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HEAT TRANSFER ANALYSIS AND DESIGN OF A PLUGGING INDICATOR SYSTEM FOR SRE

by

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INTRODUCTION

A general transient heat transfer analysis has been performed on a sodium plugging indicator system comprising a counterflow, concentric-pipe economizer, heat exchanger, flowmeter, plug, and connecting pipe. The entire system is assumed to be at some initial temperature equal to the inlet sodium temperature and suddenly loses heat to some medium in the heat exchanger. While sodium at a constant temperature enters the plugging indicator system from the main sodium line of the SRE loop, heat is removed by the heat exchanger reducing the heat stored in the sodium and components and lowering the temperature at the plug. The rate at which the minimum temperature at the plug decreases is of primary interest for two reasons: (1) It is desirable to reduce the sodium temperature to the plugging temperature in a reasonable short time. (2) Once the plugging temperature range is approached, the rate of change should be small to make it possible to detect the plugging temperature accurately.

The particular requirements of the plugging indicator system have been suggested in an IOL from D. L. Condotta to D. T. Eggen on March 7, 1955. On the basis of these suggestions the system is designed to be capable of cooling 1 gpm of sodium from 750° F to any plugging temperature. The design has a wide range of control of the time rate of change of sodium temperature; in the range from 500-300° F a rate of 5° F/min or less is obtainable. At the plugging temperature cooling may be interrupted to produce an immediate reversal of temperature change at the plug. To meet these requirements, gas (specifically nitrogen in the galleries) with forced convection has been selected as the heat exchange medium.

RESULTS

A design for a plugging indicator system is that based upon conclusions reached by the general analysis given in the Appendix. The design and operating data is presented in Table I. A schematic sketch of the design is shown in Fig. 1,

and a detail drawing of a cross section of the heat exchanger is given in Fig. 2. A typical cooling rate curve for the system where the nitrogen flow rate is decreased from 365 cfm to 70 cfm when the minimum (or plug) temperature reaches 400° F is shown in Fig. 3. A blower capacity of 500 cfm is specified enabling a more rapid initial cooling rate than is shown in the figure. The outside of the duct covering the heat exchanger, as well as the other components in the system, should be insulated so that there will be a minimum of cooling and temperature drop during unplugging and cleaning.

The design consists of a U-type economizer having concentric pipes. Its shell is a 1-1/4 inch standard 304 stainless steel pipe. The inner tube is also 304 stainless steel and has a 1 inch outside diameter with a 35 mil wall thickness. The economizer may be designed similarly with the SRE cold trap economizers. The heat exchanger consists of a bank of 6 parallel longitudinal finned tubes of 3/4 inch standard pipe each 2 feet long, enclosed in a suitable duct that may be a pentagon in cross section as shown in Fig. 2. The fins are placed longitudinally to accommodate a "Calrod" type heater for thawing frozen sodium, for preheating, or for producing a rapid reversal of temperature change at the plug during incipient plugging. The fins are stainless steel and are welded to the pipe to insure that melting of fin material or bond between fin and pipe will not occur at the highest temperatures of operation. There are 14 fins per tube, spaced 24° apart, each 1/16 inch thick and 1/2 inch long. An equivalent standard finned tube may be substituted; however, the thermal capacity of the system must remain at 15 Btu/° F to preserve the same transient behavior. A variable speed drive for supplying from 0 to 500 cfm over the ducted finned tubes is required. The pressurehead required of the fan is not specified, since the relative position of the fan and heat exchanger is not yet known. The fan and motor might be placed outside of the gallery using air cooling if placing them in the gallery is objectionable.

TABLE I

Design Data

Economizer

Type - sodium-to-sodium, counterflow, concentric pipe
Shell - 1-1/4 inch standard 304 stainless steel pipe
Inner tube - 1 inch OD, 0.035 inch wall, 304 stainless steel
Length - 6 feet plus 180° standard weight, long radius return
Annular flow area . . . . 0.711 in^2

Economizer (Continued)

Inside flow area	0.680 in^2
Annular sodium velocity	0.451 ft/sec
Inside sodium velocity	0.472 ft/sec
Overall heat transfer coefficient	960 Btu/hr-ft^2-
Thermal capacitance, inc. sodium	~3.43 Btu/°F

Heat Exchanger*

Type - sodium-to-nitrogen, longitudinal finned tube, counterflow

Number of parallel tubes - 6

Tube - 3/4 inch standard pipe, 304 stainless steel

Fins - 1/16 inch thick, 1/2 inch long, 304 stainless steel welded

Length - 2 feet of finned surface

Number of fins - 14 per tube

Fin spacing - 24°

Inside heat transfer area	2.59 ft^2
Ratio of outside area to inside area	8.31
Nitrogen flow area	21.8 in^2
Nitrogen heat transfer coeff. at 40 ft/sec	10.2 Btu/hr-ft^2-°F
Fin effectiveness	82.3%
Overall heat transfer coeff. based on inside area	69.5 Btu/hr-ft^2-°F

Heaters - 6 - G.E. "Calrods", Cat. No. 4A629, operating 3 in series across 230 v., 111 w each.

Blower capacity	0-500 cfm

Operating Data

Constants

Sodium flow rate	1 gpm, 450 lb/hr
Inlet sodium temperature	750° F
Nitrogen pressure	~1 atm.
Nitrogen temperature	150° F

Steady State

Minimum sodium temperature**	250° F
Economizer parameter, U_1A_1/wc, (Ratio of temp. drop to temp. approach)	10
Temperature approach in economizer	~45° F

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*An equivalent finned tube heat exchanger may be substituted.

**Other steady state minimum temperatures can be obtained by varying cooling.

Nitrogen velocity thru heat exchanger	7.8 ft/sec
Nitrogen flow	70 cfm
Heat exchanger parameter, U_2A_2/wc, (ratio of temp. drop to mean temp. diff.)	0.37
Heat loss to nitrogen	1.9 KW

Transient State (Typical Case, see Fig. 3)

A. Plug temp. range 750 - 400° F

Initial system temperature.	750° F
Nitrogen velocity thru heat exchanger	40 ft/sec
Nitrogen flow	365 cfm
Heat exchanger parameter, U_2A_2/wc	1.1
Initial rate of temp. change at plug.	-31.7°F/min
Rate of temp. change at plug at 400° F.	-12.5°F/min
Time required to drop temp. to 500° F	16 min.

B. Plug temp. ≤ 400° F

Nitrogen velocity thru heat exchanger	7.8 ft/sec
Nitrogen flow	70 cfm
Heat exchanger parameter, U_2A_2/wc	0.37
Rate of temp. change at plug at 400° F.	6.4 °F/min
Rate of temp. change at plug at 300° F.	2.1 °F/min

FIG. 1

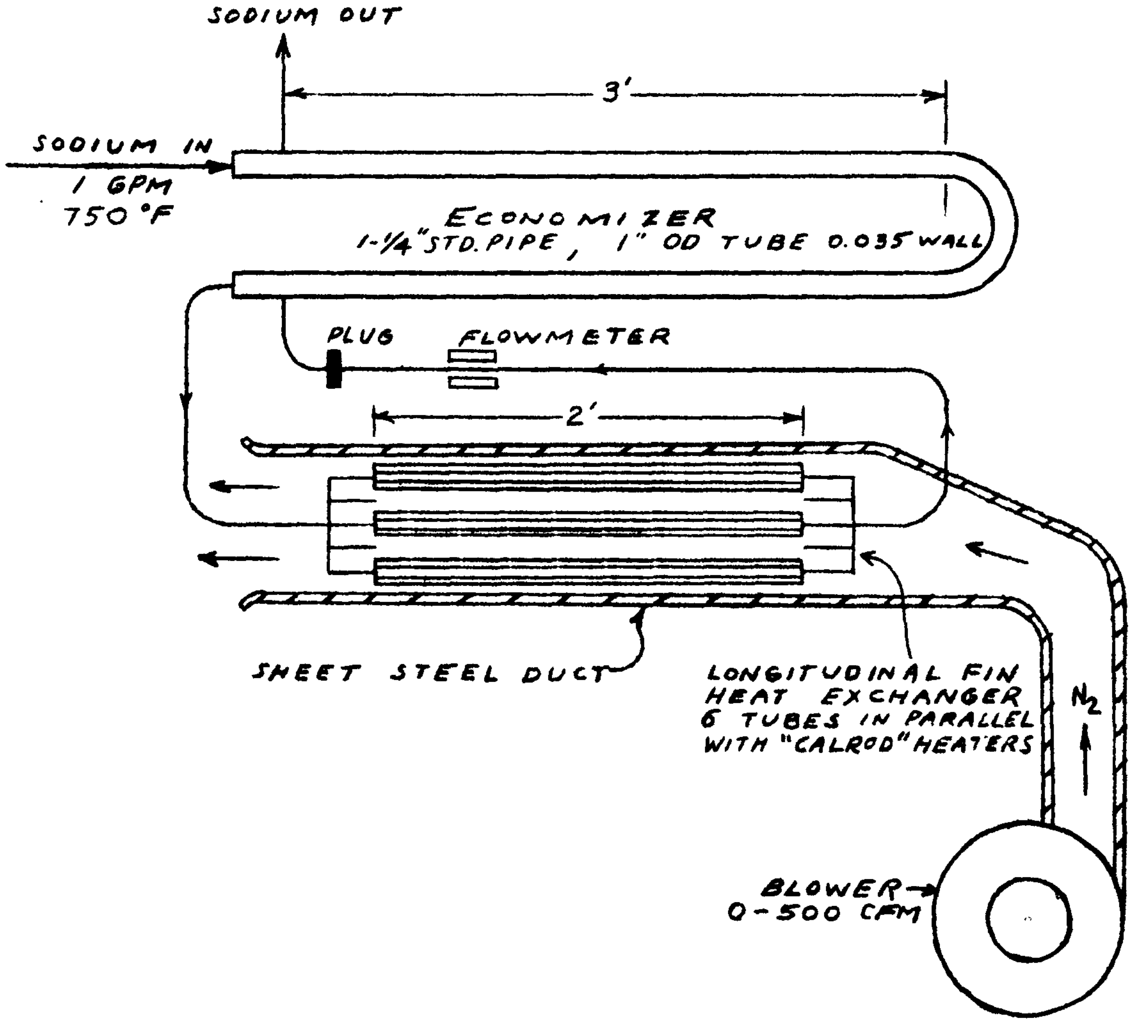

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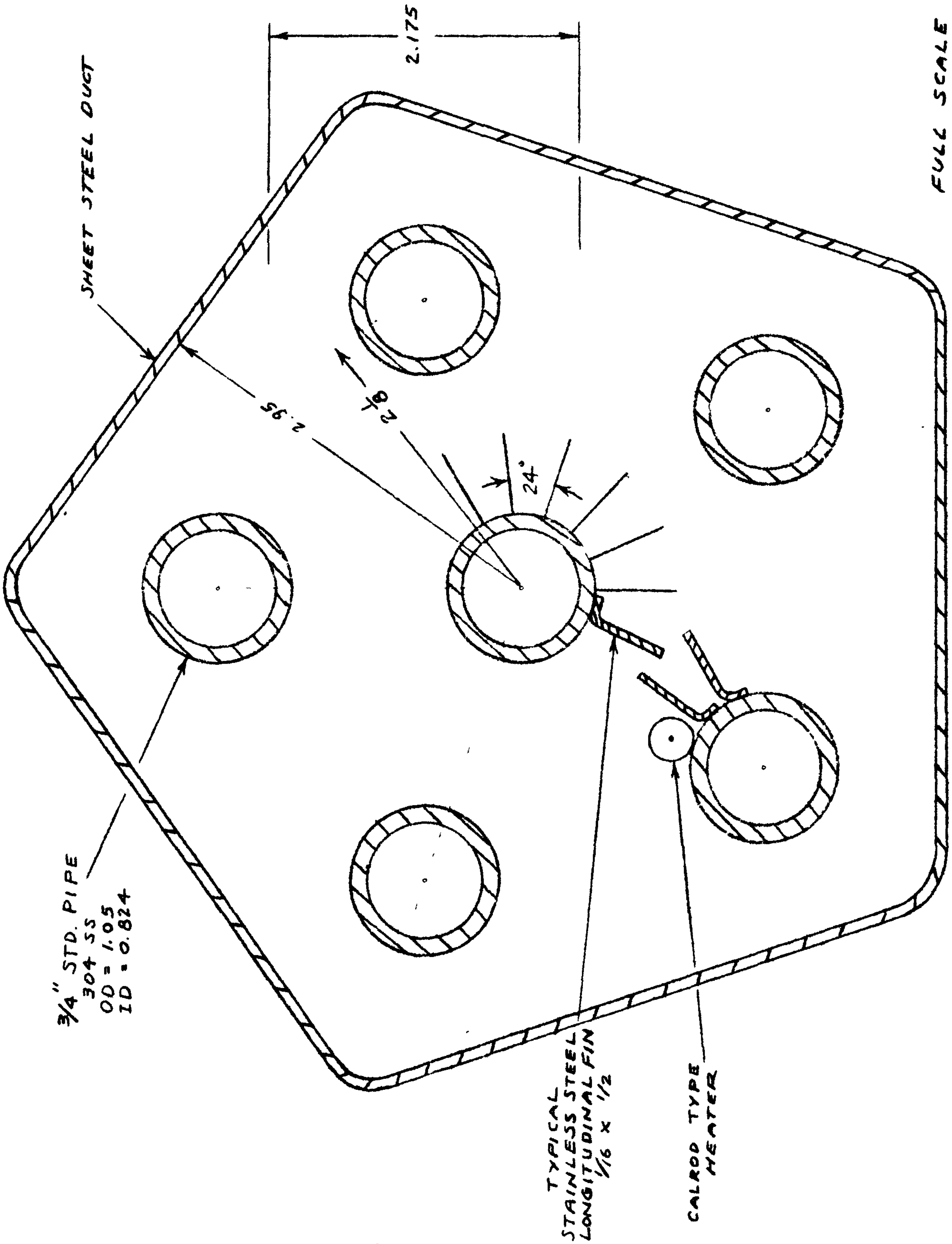
FIG. 2



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CHECKED BY:		REPORT NO.
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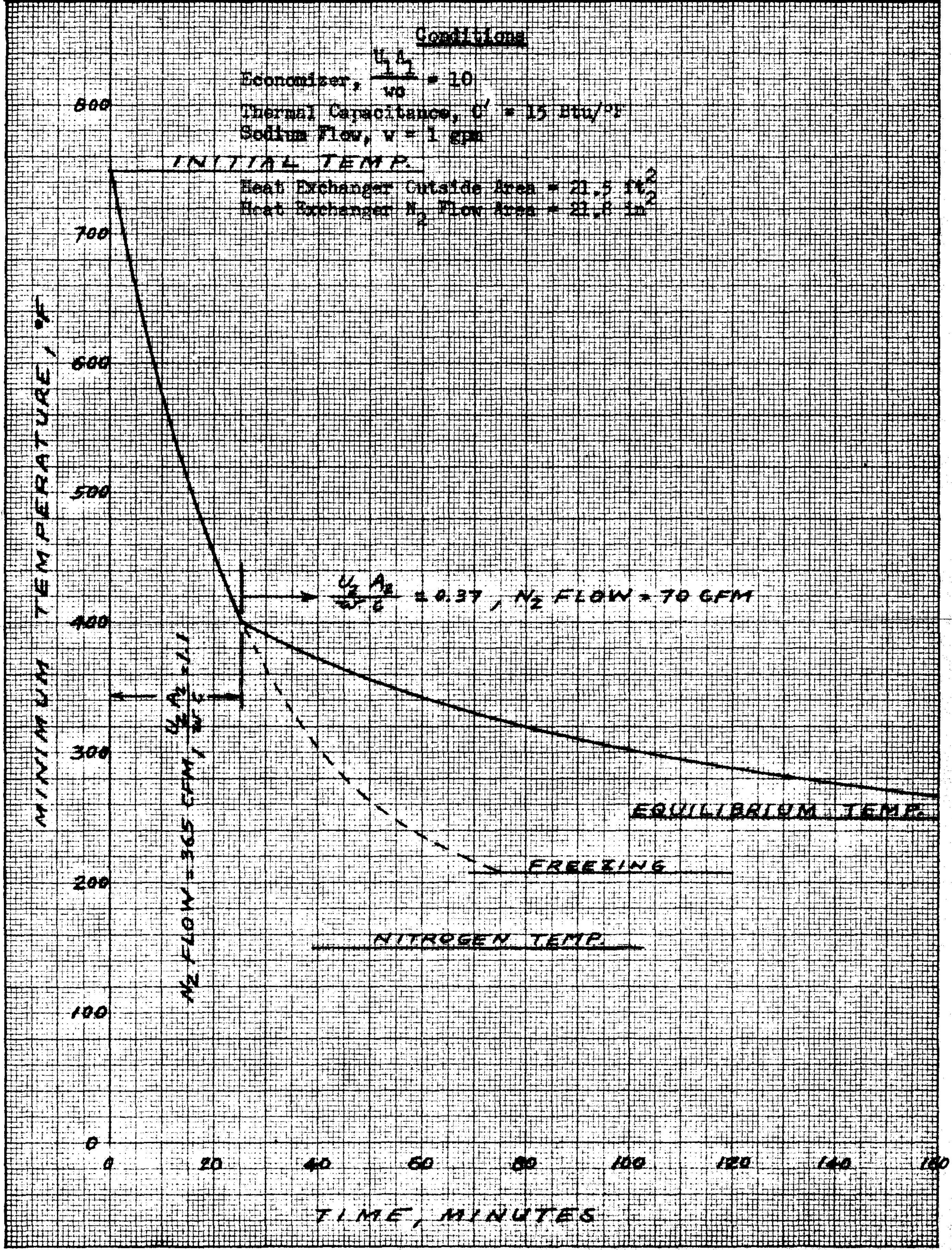


Conditions

Economizer, $\frac{U_1 A_1}{wc} = 10$

Thermal Capacitance, $C' = 15$ Btu/°F

Sodium Flow, w = 1 gpm

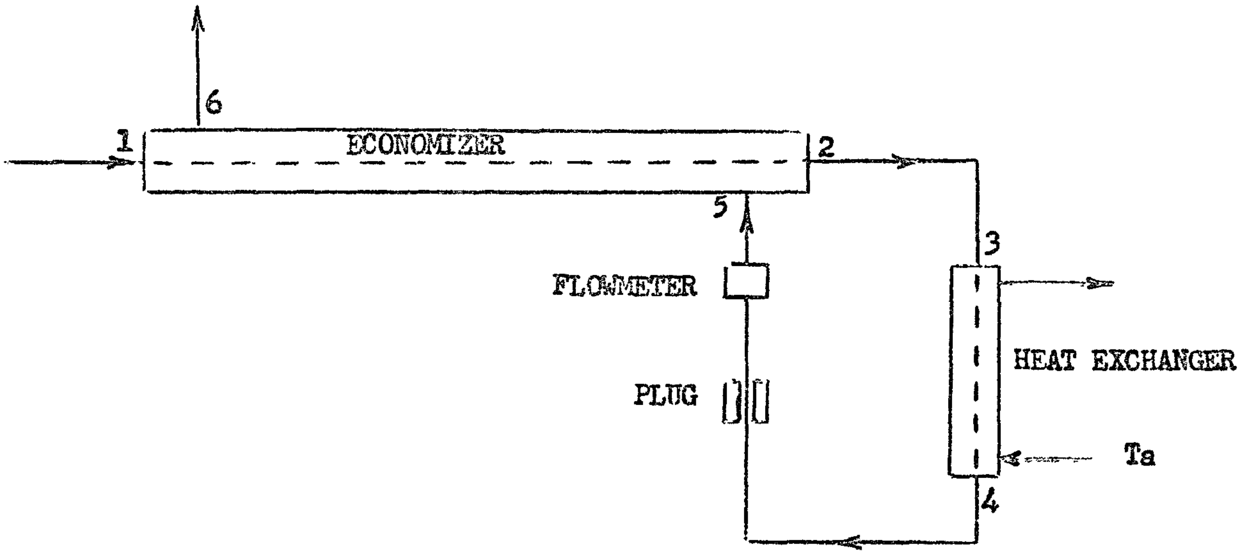
Heat Exchanger Outside Area = 21.5 ft^2

Heat Exchanger N_2 Flow Area = 21.8 in^2

APPENDIX

Theory

The system is composed of the components in the schematic sketch below.



Considering an energy balance of the entire system, the heat added between 1 and 6 is

$$w\ c\ (T_1 - T_6)\ \text{Btu/hr.}$$

The heat added between 3 and 4 is

$$U_2A_2\ \Delta T_m$$

$$\cong\ U_2A_2\ (T_a - \frac{T_3 + T_4}{2})\ \text{Btu/hr.}$$

The heat stored in the system is

$$\frac{d}{d\theta} \sum_{i=1}^{n} m_i\ c_i\ T_i \quad \text{Btu/hr.}$$

Provided the economizer, plug, flowmeter, and connecting piping is well insulated, the algebraic sum of the heats added as given above is equal to the heat stored, or

$$wc\ (T_1-T_6) + U_2A_2 \left(T_a - \frac{T_3+T_4}{2}\right) = \frac{d}{d\theta} \sum_{i=1}^{n} m_ic_iT_i \qquad \ldots . (1)$$

where w = flow rate of sodium, lb/hr
c = specific heat of sodium, Btu/lb-°F
T_1 = inlet temp. to economizer, °F
T_6 = outlet temp. from economizer, °F
U_2 = overall heat transfer coeff. of heat exchanger, Btu/hr-ft^2-°F
A_2 = heat transfer area of heat exchanger, ft^2
T_a = temp. of medium cooling heat exchanger, °F
T_3 = inlet sodium temp. to heat exchanger, °F
T_4 = outlet sodium temp. from heat exchanger, °F
θ = time, hours
m_i = mass of sodium or metal in ith component, lb
c_i = specific heat of sodium or metal in ith component, Btu/lb-°F
T_i = temperature of sodium or metal in ith component, °F

The storage term on the right in Eq. (1) may be simplified by writing

$$\sum_{i=1}^{n} m_i c_i \frac{dT_i}{d\theta} = C \frac{dT_{avg}}{d\theta} \qquad \ldots\ldots (2)$$

where C is the total thermal capacitance of the entire system and T_{avg} is a weighted average temperature defined by

$$T_{avg} = \frac{\sum_{i=1}^{n} m_i c_i T_i}{\sum_{i=1}^{n} m_i c_i} = \frac{\sum_{i=1}^{n} m_i c_i T_i}{C}$$

If an arithmetic average temperature, $\frac{T_1+T_4}{2}$, is used for the purpose of further simplification, a corresponding hypothetical thermal capacitance defined by the following expression must be introduced.

$$C' = \frac{T_{avg}}{\frac{T_1+T_4}{2}} C \qquad \ldots\ldots (3)$$

A calculation reveals that the ratio of C'/C is less than unity and about 0.8. Substituting Eq. (3) into (2) and the result into Eq. (1) and noting that $T_1-T_6 = T_2-T_5$,

$$wc(T_2 - T_5) + U_2A_2 \left(T_a - \frac{T_3 + T_4}{2}\right) = C' \frac{d}{d\theta}\left(\frac{T_1 + T_4}{2}\right) \quad \ldots . (4)$$

Now, $T_2 = T_3 = T_4 + F\ (T_1 - T_4)$ and $T_5 = T_4$

where F is the fraction of the total temperature drop in the system that occurs in the heat exchanger; that is,

$$F = \frac{T_3 - T_4}{T_1 - T_4} \ .$$

Eliminating T_2, T_3, and T_5 from Eq. (4) by substituting the expressions above gives,

$$F\ (T_1 - T_4) + \frac{U_2A_2}{wc}\left[T_a - T_4 - \frac{F}{2}(T_1 - T_4)\right] = \frac{C'}{2wc}\ \frac{dT_4}{d\theta} \quad \ldots . (5)$$

Since

$$wc\ (T_1 - T_3) = U_1A_1\ (T_3 - T_4)\ ,$$

$$F = \frac{1}{\frac{U_1A_1}{wc} + 1} = \frac{1}{K_1 + 1} \ .$$

Letting $\frac{U_2A_2}{wc} = K_2$, Eq. (5) becomes

$$\frac{dT_4}{d\theta} + \frac{2wc}{C'}\left(K_2 + \frac{1}{K_1+1} - \frac{1}{2}\ \frac{K_2}{K_1+1}\right)T_4 = \frac{2wc}{C'}\left(K_2T_a + \frac{1}{K_1+1}\ T_1 - \frac{1}{2}\ \frac{K_2}{K_1+1}\ T_1\right)$$

or $\frac{dT_4}{d\theta} + \psi\, T_4 = \varkappa$ $\quad \ldots . (6)$

The solution of Eq. (6) for the initial condition,

$$T_4 = T_1 \text{ when } \theta = 0,$$

is

$$T_4 = \frac{\varkappa}{\psi} + \left(T_1 - \frac{\varkappa}{\psi}\right)\ e^{-\psi\theta} \quad \ldots . (7)$$

The steady state value of T_4 is

$$\lim_{\theta \to \infty} T_4 = \frac{\mathcal{H}}{\psi} = \frac{K_2 T_a + \frac{1}{K_1+1} T_1 - \frac{1}{2} \frac{K_2}{K_1+1} T_1}{K_2 + \frac{1}{K_1+1} - \frac{1}{2} \frac{K_2}{K_1+1}} \quad \ldots . (8)$$

Eq. (7) is plotted in Fig. 5 for various values of the hypothetical thermal capacitance, C', an economizer parameter, $\frac{U_1 A_1}{wc} = 10$, and an equilibrium temperature of 250° F. The value of the heat exchanger parameter, $\frac{U_1 A_1}{wc}$, that gives the equilibrium temperature of 250° F is obtained by solving for K_2 in Eq. (8):

$$K_2 = \frac{T_1 - \frac{\mathcal{H}}{\psi}}{\frac{T_1}{2} - (K_1+1)T_a + (K_1+\frac{1}{2}) \frac{\mathcal{H}}{\psi}} \quad \ldots . (9)$$

Eq. (9) is plotted in Fig. 6 for an equilibrium temperature, $\frac{\mathcal{H}}{\psi} = 250°$ F.

Eq. (7) is also represented in Fig. 5 showing the effect of varying the economizer parameter, $\frac{U_1 A_1}{wc}$, on the change in plug temperature, T_4, with time, holding the equilibrium temperature constant at 250° F.

CONCLUSIONS

Several conclusions may be drawn from the general analysis. For a fixed system to cool from 750° F at the plug to the plugging temperature (presumably in the range 300-500° F) in a reasonable length of time either the thermal capacitance (mass x specific heat) of the system must be extremely small or the temperature drop that occurs in the heat exchanger at equilibrium must be a large fraction of the total drop. These facts are seen clearly in Figs. 4 and 5, respectively.

Further, when the time required to cool down to the plugging temperature range is reasonably small, the rate at which the temperature is changing is too large to get an accurate reading of the plugging temperature. Apparently some method is required to decrease the rate of cooling once the plugging temperature range is approached. The best method of control is to vary the heat exchanger parameter, U_2A_2/wc. A wide range of control can be obtained in this parameter if a gas is used as the coolant because it would be the controlling resistance making up the overall heat transfer coefficient, U_2. This is done very effectively by changing the gas velocity.

Figure 5 indicates that a large value of the economizer parameter, U_1A_1/wc, is required to obtain a low cooling rate in the plugging range. The corresponding value of the heat exchanger parameter indicated must be increased by three or four times to obtain a reasonably rapid initial cooling rate.

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FIG. 4

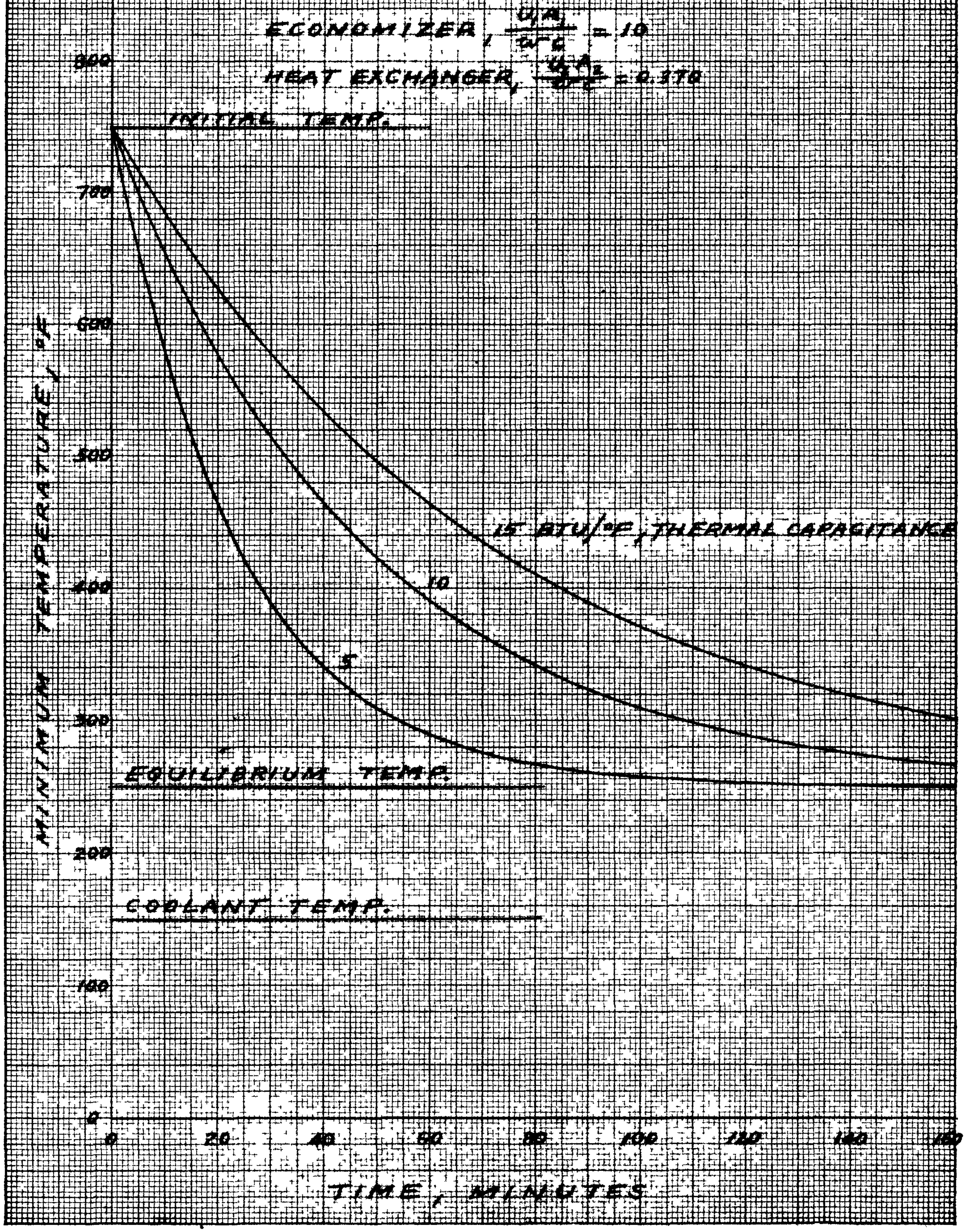

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FIG. 5

SYSTEM THERMAL CAPACITANCE = 10 BTU/°F

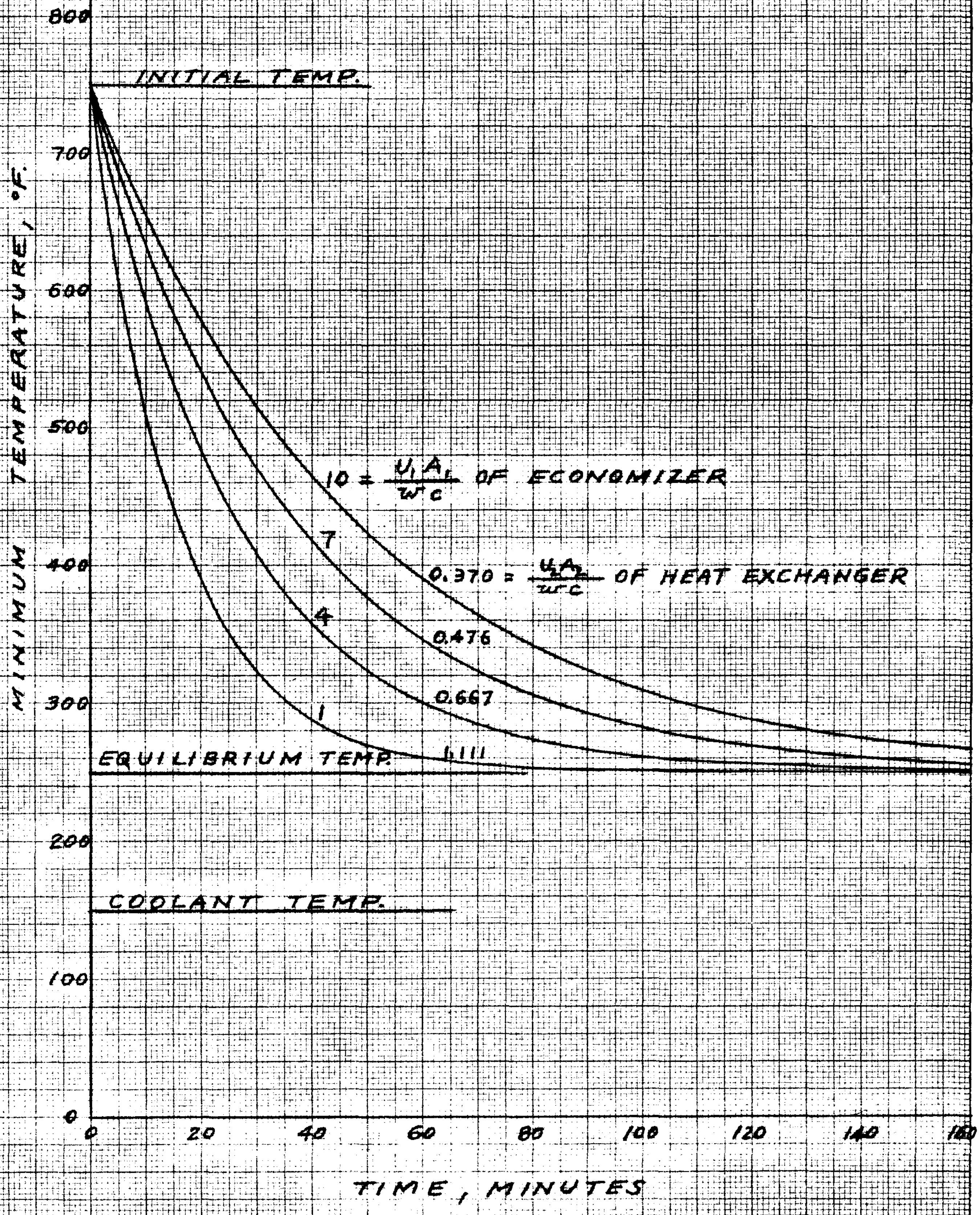

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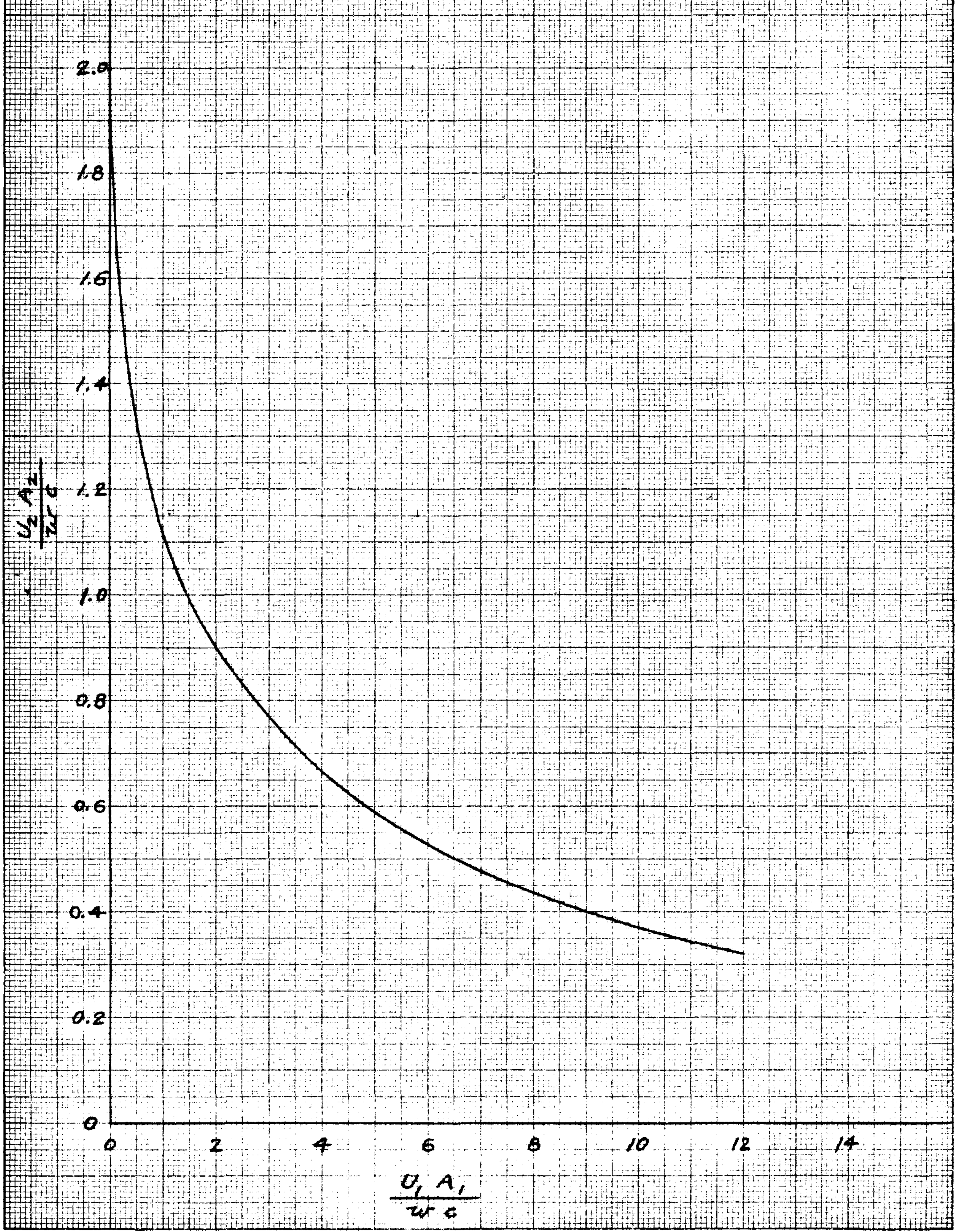
FIG. 6



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