

$$\frac{dD_i}{dL} = - \frac{360 n_T d}{\pi \theta n_h^2} \cdot \frac{dn_h}{dL} \quad (24)$$

Finally, the optimum length is found by iteration of equations 17, 19, 20 or 21, 23 and 24.

Option 4

When both the length and the hole pattern are to be optimized for minimum volume, the computations are essentially the same as for a fixed n_h (option 3), except that $dn_h/dL \neq 0$; therefore, equation 22 should be used instead of equation 23.

An expression for dn_h/dL is found by differentiating the relationship leading to equation 13. This will lead to

$$\frac{dn_h}{dL} = - \frac{\left[\psi \left(\frac{dD_i}{dL} + \frac{dt_S}{dL} \right) - 1 \right] n_h^{-1}}{\psi (D_i + t_S) + (L + d)} \quad (25)$$

where

$$\psi = \frac{2(360)}{\pi \theta} \left[\frac{(L + d)}{(D_i + t_S) n_h} \right]^2 \quad (26)$$

After the optimum value of n_h is found by iteration of equations 17, 19, 20 or 21, 22, 24, 25 and 26; it is raised to the nearest whole number value and the computation repeated using option 3.

4.1.3 Head

This routine is also capable of designing ellipsoidal, torispherical (concave to pressure), or hemispherical heads for pressure vessels in accordance with the ASME code. The ellipsoidal section has the options of either accepting an input head height or computing the optimum head height and thickness for minimum material volume. The torispherical section accepts only fixed dimensions and computes the thickness required.

To date, the optimization program has been restricted to a hemispherical head. The thickness of the head is then given by

$$t_h = \frac{P D_i}{4(S - .1P)} \quad (27)$$

4.2 RISERS

The sections of tubing which connect the heat exchangers of the steam generators to their respective headers are referred to as risers. The length of the risers are computed as a function of the size of the headers and the heat transfer surfaces. For cost purposes the length is added to the heat transfer surface.

5. COST

The steam generator cost is a function of the following major items:

1. Manufacturer's Tube Cost (Tube Base Price)
2. Fabrication Costs
3. Installation Costs
4. Engineering Costs
5. Shipping Costs

Very little reliable cost data are currently available that will permit a detailed cost analysis of the random steam generators designed by the optimization program. However, tube costs plus fabrication price estimates for several superheater/reheater and economizer-evaporator section of the type used by the optimization code have been received by Cost Engineering. An approximate method of normalizing this data was derived that will permit a preliminary cost estimate to be computed for the first version of the optimization code. These estimates will include the risers. The header costs are computed from a single price estimate by a ratio of the square of the material volume.

5.1 SUPERHEATER/REHEATER TUBE COST

The steam generator total tube cost is primarily a function of tube diameter and tube wall thickness for a given steam generator configuration. The tube base price is also a function of diameter and wall thickness; therefore, the cost per 100 feet may be represented functionally by

$$\frac{\text{COST}}{L_{100}} = f(d,t) = g(\text{Base Price}) \quad (28)$$

The base price was taken from Reference 1.

Reference 2 contains the combined cost estimates of the superheater/reheater for various tube sizes based on a total heat transfer surface area of 5500 sq. ft. These costs were separated into the superheater and reheater component costs per 100 ft of tubing by assuming that, if superheater and reheater are structurally similar, their costs should be equal when the base prices of their tubing are equal. This assumption results in a single curve of total cost vs. base price for both superheater and reheater. Thus a given point on the curve of Ref. 2 corresponds to two points on the proposed curve: one for the superheater and one for the reheater.

The problem of separating the data of Ref. 2 into the superheater and reheater component costs was solved graphically by an iterative technique as follows. A first estimate of the component costs was computed by noting that

$$C = C_{SH} + C_{RH} = f(\text{Base Price})_{SH} + g(\text{Base Price})_{RH} \quad (29)$$

where C is the data of Ref. 2 times 5500 sq. ft as a first estimate, letting

$$C_{SH} = C_{RH} = \frac{1}{2} C \quad (30)$$

and plotting C_{SH}/L_{SH} versus $(\text{Base Price})_{SH}$ and C_{RH}/L_{RH} versus $(\text{Base Price})_{RH}$ yields Fig. 6. These two curves were then averaged as shown by the dashed curve in Fig. 6.

For the second estimate of component costs, the dashed curve of Fig. 6 was assumed as representing C'_{SH} as shown in Fig. 7, and C'_{RH} was computed from

$$C'_{RH} = \frac{C - C'_{SH} \frac{L_{SH}}{L_{RH}}}{1} \quad (31)$$

Again, a dashed average curve was drawn and taken as the next estimate of C'_{SH} from which C'_{RH} was computed by equation 31.

This iteration was continued until essentially a single curve was converged upon for both the superheater and the reheater tube costs as shown in Fig. 8.

Reference 3 transmitted cost figures for a later version of the steam generator for a single reheater and superheater tube size, but without stub tubes. It was assumed that the savings in costs by eliminating stub tubes could be divided equally between the superheater and reheater. Given the tube base prices corresponding to the configuration of Ref. 3, Fig. 8 yielded the separate total costs of superheater and reheater tubing with stub tubes. Then these costs minus one-half the cost savings due to eliminating stub tubes equalled the new cost components for superheater and reheater. The above procedure produced two data points as shown in Fig. 8. A curve was faired through these points similar to the first curve. This last curve was programmed into the optimization code as a table along with a table of Ref. 1.

The curves are used as follows: Given a tube diameter and thickness for the superheater or reheater compute a base price from Ref. 1. Enter Fig. 8 with this value and read the cost/100 feet.

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9

5.2 ECONOMIZER-EVAPORATOR TUBE COST

The total cost versus base price curve given for the evaporator-economizer is given. The iteration method was not needed here, however.

The cost per 100 feet versus the base price of the economizer-evaporator (see Figure 9) was derived from the cost data contained in Reference 2 by the same technique used for the superheater/reheater.

5.3 HEADER COSTS

The header costs were assumed to vary with the square of the material volume. A cost estimate of the reference header is given by Reference 3. The reheater/superheater header reference volume is 51.48 cu.ft. and the economizer-evaporator header is 23.22. These volumes were computed from Drawings 580-SK-72(B-2201) and SK-82(B-2201).

6. GLOSSARY OF TERMS

This section contains an alphabetical list of the definition of all the variables used in the report.

C	total combined cost
COST	tube cost in dollars and cents
C_{RH}	total reheater tube cost
C'_{RH}	reheater tube cost per 100 ft
C_{SH}	total superheater tube cost
C'_{SH}	superheater tube cost per 100 ft
D_i	inside diameter of shell
d	outside diameter of riser tube
E_L	longitudinal ligament efficiency
E_C	circumferential ligament efficiency
L	header section length
L_{100}	tube length in units of 100 ft
L_{RH}	reheater tube length in 100 ft units
L_{SH}	superheater tube length in 100 ft units
n_h	number of riser-tube holes in a longitudinal row
n_R	number of longitudinal rows of riser-tube holes
n_T	total number of riser tubes
P	design pressure
P_C	circumferential pitch
P_L	longitudinal pitch
S	allowable tension stress
t	tube wall thickness
t_h	head wall thickness
t_S	shell thickness
t_{SC}	shell thickness required due to circumferential ligament strength requirement

GLOSSARY OF TERMS Continued.

t_{SL}	shell thickness required due to longitudinal ligament strength requirement
W	circumferential width of hole pattern
θ	internal angle subtending W

REFERENCES

- (1) USS Schedule B-2 for cold-drawn, minimum-wall stainless tubing.
- (2) Memo E-64-314, by G. W. Cummins, dated September 28, 1964.
- (3) Memo E-64-361, by G. W. Cummins, dated November 3, 1964.