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A cold trap is a device used to remove certain impurities from a liquid metal by controlled precipitation of such impurities.

An investigation of the thermal characteristics of laminar flow in two air-cooled cold traps was made. This investigation showed that the sodium heat transfer rate is a function of the Peclet number.

Generally accepted methods of calculating heat transfer to air produce satisfactory results when used to predict cold trap heat rejection rates.

A computer code for mathematical simulation of cold trap performance was written and tested. Simulation of cold trap operation was excellent, but prediction of economizer performance was disappointing.

The bases for constant trapping temperature and constant impurity removal trapping rates were developed. The constant impurity removal trapping rate, a linear function, is used most often in cold trap operation.

Cold Trap Performance - A General Analysis

by

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COLD TRAP PERFORMANCE--A GENERAL ANALYSIS

I. INTRODUCTION

"Cold Trap" is a generic term for a class of equipment used to control impurities in a fluid system where the concentration of such impurities is temperature dependent. Cryogenic cold traps, for example, are routinely used in the laboratory to remove impurities in a gas system by condensation or precipitation.

The cold traps discussed herein are used to control impurities in liquid sodium. Liquid sodium has been adopted as the coolant for the Atomic Energy Commission's current Liquid Metal Fast Breeder Reactor (LMFBR) development program because of its favorable nuclear characteristics and its desirable physical properties, which include high thermal conductivity, low viscosity, and large temperature range between its melting point (208° F) and its boiling point (1609.5° F).

Early investigations of sodium as a heat transfer medium identified two major problems arising from the presence of oxygen as an impurity dissolved in the sodium. These problems are:

1. increased corrosion of structural materials with increased oxygen content.
2. plugging of sub-cooled passages as a result of sodium oxide precipitation.

At LMFBR operating temperatures (~1000° F) even a few parts per million of sodium oxide can have a deleterious effect on the performance and reliability of a fast breeder reactor and its heat transfer system.

In a cold trap the sodium is cooled and impurities present in amounts exceeding those which will dissolve at the lower temperature precipitate. Cold traps are designed to promote controlled precipitation and to retain the precipitate in the trap.

The practical lower limit of oxide concentration in sodium achievable by cold trapping has not been clearly established, but is considered to be in the range of 2-5 weight parts per million.

The first reported work on sodium traps was done by Bruggeman and others at Knolls Atomic Power Laboratory (KAPL) in support of the Submarine Intermediate Reactor (SIR) program in the early 1950's. During that period various means of sodium purification, including distillation, filtration, chemical reduction (gettering), and precipitation were investigated. Precipitation of the sodium oxide was found to be the simplest and most effective method of reducing the oxide level in a sodium system. Cold trapping has subsequently been adopted as the primary sodium purification method in all sodium cooled nuclear installations in the United States and abroad.

After the SIR program, Atomics International extended cold trap technology in developing traps for the Sodium Reactor Experiment and for the Sodium Graphite Reactor at the Hallam Nuclear Power Facility.

Work has also been done at Los Alamos Scientific Laboratory as a part of their liquid metal testing program and at Argonne National Laboratory in connection with the Experimental Breeder Reactor (EBR) programs.

In the commercial sector, MSA Research Corporation has developed and presently markets sodium cold traps of various sizes. The MSA traps include most of the design features of the traps that MSA furnished for the Enrico Fermi Fast Breeder Reactor.

Experimental work that has been done to date has been concerned primarily with empirical testing of particular cold trap designs which were intended for use in specific applications. Such development work has been well reported. In general however, existing literature deals with results of operation of cold traps without detailed explanation of the underlying principles, or extensive analysis of observations. Consequently, the information available does not appear to provide enough correlation of design parameters to permit extrapolation with confidence to large scale traps for central station power plant use.

The simplicity and success of rudimentary models of sodium cold traps has, however, discouraged support of extensive additional study of trapping phenomena. Funding of cold trap development within the LMFBR program is currently at a very low level.

II. COLD TRAP TECHNOLOGY

Related Technical Information

An appreciation of cold trap technology requires knowledge of a number of related subjects. This section includes a brief discussion of several of the most pertinent of these subjects.

Oxygen Solubility

The solubility of sodium oxide in sodium has been extensively investigated. Early (1950's) experimenters were handicapped by methods available at that time and the lack of need for accurate data below 20-30 ppm. Recent (mid- and late-1960's) work involved techniques believed accurate at concentrations as low as 1 ppm.

Perhaps the best work on oxide solubility is reported by Rutkauskas in reference 22. Rutkauskas developed the relation:

$$\log_{10} S = 4.25 - \frac{3499}{T(^\circ K)}$$

where S is weight percent oxygen.

The standard deviation of this correlation is reported to be 0.5 ppm in the oxygen concentration range of 1 to 10 ppm and 5 percent above 10 ppm.

A recent report by Atomics International (7) compiled the work of many investigators and derived the following relationship:

$$\log_{10} S = 6.239 - \frac{2447}{T(^\circ K)}$$

where S is solubility in weight parts per million. The two expressions are compared in Figure 1.

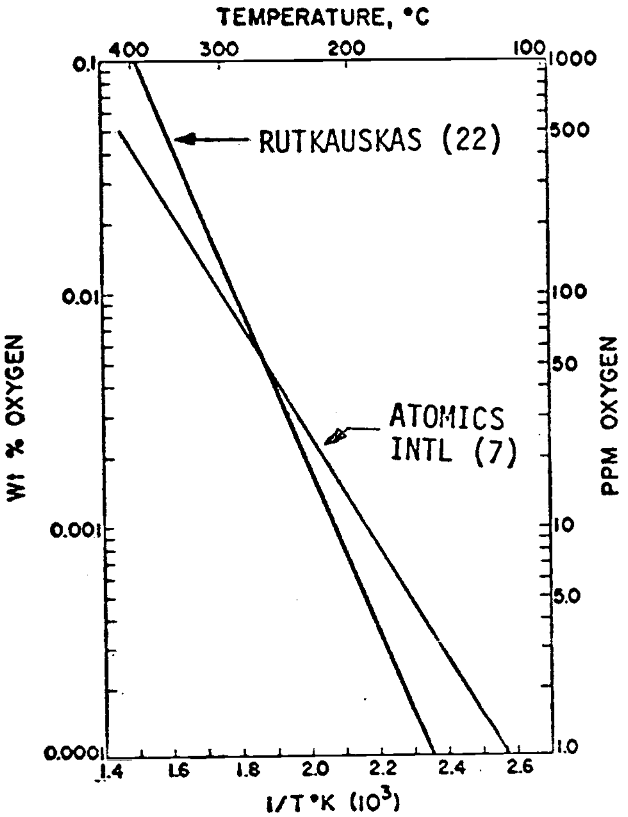

Figure 1. Solubility of Oxygen in Liquid Sodium

Sodium Analysis Methods

The primary methods of determination of the oxide content of a sodium sample are Amalgamation and Distillation.

The Amalgamation method consists of amalgamation of free sodium with mercury in an inert atmosphere followed by acid-base titration of the oxide containing residue. Under carefully controlled conditions oxygen concentrations in sodium to 1 ppm with a precision of ± 1 ppm at the lower concentration levels can be determined.

Vacuum distillation is carried out at a pressure of approximately 10^{-5} mm of mercury. After sodium distillation, the quantitative measurement of the separated residue is performed in the same manner as in the Amalgamation method. Vacuum distillation is capable of accuracy of ± 5 ppm, to a lower concentration level of 5 ppm.

Sampling methods produce accurate, reproducible results, but are difficult and time consuming. They are used primarily as calibration references for on-line methods of determination of oxide contamination.

Plugging Meters

The on-line instrument most used to measure oxide concentration in a sodium stream is the "plugging meter." The principal parts of a plugging meter are a flow meter, a calibrated flow restriction and a constant head flow device.

Plugging temperature is determined by slowly lowering the temperature of the sodium. When the saturation temperature is reached, sodium oxide precipitates, plugs the flow restriction, and causes a sharp break in the plugging meter flow rate. The temperature at which plugging occurs can be related to oxide content by a temperature-solubility correlation.

This device has been thoroughly tested for oxide concentrations ranging from 10 to 200 ppm. Agreement with chemical methods is within the precision of both methods.

The main advantages of the plugging meter are speed and simplicity of operation, and avoidance of additional system contamination in sample withdrawal.

A disadvantage is the meter may be subject to interference from other impurities that precipitate in the measured temperature range.

Cold Trap Types

Several types of cold traps have been developed. These include:

- forced circulation trap
- natural circulation (diffusion) trap
- batch type trap

Forced circulation cold traps are usually installed in bypass loops. The equipment consists of a cooling system and tank for impurity precipitation and retention. When economically justified, the trap is coupled with a regenerative heat exchanger (economizer) to conserve thermal energy.

Natural circulation (diffusion) cold traps depend upon density differences to circulate sodium through the trap. The diffusion unit is usually a small container attached to the sodium system in a position that under normal operating conditions is at, or near, the lowest temperature in the system.

Natural circulation traps are simple and require no attention after they are installed. They continue to remove impurities until they attain their full capacity (about 20% of trap volume) of precipitates.

Batch type trapping seeks to concentrate and trap impurities in relatively large tanks, on a batch basis, by lowering the temperature of the contents of the tank. The description and analysis of results of one experiment in batch trapping is reported in reference 17.

In general, the forced circulation trap has proved the most versatile and effective and is the only type which will be considered in this report.

Residence Time

Residence time is defined as the total time the sodium is present in the trap, measured at equilibrium flow conditions. This time is calculated on the basis:

$$R = (\text{mass of Na in trap})\ \text{lb} \times \frac{1 \qquad\qquad \text{min}}{(\text{mass flow rate through trap})\ \text{lb}}$$

The unit of R (residence time) is time.

The definitive work on the effect of residence time on cold trap effectiveness was done by Bruggeman at KAPL and is reported in reference 3.

Bruggeman varied the residence time of a test loop cold trap and measured the reduction in oxygen content as a function of operating time. He found an appreciable gain in trap effectiveness when the residence time was increased from 2-1/2 to 5 minutes and little increased effectiveness when the time was further increased to 10 minutes.

This early work (reported in 1956) is the basis for establishing five minutes as the design residence time in almost all of the cold traps built in the United States since that time.

However, Russian experiments, reported by Subbotin (24), show that optimum oxide retention effectiveness is achieved with a residence time of 15-20 minutes.

The effect of residence time on trap operation has not been reported in sufficient detail to clearly establish an optimum residence time.

Trapping Rate

The "trapping rate" is defined as the rate at which impurities are removed from liquid metal by the trap. The dimension of trapping rate is weight of impurity removed per unit time. This rate is determined by rate of flow through the trap; concentration of impurities at the trap inlet; and the trapping temperature. A number of references (3, 23, 24, 26) report the relationship of these variables as:

$$\frac{c - c_t}{c_i - c_t} = e^{-(\frac{w}{W})t} \tag{1}$$

This equation is based on the following assumptions:

- No impurity enters the system during trapping
- Flow rate is constant
- Trapping temperature is constant
- The trap is 100% effective (i.e., all oxide that can theoretically be trapped is retained in the trap).

and is derived as follows:

The total mass of impurity in the system at any time is

$$I = Wc. \tag{a}$$

Differentiating I with respect to time yields

$$\frac{dI}{dt} = W\frac{dc}{dt} + c\frac{dW}{dt} \quad . \tag{b}$$

But since W does not vary with time

$$\frac{dI}{dt} = W\frac{dc}{dt} . \tag{c}$$

Also,

$$\frac{dI}{dt} = - wc + wc_t , \tag{d}$$

equation (d) being the impurity mass balance on the sodium system at time t.

Equating the two expressions of $\frac{dI}{dt}$

$$W\frac{dc}{dt} + wc - wc_t = 0 \qquad (e)$$

The solution to this differential equation is

$$c = c_i e^{-\left(\frac{w}{W}\right)t} - c_t e^{-\left(\frac{w}{W}\right)t} + c_t \qquad (f)$$

which reduces to equation (1).

If one defines "turnover" as one complete pass of system volume through the cold trap, it can then be shown that the dimension of the exponent of e in equation (1) is "turnovers" and the reduction in impurity concentration is exponential with system turnovers as shown in Figure 2.

Equation (1) has been generally accepted as the basis for predicting the trapping rate of a cold trap. However, the method of trap operation necessary to produce the trapping rate derived above should not be used for cleaning up anything more than mildly contaminated liquid metal systems. Maintaining a trapping temperature sufficiently low to achieve the final impurity concentration desired produces a highly super-saturated solution in the trap at the start of a purification run and causes localized deposition of impurities near the inlet which greatly enhances the possibility of plugging the trap.

Most trap operators try to achieve a constant impurity removal rate by varying the trapping temperature. Operating procedures often require that the trapping temperature be no more than some fixed number of degrees less than the system plugging temperature.

The equation for constant impurity removal rate similar to equation (1) for constant trapping temperature is derived as follows, based on the following assumptions:

- No impurity enters the system during trapping
- Flow rate is constant
- Impurity removal rate is constant
- The trap is 100% effective

The concentration reduction curve for a constant impurity removal rate will be linear with time, and if some minimum concentration is desired at the end of "a" turnovers equivalent to that which could be achieved by holding a constant trapping temperature, the concentration curve will be a straight line intersecting the exponential curve at "a" on the abscissa, as shown on Figure 2 on the following page for a = 5. The equation of the straight line in Figure 2 is

$$c = c_i - \frac{c_i - c_m}{a\left(\frac{W}{w}\right)} t \qquad \text{(a)}$$

It has been previously shown in the constant trapping temperature case that

$$W\frac{dc}{dt} = - wc + wc_t \,. \qquad \text{(b)}$$

Differentiating c with respect to t in equation (a) yields

$$\frac{dc}{dt} = -\frac{c_i - c_m}{a\left(\frac{W}{w}\right)} \,, \qquad \text{(c)}$$

which when substituted in equation (b) results in

$$-\frac{c_i - c_m}{a} = c + c_t$$

or,

$$c - c_t = \frac{1}{a}(c_i - c_m) \,. \qquad \text{(2)}$$

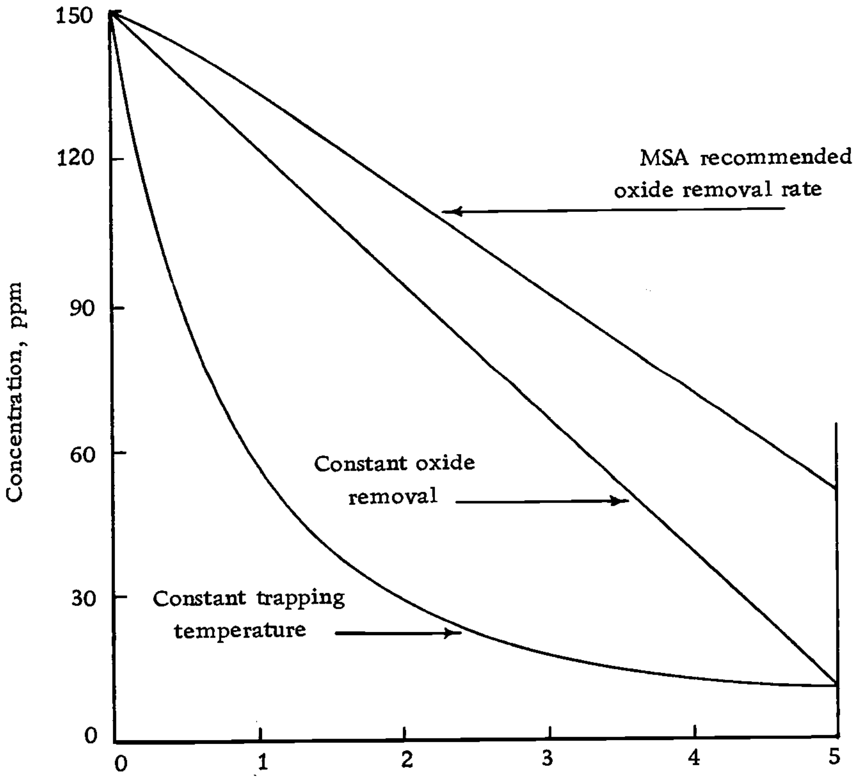

Figure 2. Oxide Trapping Rates

The relation stated in equation (2) shows that for a uniform trapping rate there should be a constant difference in concentration between cold trap entrance and exit equal to the total reduction in concentration desired divided by the number of system turnovers required to achieve the desired minimum concentration.

Figure 3 on the following page is taken from reference 20, the manufacturer's operating manual for the Small Heat Transfer Loop at the Hanford Engineering Development Laboratory. The trapping rate using this recommended maximum difference between system saturation temperature and minimum trap temperature (trapping temperature) is plotted in Figure 2.

Trap Efficiency

The efficiency of a cold trap is a measure of its capability to achieve an outlet impurity concentration approaching the saturation concentration at the trapping temperature. Efficiency is strongly influenced by residence time. Bruggeman (3) reported that the SIR prototype trap was 100% efficient with a residence time of 5 minutes and Cygan (5) states the Hallam trap was very nearly 100% efficient. However, Russian investigators (24) report carryover of oxide with a 9 minute residence time. Efficiency of the Russian trap approached 100% as residence time was increased to 15-20 minutes.

Trapping efficiency is defined as

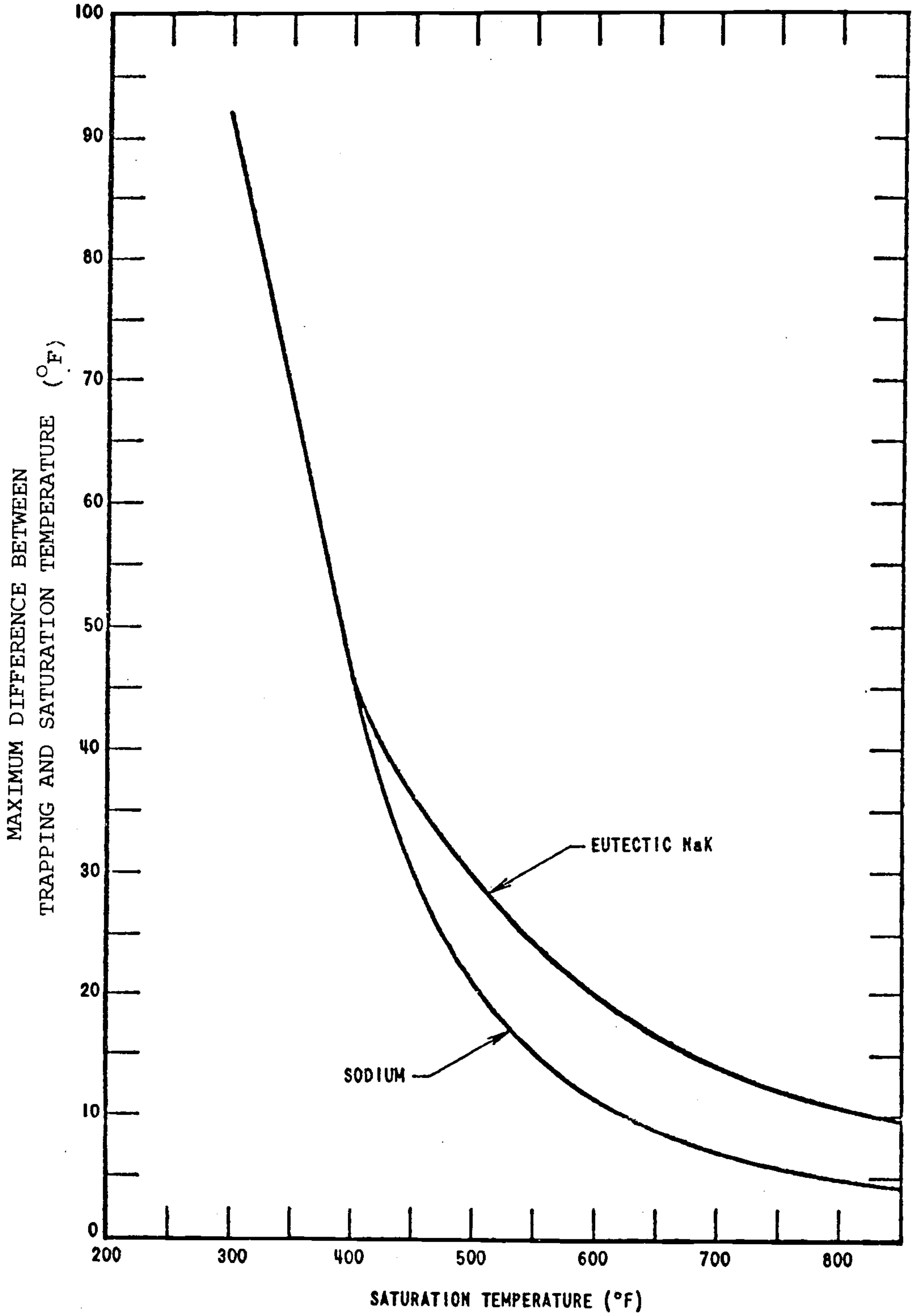

Figure 3. Recommended Cold Trap Operating Conditions

$$\alpha = \frac{c_i - c_o}{c_i - c_t} \tag{3}$$

Each of the equations developed earlier for trapping rate should be modified to include an efficiency term.

For the constant trapping temperature case the modified equation can be stated as

$$\frac{c - c_t}{c_i - c_t} = e^{-(\frac{w}{W})t\alpha} \tag{4}$$

For the constant impurity removal rate case the modified equation is

$$c - c_t = \frac{\alpha}{a}(c_i - c_m) \tag{5}$$

Most cold traps do not have sufficient instrumentation to solve the trap efficiency equation directly. However, efficiency can be approximated if the main stream plugging temperature and cold trap trapping temperature are known.

Main stream plugging temperature and trapping temperature correlate with c_i and c_t, respectively.

The quantity $(c_i - c_o)$ can be approximated as follows, assuming the trap is operating at equilibrium conditions with a constant impurity removal rate over some time period, t :

Let c_1 = concentration in main stream at $t = 0$.

and c_2 = concentration in main stream at $t = t$.

Then there is a reduction of impurity in the main stream equal to

$$\Delta I = \frac{W}{t}(c_1 - c_2)\ \frac{\text{lbs}}{\text{hr}} .$$

At the same time there is an increase of impurity in the trap equal to

$$\Delta I = w(c_i - c_o)\ \frac{\text{lbs}}{\text{hr}} .$$

Equating the two expressions of ΔI yields

$$\frac{W}{t}(c_1 - c_2) = w(c_i - c_o)$$

Therefore efficiency can be calculated as

$$\alpha = \frac{W}{wt}\ \frac{(c_1 - c_2)}{(c_i - c_t)} \qquad (6)$$

where c_i can be either c_1 or c_2, with small loss in accuracy.

Precipitation and Dissolution

Oxide precipitation in a cold trap can be considered a two step process. The first step consists of mass transfer from the bulk sodium to a very thin layer of sodium adjacent to a solid surface or to a sodium monoxide crystal. This layer is supersaturated to some degree with oxygen. The second step involves deposition of sodium monoxide molecules from the supersaturated layer onto growing crystals or other solid surfaces.

The presence of wire mesh or other foreign objects in the cold trap increases the precipitation surface area, provides favorable sites for nucleation, and decreases the hydraulic diameter. However, it has been clearly shown that wire mesh is not necessary for precipitation. Many traps do not have mesh packing in the cooling channel where saturation temperature is reached and initial precipitation occurs.

Dissolution is the process of re-entry of sodium oxide into solution, Precipitation and dissolution are reversible reactions. McPheeters (18) reports the difference between the forward and back reaction activation energies is equal to the enthalpy of solution of Na_2O in sodium. That is,

$$\Delta H = E_p - E_d .$$

The same reference (18) reports values of

$$E_{precipitation} = 3 \text{ k cal/mole}$$
$$E_{dissolution} = 19 \text{ k cal/mole}$$
$$\Delta H_{solution} = 16 \text{ k cal/mole} .$$

The considerably greater activation energy of dissolution provides an explanation for the observation that oxide tends to remain at its point of precipitation. This ability to retain impurities allows thermal cycling of a cold trap without excessive reintroduction of oxide into the sodium when trapping temperature is raised to process a more highly contaminated stream.

Cold Trap Capacity

Of all cold trap operating characteristics, capacity for retaining impurities is perhaps the most important, for retention capacity determines trap life. Retention capacity is also the least understood and controlled cold trap characteristic. Experience in operating cold traps in working systems has shown that the main problem is increasing oxide retention and extending trap life.

Ultimate capacity of a trap can be described as total free volume. However, this goal has never been achieved. Practical end of life occurs when plugging, localized or general, interrupts sodium flow and/or an acceptable flow rate cannot be maintained with the available supply pressure.

A number of expended cold traps have been dismantled. Reports of oxide distribution in expended traps (10, 21, 25) generally agree that the highest concentrations of oxide are found near the inlet and in the first few inches of mesh packing.

Sodium oxide deposits in a loose matrix with metallic sodium. Hinze (10) reports the composition of the deposits in an SRE trap as 22 wt% sodium metal and 78 wt% Na_2O, with an apparent density of 0.0208 lb Na_2O/in^3. An MSA trap was cored (21) and the same type of deposit found, with the Na_2O content being 67%. The British (25) also found a sodium/sodium oxide mixture with an Na_2O content of approximately 50%.

Billuris (1) reported an achievable trap capacity of 16-20% volume sodium oxide. Tests on SRE cold traps indicate capacities in the order of 14 vol% are attainable (11). The Russians (24) report the first increase in hydraulic resistance occurs when the oxide content reaches 15-20% of the free volume of the trap.

There are no reports of any operating cold traps reaching the oxide retention capacity cited in the previous paragraph. British traps have usually plugged when only a small proportion of their volume, in the order of 1%, had filled with oxide (25). However, in one unusual case a capacity of 13% was achieved.

Oxide content of American traps, at time of abandonment, has normally been in the range of 1-6% of the free volume of the trap.

While no consensus exists on how to maximize cold trap capacity, several principles are generally accepted. These include:

1. Use of wire mesh packing improves retention capacity
2. Wide flow passages are desirable
3. A high degree of sub-cooling below saturation temperature is undesirable.

Cold Trap Control

Cold trap control technology is rudimentary. Generally, trapping temperature is the only controlled variable. This is usually achieved by varying coolant flow or trap flow, or both.

The single variable (T_t) control technique sacrifices control of the temperature profile in the trap to trap geometry. Some additional measure of temperature profile control can be obtained by varying trap flow as well as coolant flow. However this may be undesirable if it reduces trapping rate.

Hinze (9) reports difficulty in maintaining a constant trapping temperature by varying coolant flow during fluctuations in main stream flow rate in operations at Hallam.

Simmons describes an economizer by-pass control scheme in reference 23. Economizer by-pass allows control of trap section inlet temperature without dependence on trap flow rate to regulate the intratrap temperature profile.

This increased degree of control sophistication appears to have merit, but so far has not been incorporated in any operating traps.

III. THERMAL ANALYSIS

The mathematical model of cold trap performance used in this thesis has been developed over the past decade by several authors.

The first of several publications was by Hoschouer and Casey (11) in 1961. A more detailed analysis was published by Simmons (23) in 1965. More recently MSA (21) has used the same analytical technique in a report on thermal behavior of cold traps. Of the three published works, the Simmons report is the most complete.

The entire analysis is based on the fundamental equations of heat transfer:

$$Q = Wc_p \Delta T \qquad \text{and}$$

$$Q = UA\Delta T_m$$

The present state of cold trap development does not support a more sophisticated approach.

The model is based on heat transfer in a three fluid system separated by two concentric cylinders with insulated end closures. In addition, the following assumptions are made:

- temperature does not vary across width of a channel
- steady state flow and thermal equilibrium
- constant specific heats

A schematic diagram of the type of cold trap being considered is shown in Figure 4 on the following page.

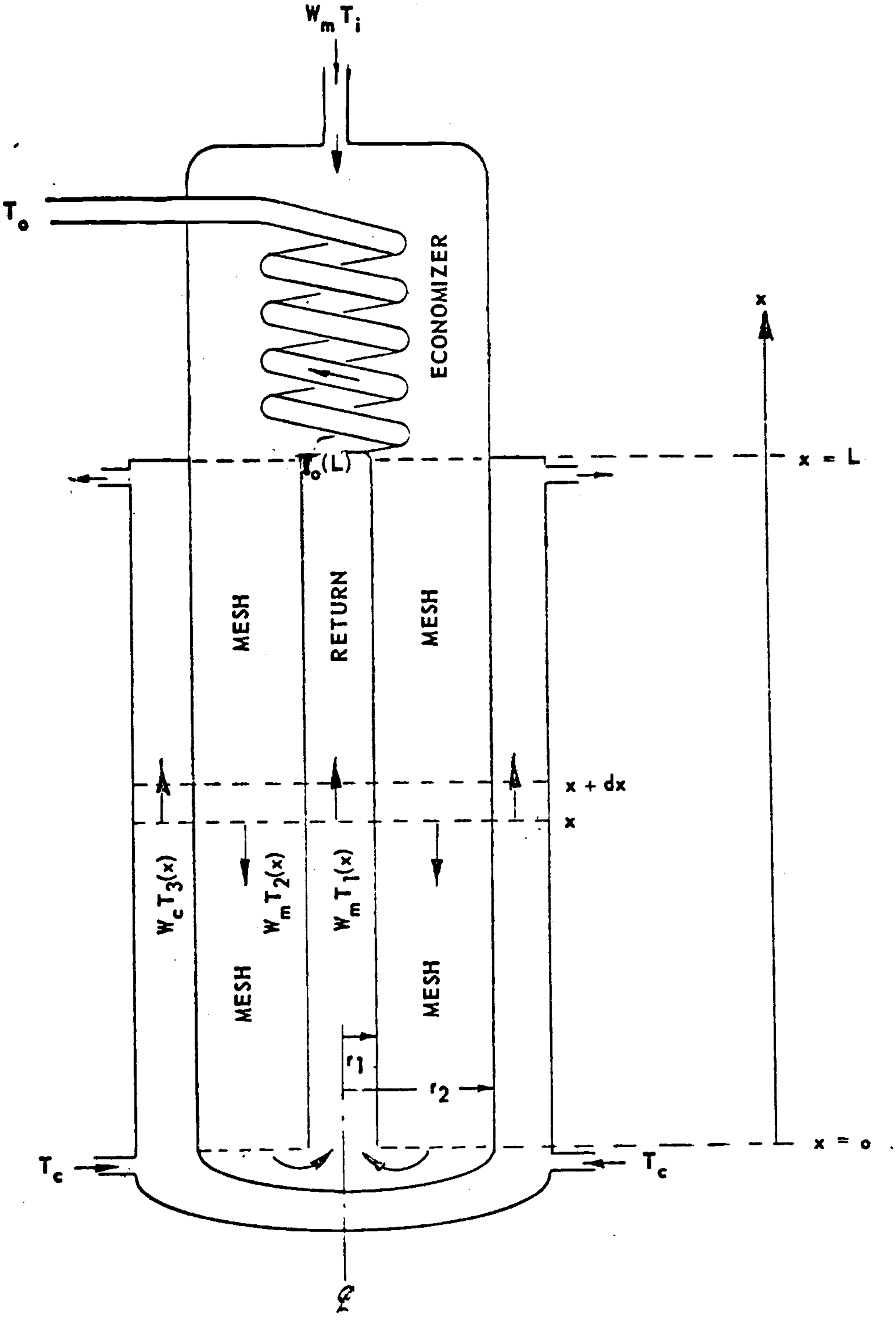

Figure 4. Schematic of a Cold Trap

Consider first the basic trap section, without economizer. Sodium enters the top of the annulus at some temperature $T_2(L)$, passes through the annulus and return channel and leaves at a lower temperature, $T_1(L)$. A coolant stream, at temperature T_c, enters the lower end of a jacket surrounding the trap and leaves at the top of the jacket at temperature $T_3(L)$.

The following dimensionless combinations are used to reduce labor in calculations:

$$k_1 = \frac{2\pi r_1 U_1 L}{W_m C_m} \qquad k_2 = \frac{r_2 U_2}{r_1 U_1}$$

$$k_3 = \frac{W_m C_m}{W_c C_c} \qquad k_4 = \frac{U_e A_e}{W_m C_m}$$

These dimensionless combinations are ratios of five heat transfer capacities in the trap:

- The main stream, $W_m C_m$
- The coolant, $W_c C_c$
- The economizer (when used), $U_e A_e$
- The wall between the annulus and return channel, $2\pi r_1 U_1 L$
- The wall between the coolant and annulus, $2\pi r_2 U_2 L$

Differential Equations of Temperature Profile

The heat balance between the annulus and return channel across the axial differential element dx in the return channel can be expressed as:

$$W_m C_m dT_1(x) = U_1(2\pi r_1 dx)\,(T_2(x) - T_1(x)) \qquad \text{(a)}$$

or

$$\frac{dT_1}{dx} = \frac{2\pi r_1 U_1 (T_2(x) - T_1(x))}{W_m C_m} \qquad \text{(b)}$$

Introducing the dimensionless combination k_1 into equation (b) yields:

$$L\,\frac{dT_1(x)}{dx} = k_1(T_2(x) - T_1(x)) \qquad (1)$$

Similarly the temperature in the annulus, $T_2(x)$, and the coolant temperature, $T_3(x)$ can be expressed as:

$$L\,\frac{dT_2(x)}{dx} = k_1(T_2(x) - T_1(x)) + k_1 k_2 (T_2(x) - T_3(x)) \qquad (2)$$

$$L\,\frac{dT_3(x)}{dx} = k_1 k_2 k_3 (T_2(x) - T_3(x)) \qquad (3)$$

Rearranging equation (1) it is possible to express $T_2(x)$ in terms of $T_1(x)$ as:

$$T_2(x) = T_1(x) + \frac{L\,dT_1(x)}{k_1\,dx} \qquad (4)$$

Combining equations (1), (2) and (3) yields an expression of $T_3(x)$ as a function of $T_1(x)$ and $T_2(x)$.

$$\frac{dT_3(x)}{dx} = k_3 \left[\frac{dT_2(x)}{dx} - \frac{dT_1(x)}{dx} \right]. \tag{5}$$

Upon integration, equation (5) becomes:

$$T_3(x) = k_3 \, [T_2(x) - T_1(x)] + C \, . \tag{a}$$

Boundary conditions at $x = 0$ are:

$$T_3(0) = T_c$$

$$T_1(0) = T_2(0) \, ,$$

assuming no heat loss through bottom of trap.

Therefore at $x = 0$, equation (a) is:

$$T_c = k_3 \, [T_1(0) - T_1(0)] + C$$

or,

$$T_c = C = \text{constant of integration,}$$

and equation (a) can be stated as:

$$T_3(x) = k_3 \, [T_2(x) - T_1(x)] + T_c \, . \tag{6}$$

Substituting equations (4) and (6) into equation (2) produces a linear, second order non-homogenous differential equation involving only $T_1(x)$ as an unknown function of x:

$$L^2 \frac{d^2T_1}{dx^2} + Lk_1k_2(k_3 - 1)\frac{dT_1}{dx} - k_1^2k_2(T_1 - T_c) = 0. \tag{7}$$

Equation (7) has a solution of the form:

$$T_1(x) = C_1e^{\lambda_1k_1x/L} + C_2e^{\lambda_2k_1x/L} + T_c \tag{a}$$

where C_1 and C_2 are arbitrary, and λ_1 and λ_2 are solutions of the auxiliary equation such that:

$$\lambda_1 = \frac{1}{2}\left[k_2(1 - k_3) + \sqrt{k_2^2(1 - k_3)^2 + 4k_2}\right] \tag{8}$$

$$\lambda_2 = \frac{1}{2}\left[k_2(1 - k_3) - \sqrt{k_2^2(1 - k_3)^2 + 4k_2}\right]. \tag{9}$$

At the boundary condition $x = 0$ equation (a) becomes

$$T_1(0) = C_1 + C_2 + T_c, \tag{b}$$

and since the temperature of T_1 at $x = 0$ is defined as the trapping temperature, T_t, the above equation becomes:

$$T_t = C_1 + C_2 + T_c, \tag{c}$$

or

$$T_t - T_c = C_1 + C_2 \tag{d}$$

Also at $x = 0$ the derivative of T with respect to x equals 0 since there is no heat transfer at this point. This fact further defines C_1 and C_2 and leads to the solution of equation (7) in closed form.

$$T_1(x) = (T_t - T_c)\left[\frac{-\lambda_2}{\lambda_1 - \lambda_2}e^{\lambda_1k_1x/L} + \frac{\lambda_1}{\lambda_1 - \lambda_2}e^{\lambda_2k_1x/L}\right] + T_c \tag{10}$$

Using this definition of $T_1(x)$ in equations (4) and (6) yields

$$T_2(x) = (T_t - T_c)\left[-\frac{\lambda_2(1+\lambda_1)}{\lambda_1-\lambda_2} e^{\lambda_1 k_1 x/L} + \frac{\lambda_1(1+\lambda_2)}{\lambda_1-\lambda_2} e^{\lambda_2 k_1 x/L} \right] + T_c \tag{11}$$

$$T_3(x) = (T_t - T_c)\left[\frac{-(\lambda_1+\lambda_2+\lambda_1\lambda_2)}{\lambda_1 - \lambda_2} (e^{\lambda_1 k_1 x/L} - e^{\lambda_2 k_1 x/L}) \right] + T_c \tag{12}$$

Temperatures at $x = L$

At the top of the trap (i. e., $x = L$) equations (10), (11), and (12) reduce to:

$$T_1(L) = \frac{(T_t-T_c)}{\lambda_1-\lambda_2}\left[-\lambda_2 e^{\lambda_1 k_1} + \lambda_1 e^{\lambda_2 k_1} \right] + T_c \tag{10a}$$

$$T_2(L) = \frac{(T_t-T_c)}{\lambda_1-\lambda_2}\left[-\lambda_2(1+\lambda_1)\, e^{\lambda_1 k_1} + \lambda_1(1+\lambda_2) e^{\lambda_2 k_1} \right] + T_c \tag{11a}$$

$$T_3(L) = \frac{(T_t-T_c)}{\lambda_1-\lambda_2}\left[-(\lambda_1+\lambda_2+\lambda_1\lambda_2)(e^{\lambda_1 k_1} - e^{\lambda_2 k_1}) \right] + T_c \tag{12a}$$

Trapping Temperature

Equations (10), (11), and (12) require the value of the trapping temperature, T_t, for direct solution. The trapping temperature is normally more difficult to measure than stream temperatures, and therefore it is desirable to calculate T_t in terms of main stream and coolant inlet temperature.

For the basic trap without economizer being considered, T_i, the main stream inlet temperature is obviously equal to $T_2(L)$. From equation (11a)

$$T_2(L) = \frac{T_t - T_c}{\lambda_1 - \lambda_2}\left[-\lambda_2(1+\lambda_1)e^{\lambda_1 k_1} + \lambda_1(1+\lambda_2)e^{\lambda_2 k_1}\right] + T_c \qquad (11a)$$

Letting the quantity inside the brackets be temporarily identified as $g(x)$, equation (11a) becomes

$$T_i = (T_t - T_c)\frac{g(x)}{\lambda_1 - \lambda_2} + T_c \qquad (a)$$

$$T_i - T_c = (T_t - T_c)\frac{g(x)}{\lambda_1 - \lambda_2} \qquad (b)$$

$$T_t - T_c = (T_i - T_c)\frac{\lambda_1 - \lambda_2}{g(x)} \qquad (c)$$

So that

$$T_t = (T_i - T_c)\left[\frac{\lambda_1 - \lambda_2}{-\lambda_2(1+\lambda_1)e^{\lambda_1 k_1} + \lambda_1(1+\lambda_2)\,e^{\lambda_2 k_1}}\right] + T_c \qquad (13)$$

Alternate Mathematical Notation

Alternative mathematical notation can be introduced to state the trap temperature profile relations more compactly. Let

$$f_a = (\alpha, \lambda_1, \lambda_2)$$

where a is an index and α is a dummy argument. Then for the purpose of this work one may substitute $\frac{k_1 x}{L}$ for the dummy α and assign values to the functions as follows:

$$f_1(\alpha, \lambda_1, \lambda_2) = \frac{1}{\lambda_1 - \lambda_2} (-\lambda_2 e^{\lambda_1 \alpha} + \lambda_1 e^{\lambda_2 \alpha}), \tag{14}$$

$$f_2(\alpha, \lambda_1, \lambda_2) = \frac{-\lambda_1 \lambda_2}{\lambda_1 - \lambda_2} (e^{\lambda_1 \alpha} - e^{\lambda_2 \alpha}) \tag{15}$$

In terms of these functions, the solutions to equations (10), (11), and (12) become

$$T_1(x) = (T_t - T_c)\, f_1(k_1 x/L,\ \lambda_1, \lambda_2) + T_c \tag{10b}$$

$$T_2(x) = (T_t - T_c)\, [f_1(k_1 x/L,\ \lambda_1, \lambda_2) + f_2(k_1 x/L,\ \lambda_1, \lambda_2)] + T_c \tag{11b}$$

$$T_3(x) = (T_t - T_c)\, k_3 f_2(k_1 x/L,\ \lambda_1, \lambda_2) + T_c \tag{12b}$$

And temperatures at $x = L$ can be stated as:

$$T_1(L) = (T_t - T_c)\, f_{1L} + T_c \tag{10c}$$

$$T_2(L) = (T_t - T_c)\, (f_{1L} + f_{2L}) + T_c \tag{11c}$$

$$T_3(L) = (T_t - T_c)\, k_3 f_{2L} + T_c \tag{12c}$$

where

$$f_{1L} = f_1(k_1, \lambda_1, \lambda_2) \text{ and } f_{2L} = f_2(k_1, \lambda_1, \lambda_2)\,.$$

The value and use of such notation will be demonstrated in subsequent sections.

Trap With Coupled Economizer

This section will consider the effect of a coupled economizer of the general type shown in Figure 4.

In this case the heat exchange and temperature profile relations developed for the basic trap are applicable, but the effect of the economizer on trap boundary conditions must be considered.

Consider heat exchange in the economizer. On the shell side

$$Q_s = W_m C_m (T_i - T_{2L}) \qquad \text{(a)}$$

And on the tube side

$$Q_t = W_m C_m (T_o - T_{1L}) \qquad \text{(b)}$$

Since $Q_s = Q_t$, it follows that

$$T_i - T_{2L} = T_o - T_{1L} ,$$

or

$$T_i - T_o = T_{2L} - T_{1L} \qquad (16)$$

Q_t can also be expressed as

$$Q_t \doteq U_e A_e \Delta t_m \qquad \text{(c)}$$

where Δt is the mean temperature difference. When temperature differences are not large the arithmetic mean temperature difference may be substituted for the log mean temperature difference normally used with small loss in accuracy.

Using an arithmetic temperature difference, equation (c) can be expressed as

$$Q_t = U_e A_e \frac{1}{2}[(T_i + T_{2L}) - (T_{1L} + T_o)] \qquad \text{(d)}$$

Equating equations (a) and (d) yields

$$T_i - T_{2L} = \frac{U_e A_e}{W_m C_m} \cdot \frac{1}{2}[(T_i + T_{2L}) - (T_{1L} + T_o)] \qquad \text{(e)}$$

Since

$$k_4 = \frac{U_e A_e}{W_m C_m}$$

it follows that

$$T_i - T_{2L} = \frac{k_4}{2}[(T_i + T_{2L}) - (T_{1L} + T_o)] \qquad (17)$$

Relation of Economizer and Trap Temperatures

T_{1L} and T_{2L} have been previously defined in equations (10a) and (11a). Subtracting equation (10a) from (11a) and equating the result with the left hand side of equation (16) yields

$$T_i - T_o = (T_t - T_c)\left(\frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}\right)\left(e^{\lambda_2 k_1} - e^{\lambda_1 k_1}\right) \qquad (18)$$

Let $\alpha = k_1$ at $x = L$, such that in equation (15)

$$f_{2L} = \frac{-\lambda_1\lambda_2}{\lambda_1-\lambda_2}(e^{\lambda_1 k_1} - e^{\lambda_2 k_1})$$

Then by reversal of signs in the second and third brackets of equation (18) these quantities equal f_{2L} and equation (18) can be restated as

$$T_i - T_o = (T_t - T_c)f_{2L} \tag{19}$$

and,

$$T_o = T_i - (T_t - T_c)f_{2L} \tag{19a}$$

From equation (16)

$$T_o = T_i - T_{2L} + T_{1L} \tag{a}$$

Combining (a) with equation (17) yields

$$T_i = T_{2L} + k_4(T_{2L} - T_{1L}) \tag{20}$$

Further,

$$T_o = T_{1L} + k_4(T_{2L} - T_{1L}) \tag{21}$$

Combining and rearranging equations (16), (20) and (21) produce the following expressions of temperatures at $x = L$

$$T_{1L} = T_i - (T_i - T_o)(1 + k_4) \tag{22}$$

$$T_{2L} = T_i - k_4(T_i - T_o) \tag{23}$$

$$T_{3L} = T_c + k_3(T_i - T_o) \tag{24}$$

Calculation of Trapping Temperature with Economizer

Calculation of trapping temperature for a cold trap with an economizer requires some modification of equation (13) developed for the basic trap. T_{2L} must be substituted for T_i in equation (13) since T_{2L} is now the inlet temperature to the trap section. Equation (13) now becomes

$$T_t = (T_{2L} - T_c)\left[\frac{\lambda_1 - \lambda_2}{-\lambda_2(1+\lambda_1)e^{\lambda_1 k_1} + \lambda_1(1+\lambda_2)e^{\lambda_2 k_1}}\right] + T_c \qquad (25)$$

The mathematical model described in this section has been coded for computer solution. The computer program is described in Appendix I.

The computer code was tested by calculating the sample cases in references 21 and 23. In every case the results calculated duplicated the values reported in references 21 and 23.

IV. COLD TRAP DESIGN

A cold trap should be designed to reduce the temperature of sodium below the saturation temperature of impurities present in the stream; control impurity level in the sodium system; provide sufficient residence time for precipitation; and provide sufficient volume and impurity retention capacity for a long service life.

The most significant design decisions to be made are:

- trap volume and dimensions,
- selection of coolant,
- range and rate of cooling,
- packing material selection and distribution.

Trap Volume and Dimensions

Principal considerations in determining cold trap size are:

- fraction of system volume to be trapped per unit time,
- desired residence time of fluid in trap,
- amount and distribution of heat transfer surface required.

A cold trap must be of sufficient size to provide desired residence time and trapping rate. Residence time and trapping rates are discussed in Section II of this thesis. The design flow rate is normally in the range of 0.2-0.4 percent of the system volume per minute, and residence time in the order of 5-15 minutes. A design residence of 5 minutes is favored in the United States. A longer time is preferred in Europe.

Required heat transfer surface influences cold trap size. Gas cooled traps will normally be larger than liquid metal cooled traps, because of the lower gas heat transfer coefficient and consequence need for greater surface area for a given heat transfer requirement.

If a single trap is greater than optimum handling size or presents shielding difficulties the designer has the option of using multiple traps for a single service. Multiple traps present the problems associated with parallel flow, however.

For a given trap volume the principal sizing decisions are the length-to-diamter (L/D) ratio and the diameter of the return channel.

Most liquid cooled American traps have an L/D ratio near one. Gas cooled traps normally have a larger L/D ratio to provide greater external heat transfer surface.

The selection of an L/D ratio near one has been accepted because of favorable operating results, and in the case of the EBR traps as a result of unpublished optimization studies.

Most American traps have a return pipe diameter which provides near equal cross sectional area in the annulus and return channel. A notable exception are MSA designed traps which have a very narrow (1/2"-1") annulus.

The equal area concept provides equal velocity in the annulus and return channel and appears to reduce the tendency for plugging.

Selection of Coolant

A number of coolants have been used in cold traps, but at present only two enjoy favor:

- liquid metal
- gas (air or nitrogen)

The liquid metal generally used is a sodium-potassium (NaK) alloy of near-eutetic composition (78% Na 22% K). The advantage of NaK over sodium is its lower freezing temperature (~ 10° F). Since it is necessary to reduce the sodium temperature in the trap to near its freezing point to achieve a low oxide concentration, use of sodium as a coolant would require low temperature differences and delicate control of coolant temperature and flow. Use of NaK, therefore, provides a greater flexibility in selection of temperature range.

Gas cooled traps normally have longitudinal external fins to increase heat transfer. Standard heat transfer correlations can be used to predict heat transfer from liquid metal in the trap to the gas coolant. An overall heat transfer coefficient in the range of 12-20 Btu/hr-ft^2-° F for turbulent gas flow over external fins, based on inside surface area, can be expected.

The selection of a heat transfer coefficient for liquid metal cooling of a cold trap is more complicated than for gas cooling. Simmons (23) suggests, without substantiation, a design value of 60 Btu/hr-ft^2-° F. Experimental work done as a part of this study indicate the value may vary from 20 to over 200 Btu/hr-ft^2-° F, depending on flow conditions.

Oxide build-up on the internal surfaces of a cold trap undoubtedly reduces the effectiveness of heat transfer. Subbotin (24) reports that in liquid metal cooled cold traps the reduction in heat exchange from initial to equilibrium performance is a factor of 1.5-2.

In gas cooled traps the effect of internal oxide buildup on the overall heat transfer coefficient is much less pronounced because of the controlling properties of the gas film coefficient.

The cold trap designer should recognize that a "fouling factor" must be included in much the same manner as it is in industrial heat exchange design. Unfortunately, there is much less experience on which to base the cold trap fouling factor than is available in industrial practice.

There is no published quantative information known to the author on the effect of oxide buildup on heat transfer. Billuris (1) gives a method of estimating oxide thickness in reporting his "cold finger" experiment. However, nothing is mentioned in reference 1 about the relation between oxide thickness and heat transfer resistance.

As a consequence of lack of study and/or published information on heat transfer the liquid metal cooled cold trap designer is forced to make an educated guess of the value of the heat transfer coefficient under equilibrium conditions. A value in the range of 75-150 Btu/hr-ft^2-° F is recommended.

Range and Rate of Cooling

Heat must be removed in the trap to achieve the degree of supersaturation necessary for precipitation of impurities. Trap flow rate, inlet temperature and desired impurity level fix the cooling rate.

Heat is removed from the entering sodium by exchanging heat with sodium leaving the trap and/or by rejecting heat to an external coolant, to the point where the sodium temperature is lowered to the required level for oxide precipitation.

Coolant inlet temperature must be low enough to provide sufficient temperature difference for adequate heat transfer at the design minimum trapping temperature. The design minimum trapping temperature is usually around 250° F and a coolant inlet temperature of ~ 100° F is often specified.

For air cooled traps the coolant inlet temperature is usually ambient and the 100° F level is easily achieved. However, for closed cooling systems (nitrogen, NaK) the heat sink temperature, temperature rise in the sink fluid, and temperature difference necessary in the heat exchange between trap coolant and sink impose restrictions on minimum trap coolant temperature. Cold trap coolants operating in a closed cycle usually enter the trap cooling jacket at around 115-125° F.

Coolant temperature rise in the cooling jacket is determined by coolant heat transfer coefficient and flow rate, heat transfer surface, and sodium temperature and flow rate. Coolant outlet temperature can be controlled by a varying coolant flow rate if needed.

An economizer is a desirable heat recovery device for traps operating with a sodium inlet temperature of less than 600-650° F. Above this inlet temperature level an economizer is a practical necessity.

Page 49 reports operation of the FFTF cold trap without an economizer. The minimum trapping temperature that can be achieved in this trap is 600° F, with infinite coolant flow.

Several economizer configuration options are open to the designer. Two of these are: an economizer coil in the cold trap shell, shown schematically in Figure 4; and a shell-and-tube heat exchanger separated from the trap. The Hallam trap is an example of the first type, and the Fermi trap is an example of the second type.

The Hallam coil economizer in a pool of incoming sodium eliminates narrow flow passages which are potential plugging sites, at some sacrifice in heat exchange coefficient. The integral economizer must usually be abandoned with the trap at end of trap life.

The separate shell-and-tube economizer has a higher heat exchange potential and probably, longer life than the coil type. However, this type of trap must be protected from plugging as a result of premature oxide precipitation in the economizer.

The economizer sodium-to-sodium heat exchange coefficient may vary over a wide range. In the eight test runs on the HTL trap reported in Section V, U_e varied from 200 to 2280 Btu/hr-ft^2-°F. Simmons (23) recommends a coefficient of 1000. Atomics International designers favor coefficients of <1000. The Hallam trap evaluation (5) reports a U_e of 353. A recent AI design (27) is based on U_e = 780.

An economizer heat exchange coefficient in the range of 1000-1300 Btu/hr-ft^2-°F is recommended.

Economizer size has a significant effect on overall cold trap operation. The FFTF cold trap will have an economizer of 160 ft^2. The expected operating conditions of such a trap are shown on page 46.

If the economizer size is reduced to 150 ft^2 it will be necessary to increase trap length from 3.67 to 4.25 feet and coolant flow from 92 to 105 gal/min to maintain design trapping temperature. A further reduction of economizer size to 130 ft^2 requires a trap length of 4.75 ft and coolant flow of 110 gal/min to achieve the design trapping temperature.

The balance between economizer and cooling jacket heat exchange surface is complex and no clear rules have been defined within the present state of cold trap design art.

Packing Material

Packing material is not a fundamental component of a cold trap. However, most investigators agree that the presence of wire mesh or other high surface objects increases trap effectiveness. Lauben (14) reports work on Hallam traps showed that the trapping rate of a packless trap was only 1/3 as great as the mesh type trap subsequently used.

A number of packing materials have been tested in cold trap service. Billuris (1) and others have demonstrated the superiority of stainless steel wire mesh over raschig rings or mesh screen types of packing in trapping and retaining precipitated impurities.

While there is general agreement on the desirability of using wire mesh, there is little agreement on the questions of distribution and density. Many traps have mesh in the return channel, with the annulus clear. However, this distribution was reversed in the Hallam trap. Specifications for FFTF traps require mesh in both the annulus and return channel.

The mesh used to date has a wire diameter of 4 to 6 mils and reported density has varied over a range of 24 to 2.5 lb/ft^3. SRE trap mesh had a density of 24 lb/ft^3. The density of early KAPL traps was about 20 lb/ft^3. FFTF trap density has not been fixed, but a figure near 15 lb/ft^3 is favored.

Billuris (1) used mesh with densities of 7.9 and 2.6 lb/ft^3 and reported more favorable results with the lower density material.

It seems reasonable to consider a two zone packing arrangement. A stainless steel mesh with a density in the range of 4-8 lb/ft^3 and a wire diameter of 6 mils is recommended for the cooling annulus where the largest amount of precipitation can be expected to occur. In the return channel the density can be increased to 10-15 lb/ft^3, maintaining the 6 mil wire diameter, to provide a greater degree of filtering in a relatively oxide free sodium stream.

Design Exercise

A key element of the AEC's LMFBR development program is the Fast Flux Test Facility (FFTF) being constructed near Richland, Washington.

A two trap configuration is planned for the FFTF primary system. Both traps will be operated in parallel during initial cleanup and after opening the reactor cover. During reactor operation, it is expected that single trap operation will be sufficient to maintain system oxide concentration at an acceptably low level.

Table 1. FFTF Primary System Cold Trap Design Conditions

System Sodium Mass		1,000,000 lb
Temperatures		
Economizer Inlet		1050 °F
Trapping Temperature		250 °F
Coolant Inlet		125 °F
Flow Rates		
Trap	60 gpm @275 °F = 27500 lb/hr	
Coolant	92 gpm @150 °F = 39975 lb/hr	
Residence Time		5 min
Heat Transfer Coefficients (Btu/hr-ft^2-°F)		
Internal Wall		120
External Wall		60
Economizer		1,000

An analysis of cold trap operation at design conditions is shown on the following page. Page 47 shows conditions to be expected during a cleanup operation prior to assent to power, with an inlet temperature of 450° F.

Design flow rate, for two trap operation, is about 0.09% of system volume per minute. This is considerably lower than the trapping capacity of other liquid sodium loops operated in the United States.

The design heat transfer coefficients appear low. Heat transfer coefficients for the two traps tested for this thesis often exceeded the

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                  RESULTS OF COLD TRAP
                    THERMAL ANALYSIS

CASE NUMBER                      DESIGN CASE     1301
CONFIGURATION                  TRAP WITH ECONOMIZER

TEMPERATURES   DEG F             INLET         OUTLET
    MAIN STREAM                  1050.          1009.
    COOLANT                       125.           164.
TRAPPING TEMPERATURE                             263.    DEG F

INTERIOR HEAT TRANSFER COEFFICIENT             120.00
EXTERIOR HEAT TRANSFER COEFFICIENT              60.00

FLOW THROUGH TRAP                              27500.    LB/HR
COOLANT FLOW                                   39975.    LB/HR

COOLANT    DUTY                               357548.    BTU/HR
ECONOMIZER DUTY                              6500883.    BTU/HR

LENGTH OF TRAP                                   3.67    FEET
DIAMETER OF TRAP                                 3.67    FEET
DIAMETER OF RETURN PIPE                          2.56    FEET

ECONOMIZER HEAT TRANSFER SURFACE               160.00    SQ FT
ECONOMIZER HEAT TRANSFER COEFFICIENT          1000.00

TEMPERATURE PROFILE        DEG F
     X          RETURN        ANNULUS        COOLANT
    .18          263.          265.           127.
    .37          263.          267.           129.
    .55          263.          269.           131.
    .73          263.          271.           133.
    .92          263.          273.           135.
   1.10          263.          275.           137.
   1.28          264.          277.           139.
   1.47          264.          280.           140.
   1.65          264.          282.           142.
   1.83          265.          285.           144.
   2.02          265.          287.           146.
   2.20          265.          289.           148.
   2.39          266.          292.           150.
   2.57          266.          295.           152.
   2.75          267.          297.           154.
   2.94          268.          300.           156.
   3.12          268.          303.           158.
   3.30          269.          306.           160.
   3.49          270.          308.           162.
   3.67          271.          311.           164.
```

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                    RESULTS OF COLD TRAP
                      THERMAL ANALYSIS

CASE NUMBER                     STARTUP CASE     1302
CONFIGURATION                 TRAP WITH ECONOMIZER

TEMPERATURES    DEG F           INLET          OUTLET
    MAIN STREAM                  450.            440.
    COOLANT                      125.            258.
TRAPPING TEMPERATURE                             250.     DEG F

INTERIOR HEAT TRANSFER COEFFICIENT             120.00
EXTERIOR HEAT TRANSFER COEFFICIENT              60.00

FLOW THROUGH TRAP                              27500.     LB/HR
COOLANT FLOW                                    3000.     LB/HR

COOLANT    DUTY                                90518.     BTU/HR
ECONOMIZER DUTY                              1645777.     BTU/HR

LENGTH OF TRAP                                   3.67     FEET
DIAMETER OF TRAP                                 3.67     FEET
DIAMETER OF RETURN PIPE                          2.56     FEET

ECONOMIZER HEAT TRANSFER SURFACE               160.00     SQ FT
ECONOMIZER HEAT TRANSFER COEFFICIENT          1000.00

TEMPERATURE PROFILE     DEG F
     X          RETURN       ANNULUS         COOLANT
    .18          250.          251.            146.
    .37          250.          253.            164.
    .55          250.          254.            179.
    .73          250.          255.            192.
    .92          250.          256.            203.
   1.10          250.          257.            212.
   1.28          250.          258.            220.
   1.47          250.          258.            226.
   1.65          251.          259.            232.
   1.83          251.          259.            236.
   2.02          251.          260.            240.
   2.20          251.          260.            244.
   2.39          251.          261.            247.
   2.57          251.          261.            249.
   2.75          252.          261.            251.
   2.94          252.          262.            253.
   3.12          252.          262.            254.
   3.30          252.          262.            256.
   3.49          252.          263.            257.
   3.67          253.          263.            258.
```

```
                    RESULTS OF COLD TRAP
                      THERMAL ANALYSIS

CASE NUMBER          HIGH HEAT TRANSFER CASE  1304
CONFIGURATION                  TRAP WITH ECONOMIZER

TEMPERATURES   DEG F           INLET        OUTLET
    MAIN STREAM                1050.         1018.
    COOLANT                     125.          271.
TRAPPING TEMPERATURE                          251.     DEG F

INTERIOR HEAT TRANSFER COEFFICIENT          120.00
EXTERIOR HEAT TRANSFER COEFFICIENT          120.00

FLOW THROUGH TRAP                           27500.     LB/HR
COOLANT FLOW                                 8500.     LB/HR

COOLANT    DUTY                            282278.     BTU/HR
ECONOMIZER DUTY                           6672033.     BTU/HR

LENGTH OF TRAP                                3.67     FEET
DIAMETER OF TRAP                              3.67     FEET
DIAMETER OF RETURN PIPE                       2.56     FEET

ECONOMIZER HEAT TRANSFER SURFACE            160.00     SQ FT
ECONOMIZER HEAT TRANSFER COEFFICIENT       1300.00

TEMPERATURE PROFILE     DEG F
     X          RETURN        ANNULUS        COOLANT
     .18         251.          255.           141.
     .37         252.          258.           155.
     .55         252.          261.           168.
     .73         252.          264.           180.
     .92         252.          266.           190.
    1.10         252.          269.           200.
    1.28         253.          271.           208.
    1.47         253.          273.           216.
    1.65         254.          275.           223.
    1.83         254.          277.           230.
    2.02         255.          279.           236.
    2.20         255.          281.           241.
    2.39         256.          282.           246.
    2.57         256.          284.           251.
    2.75         257.          285.           255.
    2.94         257.          287.           259.
    3.12         258.          288.           262.
    3.30         258.          289.           265.
    3.49         259.          291.           268.
    3.67         260.          292.           271.
```

```
                    RESULTS OF COLD TRAP
                      THERMAL ANALYSIS

CASE NUMBER                 NO ECONOMIZER CASE   1408
CONFIGURATION               TRAP WITHOUT ECONOMIZER

TEMPERATURES   DEG F            INLET       OUTLET
    MAIN STREAM                 1050.         683.
    COOLANT                      125.         220.
TRAPPING TEMPERATURE                          616.    DEG F

INTERIOR HEAT TRANSFER COEFFICIENT          120.00
EXTERIOR HEAT TRANSFER COEFFICIENT          120.00

FLOW THROUGH TRAP                           27500.    LB/HR
COOLANT FLOW                               150000.    LB/HR

COOLANT    DUTY                           3230080.    BTU/HR

LENGTH OF TRAP                                3.67    FEET
DIAMETER OF TRAP                              3.67    FEET
DIAMETER OF RETURN PIPE                       2.56    FEET

TEMPERATURE PROFILE       DEG F
     X          RETURN       ANNULUS        COOLANT
    .18          616.          630.           129.
    .37          616.          645.           132.
    .55          617.          661.           136.
    .73          618.          677.           140.
    .92          619.          694.           144.
   1.10          621.          712.           148.
   1.28          623.          730.           153.
   1.47          625.          750.           157.
   1.65          628.          770.           162.
   1.83          631.          790.           166.
   2.02          634.          812.           171.
   2.20          638.          834.           176.
   2.39          642.          858.           181.
   2.57          647.          882.           186.
   2.75          652.          908.           191.
   2.94          657.          934.           197.
   3.12          663.          961.           202.
   3.30          669.          990.           208.
   3.49          676.         1010.           214.
   3.67          683.         1050.           220.
```

design values being considered even though the traps tested were operated at significantly lower flow rates and characteristic heat transfer number (i.e., Reynolds, Peclet) values than expected in the FFTF trap.

A parametric study of the effect of a change in the interior heat transfer coefficient, U_1, showed the trapping temperature and rate of heat rejection to coolant relatively insensitive to a change in the value of U_1 in the range of 120 to 300 Btu/hr-ft^2-°F.

A change in the exterior coefficient, U_2, however, does have a significant effect. Doubling of U_2 to 120 Btu/hr-ft^2-°F, a value which can reasonably be expected early in trap life, requires throttling coolant flow to 27.5 gal/min and increasing the coolant outlet temperature to 261° F to maintain a trapping temperature of 250° F.

In addition, if the economizer heat transfer coefficient approaches the value measured in HTL loop testing, the coolant flow rate will have to be reduced even further to maintain the desired trapping temperature.

The temperature profile of the trap with heat transfer coefficients of 120 for U_2 and 1300 for U_e is shown on page 48.

It can be concluded that the FFTF primary system cold trap is conservatively designed and will operate satisfactorily, but the temperature profile and flow rates will vary significantly from design values.

V. EXPERIMENTAL

Experimental work reported herein was conducted in the Sodium Studies Facility of the Hanford Engineering Development Laboratory at Richland, Washington.

Description of Test Apparatus

Two cold traps were tested. They are located in the Sodium Purification Loop and the Heat Transfer Loop. Each has been in operation for several years.

Sodium Purification Loop

The Sodium Purification Loop (SPL) provides the Sodium Studies Facility with a source of sodium of specified purity for FFTF program needs.

Major components of the loop are:

- A 10 gallon expansion-storage tank
- A 5 gallon mesh filled cold trap
- A 3 gallon hot trap filled with Zircaloy-2 tubing ferrules.

Other loop features are an electromagnetic (EM) pump for forced circulation, EM flowmeters for the main circulating loop and the by-pass plugging indicator loop, a coil-type air cooler and a forced-draft air cooling system for the air cooler and cold trap.

The arrangement of the loop is shown on the SPL Engineering Flow Diagram, Figure 5.

The cold trap, Figure 6, consists of a section of 8 inch pipe with a capacity of about 5 gallons. Fins on the outside of the shell increase outside surface area to promote cooling. Inside is a 16 inch long inverted bucket return channel filled with stainless steel mesh.

The trap has no economizer.

Thermocouples in the loop measure trap performance and are used to control its operation. Three thermocouples extend into the mesh bed. The lower couple is connected to the cold trap air supply damper system to control coolant flow rate. Inlet and outlet thermocouples are installed in the air duct to monitor heat rise across the trap.

A plugging indicator system is used for inline measurement of the oxide content of the flowing sodium. The plugging indicator can operate in parallel with, or independently of, the cold trap.

The hot trap is included in the loop to produce high purity sodium beyond the capability of the cold trap. The hot trap was not used in the test program being reported.

The SPL loop had been operated approximately 20,000 hours at the time the data reported herein was taken. No record of time the cold trap had been operated in the loop has been kept and no estimate of sodium oxide retained in the trap has been made.

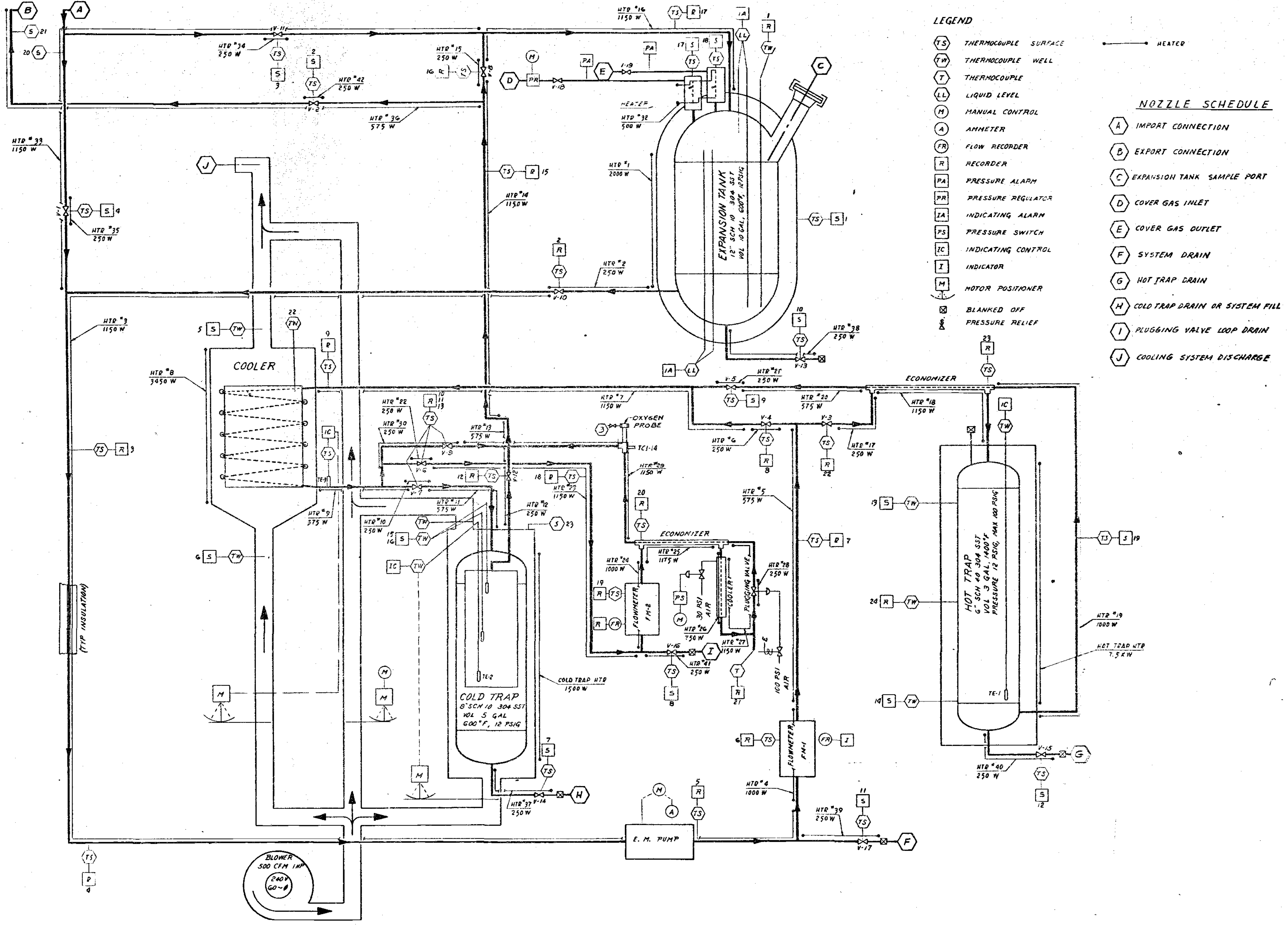

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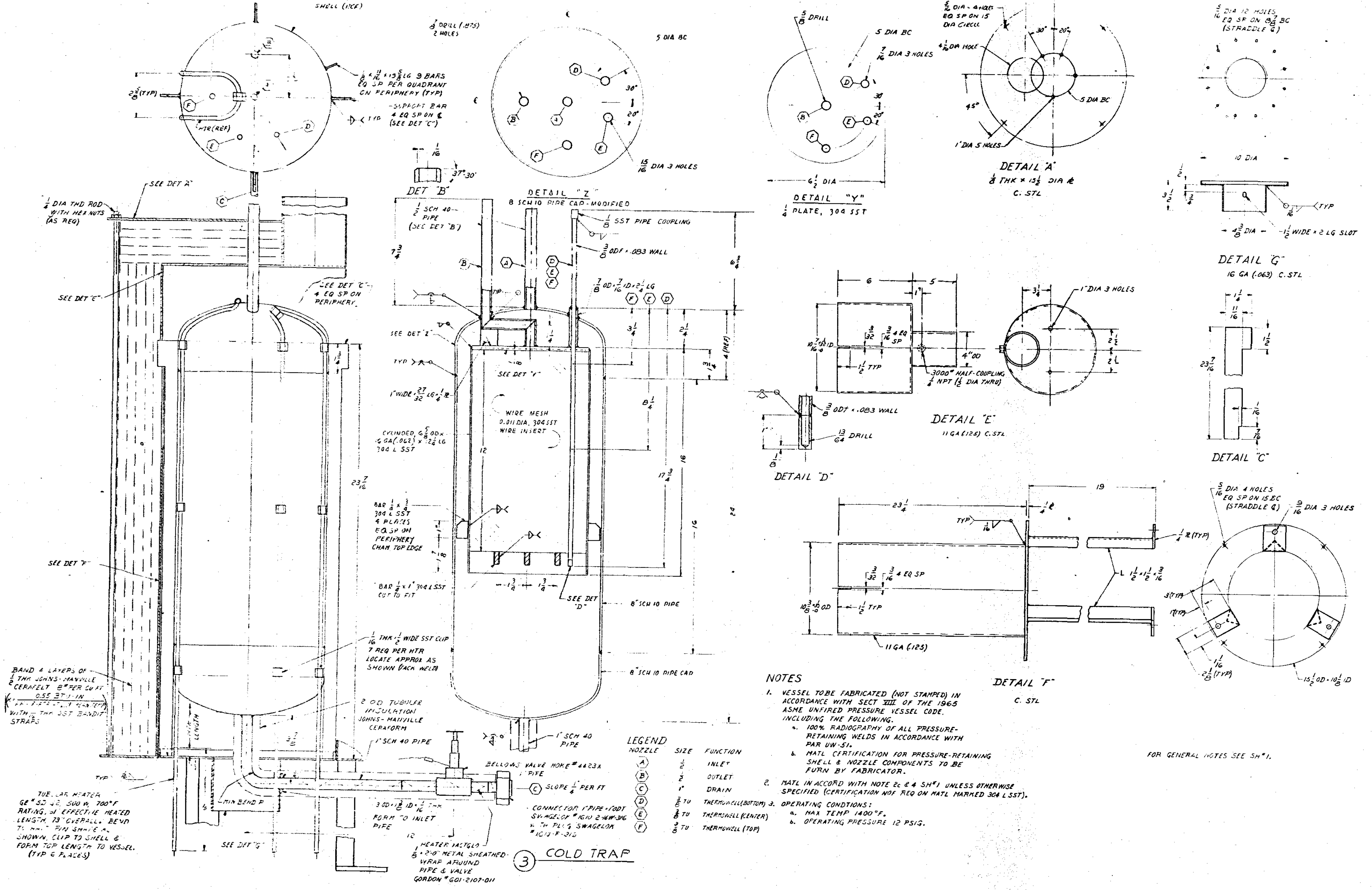
FIGURE Sodium Purification Loop
Engineering Flow Diagram



LEGEND

NOZZLE	SIZE	FUNCTION
Ⓐ	1/2	INLET
Ⓑ	1/2	OUTLET
Ⓒ	1"	DRAIN
Ⓓ	3/8 TU	THERMOWELL (BOTTOM)
Ⓔ	3/8 TU	THERMOWELL (CENTER)
Ⓕ	3/8 TU	THERMOWELL (TOP)

NOTES

1. VESSEL TOBE FABRICATED (NOT STAMPED) IN ACCORDANCE WITH SECT VIII OF THE 1965 ASME UNFIRED PRESSURE VESSEL CODE. INCLUDING THE FOLLOWING.
   a. 100% RADIOGRAPHY OF ALL PRESSURE-RETAINING WELDS IN ACCORDANCE WITH PAR UW-51.
   b. MATL CERTIFICATION FOR PRESSURE-RETAINING SHELL & NOZZLE COMPONENTS TO BE FURN BY FABRICATOR.
2. MATL IN ACCORD WITH NOTE 2c & 4 SH#1 UNLESS OTHERWISE SPECIFIED (CERTIFICATION NOT REQ ON MATL MARKED 304 L SST).
3. OPERATING CONDTIONS:
   a. MAX TEMP 1400°F.
   b. OPERATING PRESSURE 12 PSIG.

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FIGURE Cold Trap Assembly and Details

Heat Transfer Loop

The Heat Transfer Loop (HTL) is a high temperature sodium loop used for testing heat transfer apparatus and materials. The arrangement of the cold trap portion of the HTL is shown in Figure 7.

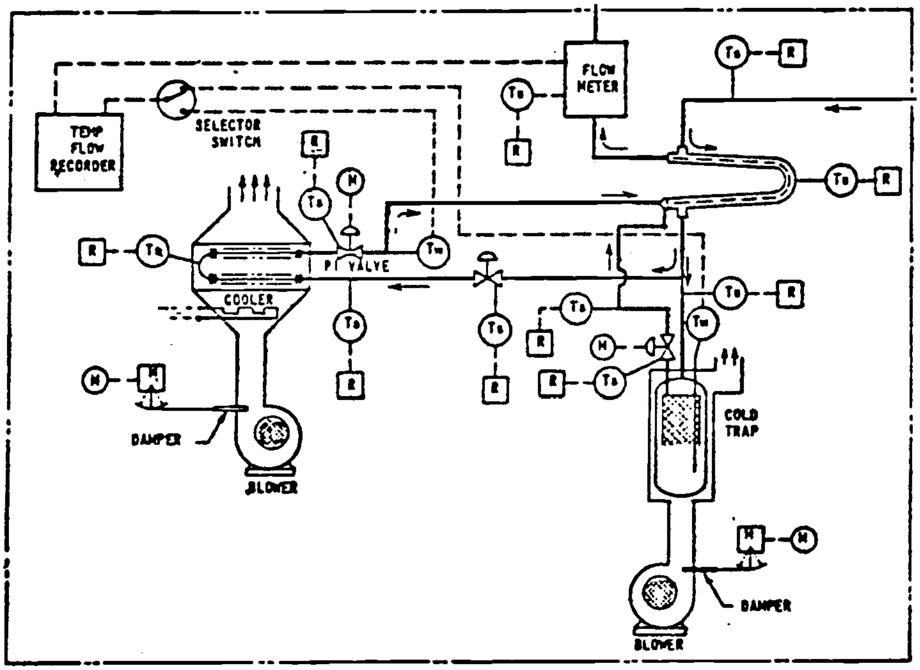

Figure 7. HTL Cold Trap Flow Diagram

The cold trap is a 16-1/2 inch long section of six inch pipe enclosing a 5-9/16 inch diameter tube, packed with stainless steel mesh. A single internal thermocouple measures the trapping temperature at the bottom of the internal tube. The external surface of the trap is finned to increase cooling surface.

The HTL trap is coupled to an economizer. The economizer is a tube-in-tube hairpin with 0.39 ft^2 heat exchange surface.

Dimensions of the trap are:

Inside diameter of outer shell	6.06 in.
Total outside surface cooling area, including fins	5.65 ft^2
Total inside surface cooling area	2.05 ft^2
Return channel mean diameter	5.45 in
Return channel length	11.12 in
Return channel surface area	1.51 ft^2

Results

Sodium Purification Loop

Seven test runs were made on the SPL loop. Test data taken are shown in Table II. Calculated values of the most significant operating parameters are reported in Table III.

Sodium heat loss in the annulus was balanced with heat gain in the sodium return channel and in the coolant. Coolant flow was not measured, but calculated using the formula $Q = Wc_p \Delta T$. Since coolant Q, c_p and ΔT are known, W was determined by direct substitution of values in the basic equation.

Coolant flow was by natural draft. The coolant blower in the loop was not used during these test runs. Average air velocity in the coolant annulus varied from 0.63 ft/sec to 1.95 ft/sec with the

Table II. Sodium Purification Loop Test Data

Case Number	101	102	103	104	105	106	107
Cold Trap Flow, gpm	0.12	0.15	0.24	0.28	0.44	0.45	0.49
Sodium Temperature In, °F	554	541	525	580	502	525	520
Sodium Temperature Out, °F	434	443	485	515	470	485	473
Ambient Temperature, °F	80	80	80	80	80	80	80
Coolant Air Out, °F	305	310	350	360	298	300	280
Temperature In Return Channel at: °F							
x = 0.042 ft	250	255	345	355	304	298	300
x = 0.833 ft	310	315	420	425	380	380	365
x = 1.25 ft	350	355	450	455	430	440	425

Table III. Sodium Purification Loop Trap Performance

Case Number	101	102	103	104	105	106	107
Cold Trap Flow, lb/hr	53	67	107	123	195	200	217
Mean Temperature Difference, Annulus and Return Channel, °F	60	49	20	32	36	21	24
Actual Heat Transfer Coefficient, Annulus and Return Channel, But/hr-ft^2-°F	18.0	28.4	82.5	67.2	112.0	199.0	170.0
Calculated Heat Transfer Coefficient, Annulus and Return Channel, Btu/hr - ft^2 - °F	26.1	35.0	62.4	75.1	133.1	135.9	183.7
Coolant Flow, lb/hr	38	39	21	38	44	48	68
Mean Temperature Difference, Annulus and Coolant Channel, °F	189	172	190	216	196	208	211
Actual Heat Transfer Coefficient, Annulus and Coolant Channel, Btu/hr - ft^2 - °F	2.82	3.32	1.78	2.56	2.67	3.24	4.33
Calculated Heat Transfer Coefficient, Annulus and Coolant Channel, Btu/hr - ft^2 - °F	2.40	2.43	1.80	2.46	2.61	2.76	3.23
Actual Heat Transfer Coefficient, Bottom Head, Btu/hr - ft^2 - °F	1.17	1.34	0.72	1.02	1.06	1.29	1.72
Calculated Heat Transfer Coefficient, Bottom Head, Btu/hr - ft^2 - °F	0.97	0.97	0.72	1.00	1.03	1.09	1.28
Heat Transferred to Coolant, Btu/hr	2040	2090	1360	2530	1995	2560	3270

average being in the order of 1.25 ft/sec.

Internal Wall Heat Transfer Coefficient

The actual overall heat transfer coefficient through the wall between the annulus and the return channel was determined from test data and compared with values calculated from heat transfer correlations.

Heat is transferred from incoming sodium to the stream leaving the trap through the internal cylinder wall and top plate. The heat transfer coefficients of the cylinder wall and top plate were assumed to be equal.

Heat transfer through the top plate was approximated by:

$$Q_{top} = U_1 A_{top}(T_i - T_o)$$

Heat transfer through the cylinder wall was calculated using the equation

$$Q_{cyl} = U_1 A_{cyl} \Delta Tm$$

Heat gain in the return channel is

$$Q_{return} = W_m C_m (T_o - T_t)$$

Since

$$Q_{return} = Q_{top} + Q_{cylinder}$$

it follows that

$$U_1 = \frac{W_m C_m (T_o - T_t)}{A_{top}(T_i - T_o) + A_{cyl} \Delta T_m} \qquad (1)$$

Equation (1) was used to calculate the Actual Heat Transfer Coefficients reported in Table III.

All sodium flow in the SPL tests was laminar. Reynolds numbers in the annulus varied from 55 to 216 and in the return channel from 119 to 453.

Published correlations (4) of sodium heat transfer coefficients report that in the laminar flow region the Nusselt number is a constant.

That is,

$$Nu = 4.36 \qquad Re < 3000$$

This relation was used to calculate the heat transfer coefficient through the wall between the annulus and return channel. This correlation did not produce acceptable results. The calculated coefficient was as much as 18 times higher than the actual heat transfer coefficient.

Analysis of the test data showed clearly that U_1 is a function of flow rate in the laminar as well as turbulent region.

A correlation of Nusselt and Peclet numbers for laminar flow of sodium was developed from SPL data. These data were fit to a curve of the form $Nu = f\ Pe^a$. This equation form was chosen because of its similarity to the Lubarsky-Kaufman relation for turbulent sodium flow in circular tubes.

The best fit (i.e., lowest standard deviation) occurred with the constants,

$$Nu = 0.64\ Pe^{1.3} \tag{2}$$

This correlation was used to calculate heat transfer coefficients reported in Table III.

External Wall Heat Transfer Coefficient

Heat is transferred from sodium to the air coolant through the external wall and bottom head of the trap. The outer film coefficient of the bottom head and the finned cylindrical wall were assumed to be equal.

Cooling air enters under the bottom head of the trap at ambient temperature. Heat transferred through the bottom head amounts to

$$Q_{btm} = U_3 A_b (T_b - T_c)$$

The temperature of air is increased as a result of heat transfer through the bottom head so that coolant temperature at $x = 0$ (T_{30}) is

$$T_{30} = \frac{Q_{btm}}{W_c C_c} + T_c$$

Heat is also transferred through the wall of the cylinder below the entrance to the return channel. The lower cylinder outer heat transfer surface area equals

$$A_{low} = EA_f + A_b$$

where A_f and A_b are areas of that portion of the cylinder below the entrance to the return channel. Heat transferred through the lower cylinder equals

$$Q_{low} = U_2 A_{low} \left[\frac{T_t + T_b}{2} - \frac{T_{3x} + T_{30}}{2} \right]$$

Heat transferred through the upper cylinder wall is calculated in the same way as for the lower cylinder. This heat transfer amounts to

$$Q_{up} = U_2 A_{up} \left[\frac{T_i + T_t}{2} - \frac{T_{3L} + T_{3x}}{2} \right]$$

Total heat transferred to the air coolant is equal to the heat lost by the sodium in passing through the trap. That is,

$$Q_{air} = W_m C_m (T_i - T_o)$$

also,

$$Q_{air} = Q_{btm} + Q_{low} + Q_{up}$$

The number of unknowns in the above equations preclude direct solution for U_2, the overall heat transfer coefficient. However, it is possible to solve for U_2 using an iterative technique.

The overall external heat transfer coefficient, U_2, equals

$$\frac{1}{U_2} = \frac{1}{h_o} + \frac{t}{k} + \frac{1}{h_i} \times \frac{d_o}{d_i} \qquad \text{(a)}$$

However, since the air film resistance in natural convection is so much larger than the other two terms in equation (a) U_2 is effectively h_o, the outside film coefficient.

The Actual U_2 values reported in Table III are related to the inside surface area of the trap wall.

The calculated air side heat transfer coefficient was taken from the Norris and Spofford correlation published in McAdams (16):

$$\frac{h_m}{c_p G_{max}} \left[\frac{c_p \mu}{k}\right]_f^{2/3} = \left[\frac{z_p G_{max}}{\mu_f}\right]^{-1/2}$$

The fin efficiency equation used is from McAdams (16)

$$E = \frac{\tanh ax_f}{ax_f}$$

where

$$a = \left[\frac{hb}{kS}\right]^{1/2} \qquad \text{and}$$

x_f is fin length.

The effective cylindrical coolant heat transfer coefficient is determined by:

$$h_o = h_m(EA_f + A_o)$$

The overall heat transfer coefficients were calculated using the standard equation

$$\frac{1}{U} = \frac{1}{h_o} + \frac{t}{k} + \frac{1}{h_i} \times \frac{d_o}{d_i} \qquad \text{(b)}$$

The value of the inside film coefficient used was the same as that calculated for the outside film coefficient of the interior wall between the annulus and return channel.

The terms t/k and $1/hi$ in equation (b) had very little effect on the calculated value of U_2.

Heat Transfer Loop

Eight test runs were made on the HTL loop. Test data recorded is shown in Table IV. Calculated values of the most significant trap operating parameters are reported in Table V.

Internal Wall Heat Transfer Coefficient

The Actual Heat Transfer Coefficients were calculated using equation (1), page 60.

A correlation of Nusselt and Peclet numbers for laminar flow of sodium in the HTL trap was developed. The data were fit to a curve of the form $Nu = f\ Pe^a$. The best fit occurred with the constants

$$Nu = 0.415\ Pe^{1.0} \qquad (3)$$

Table IV. Heat Transfer Loop Test Data

Case Number	201	202	203	204	205	206	207	208
Cold Trap Flow, gpm	0.12	0.16	0.20	0.20	0.41	0.43	0.46	0.50
Sodium Temperature In Economizer, °F	636	636	670	730	655	665	683	665
Sodium Temperature Out Economizer, °F	594	582	635	640	622	612	637	620
Sodium Temperature In Trap, °F	485	285	380	475	485	348	370	400
Sodium Temperature Out Trap, °F	470	270	375	455	476	313	342	380
Ambient Temperature, °F	72	72	72	80	72	72	72	72
Coolant Air Out, °F	NR	220	NR	415	420	210	260	310
Trapping Temperature, °F	445	240	360	430	465	240	305	360
Plugging Temperature, °F	410	220	330	410	440	240	280	NR

NR = Not Recorded

Table V. Heat Transfer Loop Trap Performance

Case Number	201	202	203	204	205	206	207	208
Cold Trap Flow, lb/hr	53	71	88	90	183	196	208	226
Mean Temperature Difference, Annulus and Return Channel, °F	8	8	2.5	10	5	18	14	10
Actual Heat Transfer Coefficient, Annulus and Return Channel, Btu/hr - ft^2 - °F	31.5	52.5	101	42.5	77.5	156	106	86.5
Calculated Heat Transfer Coefficient, Annulus and Return Channel, Btu/hr - ft^2 - °F	33.7	46.6	56	56.3	115	126	129	137
Coolant Flow, lb/hr	NC	10	NC	7	6	73	42	25
Mean Temperature Difference, Annulus and Coolant Channel, °F	NC	94	NC	136	148	142	150	163
Actual Heat Transfer Coefficient, Annulus and Coolant Channel, Btu/hr - ft^2 - °F	NC	2.01	NC	1.73	1.70	8.35	6.30	4.20
Calculated Heat Transfer Coefficient, Annulus and Coolant Channel, Btu/hr - ft^2 - °F	NC	2.04	NC	1.75	1.65	6.20	5.10	3.00
Heat Transfer to Coolant, Btu/hr	250	347	141	568	521	2240	1885	1445

NC = Not Calculated

This correlation was used to calculate heat transfer coefficients reported in Table V.

External Wall Heat Transfer Coefficient

The HTL external wall overall heat transfer coefficients were determined in the manner described previously for the SPL trap.

HTL Trap Economizer

Economizer tests data and calculated results are shown in Table VI.

Flow in the HTL trap economizer is countercurrent. Since mass flow rates in both tube and annulus are equal, temperature drop in the annulus should equal temperature rise in the tube. None of the temperature differences reported in Table VI for any of the eight cases were equal. Annulus temperature drop in each case was greater than tube temperature rise. This result is indicative of thermocouple error. Thermocouples were not calibrated before these test runs.

The effect of temperature measurement error is shown in calculation of annulus heat loss and tube heat gain reported in Table VI. The overall heat transfer coefficient was based on the average value of measured heat loss and heat gain.

The actual heat transfer coefficient was calculated using the

Table VI. Heat Transfer Loop Economizer Performance

Case Number	201	202	203	204	205	206	207	208
Economizer Flow Rate, lb/hr	53	71	88	90	183	196	208	226
Temperatures, °F								
Annulus In	636	636	670	730	655	665	683	665
Annulus Out	485	285	380	475	485	348	370	400
Tube In	470	270	375	455	476	313	342	380
Tube Out	594	582	635	640	622	612	637	620
Mean Temperature Difference, Economizer, °F	28	34	20	56	21	24	38	32
Actual Heat Transfer Coefficient, Economizer, Btu/hr - ft^2 - °F	207	560	970	280	1100	2280	1340	1430
Calculated Heat Transfer Coefficient, Economizer, Btu/hr - ft^2 - °F	1400	1410	1550	1540	1730	1770	1780	1785
Fouling Resistance x 10^{-4}	41.1	10.8	3.84	29.2	3.30	- 0 -	1.83	1.39
Heat Loss, Annulus, Btu/hr	2480	7850	7970	7080	9700	24450	20430	18800
Heat Gain, Tube, Btu/hr	2050	7000	7160	5180	8350	18300	19400	17100
Average Heat Transferred, Btu/hr	2265	7425	7565	6130	9025	21375	19915	17900

equation

$$U_e = \frac{Q}{A_e \Delta T_m} \tag{4}$$

The Lyon correlation for liquid metal heat transfer in an annulus, published in McAdams (16), was used to calculate the outside sodium film coefficient. This correlation is:

$$Nu = 4.9 + 0.0175\ Pe^{0.8} \tag{5}$$

The Lubarsky-Kaufman relation for turbuluent sodium flow in circular tubes was used to calculate the inside film coefficient. This correlation is:

$$Nu = 0.625\ Pe^{0.4} \tag{6}$$

The film coefficients and thermal resistance of the tube wall were combined using the standard equation

$$\frac{1}{U_e} = \frac{1}{h_o} + \frac{t}{k} + \frac{1}{h_i} \times \frac{d_o}{d_i} \tag{7}$$

to calculate the value U_e.

The difference between actual U_e and calculated U_e was attributed to fouling resistance. Fouling resistance was calculated in accordance with:

$$R_{foul} = \frac{1}{U_{act}} - \frac{1}{U_{calc}} \tag{8}$$

Equation 8 is a rough measure of fouling resistance, but also includes all measurement and correlation errors.

Air Coolant Heat Transfer Coefficient

Hoschouer and Casey (11), reporting on nitrogen cooling of a plugging meter sodium cooler approximating SPL and HTL trap dimensions, state that the overall heat transfer coefficient is a function of the variable nitrogen flow rate. That is,

$$U = f(W_c)^{0.8} \tag{9}$$

It follows that air cooling heat transfer should exhibit characteristics similar to nitrogen. Also, if equation (9) holds, there is reason to believe that

$$Nu = f\ Re^{0.8} \tag{10}$$

which is a more general expression of the relationship.

The applicability of equation (10) was tested with SPL and HTL test data. The factor, f, was determined by averaging f_i in the equation

$$f_i = Nu_i/Re_i^{0.8}$$

Calculated in this manner,

$$\text{SPL } f = 0.0404$$

$$\text{HTL } f = 0.0533$$

Actual and calculated Nusselt numbers are compared in Table VII.

Table VII. Coolant Nusselt Numbers

SPL Trap Nu = 0.0404 $Re^{0.8}$				HTL Trap Nu = 0.0533 $Re^{0.8}$			
Case Number	Actual Nu	Calculated Nu	Difference %	Case Number	Actual Nu	Calculated Nu	Difference %
101	6.10	6.18	+1.3	202	3.94	4.43	+12.5
102	6.63	6.22	-6.2	204	2.56	2.38	- 7.0
103	3.67	3.78	+3.3	205	2.33	2.13	- 8.6
104	6.08	5.95	-2.1	206	15.05	17.05	+13.3
105	5.95	6.90	+15.9	207	10.83	11.71	+ 8.1
106	7.21	7.55	+4.7	208	8.30	7.50	- 9.6
107	10.82	9.90	-8.5				

Note: Difference = $\frac{\text{Calc Nu - Actual Nu}}{\text{Actual Nu}} \times 100$

Calculation of Cold Trap Temperatures

The ability of the cold trap thermal analysis model developed in Section III to predict trap temperatures was tested using SPL and HTL data.

The model assumes certain idealized conditions, one of which is insulated end closures. This condition does not exist in either of the traps tested. The basic model computer code was modified to account for heat transferred through the top and bottom of the traps and the modified code used to calculate temperatures reported in Tables VIII, IX and X.

The code was modified in the following manner:

An initial estimate of the cold trap outlet temperature is made using basic model equations.

Heat transfer through the top plate closure of the return channel was approximated by

$$Q_{top} = U_1 A_{top}(T_i - T_o)$$

Temperature of sodium in the annulus at $x = L$ is reduced to

$$T_{2L} = T_i - \frac{Q_{top}}{W_m C_m}$$

and the temperature of sodium in the return channel at $x = L$ is reduced to

$$T_{1L} = T_o - \frac{Q_{top}}{W_m C_m}$$

to account for temperature change above $x = L$ (i.e., through the top plate).

Trapping temperature is effected by the lowering of T_{1L} and T_{2L}, and T_t is recalculated using these lower values.

Trapping temperature is further reduced by heat loss through the bottom head. This heat loss is approximated by:

$$Q_{btm} = U_3 A_{btm} (T_t - T_c)$$

The trapping temperature is reduced to approximately

$$T_t = T_t - \frac{Q_{btm}}{W_m C_m}$$

The temperature of the coolant at $x = o$ is increased to

$$T_{c(x=0)} = T_c + \frac{Q_{btm}}{W_c C_c}$$

The temperature profile is then calculated using the new values of T_{2L}, T_{1L}, T_t and T_c.

When the trap is coupled with an economizer the return stream economizer inlet and outlet temperatures are recalculated after the bottom heat loss has been factored into the model, and the economizer and coolant duties calculated on the basis of these modified values.

For calculating purposes, $x = 0$ is set at the entrance to the return channel. The cylindrical portion of both traps tested extended below the entrance to the return channel. The reduction in outer shell heat transfer surface resulting from this selection of the axial lower boundary was compensated for by increasing the outer shell heat transfer coefficient by the inverse ratio of return channel and outer shell lengths.

The results of calculations made with modified program described above are reported in Table VIII for the SPL trap; Table IX for the HTL trap only; and Table X for the HTL trap with economizer.

Table VIII. Sodium Purification Loop Temperature Profile

Case Number		101	102	103	104	105	106	107
Sodium Temperature In, °F		554	541	525	580	502	525	520
Sodium Temperature Out, °F	Actual	434	443	485	515	470	485	473
	Calculated	419	422	475	509	459	476	462
Trapping Temperature, °F	Actual	250	255	345	355	304	298	300
	Calculated	264	258	348	371	368	318	309
Ambient Temperature, °F		80	80	80	80	80	80	80
Coolant Air Out, °F	Actual	305	310	350	360	298	300	280
	Calculated	277	286	325	319	287	280	270
Temperature in Return Channel, °F at:								
x = 0.833 ft	Actual	310	315	420	425	380	380	365
	Calculated	310	307	389	415	398	367	356
x = 1.25 ft	Actual	350	355	450	455	430	440	425
	Calculated	366	367	436	466	432	425	413
Heat Transfer to Coolant, Btu/hr	Actual	2040	2090	1360	2530	1995	2560	3270
	Calculated	1807	1935	1239	2191	2193	2317	3113

Table IX. Heat Transfer Loop Temperature Profile Without Economizer

Case Number		202	204	205	206	207	208
Sodium Temperature In, ° F		285	475	485	348	370	400
Sodium Temperature Out, ° F	Actual	270	455	476	313	342	380
	Calculated	265	451	473	308	338	378
Trapping Temperature, ° F	Actual	240	430	465	240	305	360
	Calculated	237	427	463	244	302	360
Ambient Temperature, ° F		72	80	72	72	72	72
Coolant Air Out, ° F	Actual	220	415	420	210	260	310
	Calculated	216	393	426	193	236	291
Heat Transfer to Coolant, Btu/hr	Actual	347	568	521	2240	1885	1445
	Calculated	347	528	512	2119	1852	1322

Table X. Heat Transfer Loop Temperature Profile with Economizer

Case Number		202	204	205	206	207	208
Sodium Temperature In Economizer, ° F		636	730	655	665	683	665
Sodium Temperature Out Economizer, ° F	Actual	582	640	622	612	637	620
	Calculated	609	701	644	637	648	641
Sodium Temperature in Trap, ° F	Actual	285	475	485	348	370	400
	Calculated	374	613	568	270	409	477
Sodium Temperature Out Trap, ° F	Actual	270	455	476	313	342	380
	Calculated	358	591	559	246	380	456
Trapping Temperature, ° F	Actual	240	430	465	240	305	360
	Calculated	329	564	549	207	346	438
Ambient Temperature, ° F		72	80	72	72	72	72
Coolant Air Out, ° F	Actual	220	415	420	210	260	310
	Calculated	403	630	599	183	296	392
Heat Transfer to Coolant, Btu/hr	Actual	347	568	521	2240	1885	1445
	Calculated	797	927	762	1938	2542	1927
Heat Transferred in Economizer, Btu/hr	Actual	7425	6130	9025	21375	19915	17900
	Calculated	5856	3143	4889	24972	18065	13354

VI. DISCUSSION AND CONCLUSIONS

The most significant conclusions to be drawn from this work are:

1. The optimum trapping rate curve is linear, not exponential.
2. The heat transfer coefficient (Nusselt number) for sodium in the laminar flow regime is not a constant.
3. Generally accepted methods of calculating air coolant heat transfer coefficients produce satisfactory results in predicting cold trap performance.
4. The cold trap mathematical model developed by this, and several other, authors accurately simulates cold trap performance. The model of a trap coupled with an economizer is less reliable.

The exponential constant trapping temperature method of calculating trapping rate is an accepted part of cold trap technology. This method is unrealistic. The linear constant impurity removal rate more closely describes conditions under which cold traps are normally operated. See pages 10-15 for justification of this conclusion.

This work showed clearly that in a cold trap the sodium Nusselt number is not a constant for laminar flow as has been reported in the literature.

There are several possible explanations for this disagreement with previous findings. The effect of mesh on heat transfer characteristic number values must be considered.

Reynolds number is a ratio of inertia forces to viscous forces and Prandtl number is the ratio of momentum diffusion to heat diffusion. Obviously, inertia forces and momentum diffusion are effected by the presence of wire mesh in the flow passage. Therefore, it is not surprising that heat transfer does not conform to findings of experiments with clear flow channels.

The thermal entrance region which produces deviations from laminar equilibrium conditions is very short in sodium and should have little effect in cold trap heat transfer calculations.

The sodium heat transfer coefficient correlations developed from SPL and HTL data are entirely empirical. The fact that constants computed for the two traps bore little relation to each other casts doubt on the applicability of the correlations over a very wide range. Nevertheless, there is solid evidence that sodium heat transfer in a laminar flow regime is influenced by the value of the Reynolds and Prandtl numbers. The difficult task is determining exactly what these values are in operating cold trap.

The testing of the Hoschauer and Casey (11) sodium-to-gas heat transfer correlation was an interesting, but inconclusive exercise.

The data for each trap behaved fairly well but the constants relating Nusselt number and Reynolds number in the two traps of almost identical geometric proportions differed significantly. The inability of the constant from one trap to correlate data from the other casts doubt on the credibility of the underlying principle.

The relation between actual and calculated heat transfer coefficients in the HTL economizer was unfortunate. Correlations which have been successful in predicting sodium heat transfer in the past were ineffective. Calculation of U_e based on the Peclet number clustered in the range of 1400-1800 Btu/hr-ft-° F while actual U_e, based on measured temperatures, ranged from 200 to 2300 Btu/hr-ft^2-° F.

The HTL trap was tested in a partially plugged condition. It was abandoned shortly after completion of the tests. Thermal shocking between test runs may have had some influence on conditions in the economizer but there is no evidence of this other than erratic behavior.

The overall conclusion of study of the HTL economizer is that the work produced no meaningful results.

The mathematical model developed was successful in duplicating measured temperatures in the cold trap. The results from the trap/economizer model were less satisfactory.

Trapping and sodium outlet temperatures are key operating parameters and a calculational model must be able to simulate these temperatures accurately to be accepted for use. The model does this very well in the trap only mode. Correlation of actual and calculated HTL trapping and sodium out temperatures was excellent and SPL results are acceptable.

The large difference between calculated and measured trapping temperature in Case 105 is an unexplained anomaly.

The model consistently underestimated the rate of heat rejection to coolant. The most logical explanation for this is that increasing U_2 by the ratio L_{shell}/L_{return} does not adequately compensate for reducing shell surface area due to non-linearity of equations using the constant k_2.

In the trap-with-economizer simulation, results were disappointing. Some of the lack of correlation may be due to inaccurate temperature measurement but it is obvious that the program needs more work before it can be used as a design or operating tool.

A fundamental conclusion of this work is that cold trap technology is in a rudimentary state. The cause of science will be well served if this is recognized and further study encouraged.

ABBREVIATIONS AND SYMBOLS

A_b	Outside surface area of bottom head, ft^2
A_e	Economizer heat transfer surface, ft^2
A_f	Area of extended (finned) heat transfer surface, ft^2
A_o	Area of outside heat transfer surface, ft^2
a	System turnovers, dimensionless
b	Exposed perimeter of fin, ft
C_c	Specific heat of coolant, Btu/lb-°F
C_m	Specific heat of main stream, Btu/lb-°F
c	Impurity concentration at time t, ppm
c_i	Initial or inlet impurity concentration, ppm
c_m	Minimum impurity concentration achieved by linear concentration reduction, ppm
c_o	Outlet impurity concentration, ppm
c_p	Specific heat, Btu/lb-°F
c_t	Impurity concentration at trapping temperature, ppm
d	Diameter, feet
E	Fin efficiency, fractional
f	Subscript, refers to surface film values
G_{max}	Mass velocity, $lb/hr\text{-}ft^2$
h_m	Mean value of heat transfer coefficient, $Btu/hr\text{-}ft^2\text{-}°F$
h_o	Outside heat transfer coefficient, $Btu/hr\text{-}ft^2\text{-}°F$

ABBREVIATIONS AND SYMBOLS (Continued)

I	Impurity, lbs
k	Thermal conductivity, Btu/hr-ft-° F
k_1	$2\pi r_1 U_1 L/W_m C_m$, dimensionless
k_2	$r_2 U_2/r_1 U_1$, dimensionless
k_3	$W_m C_m/W_c C_c$, dimensionless
k_4	$U_e A_e/W_m C_m$, dimensionless
L	Length of trap, ft
Nu	Nusselt Number, hd/k, dimensionless
Pe	Peclet Number, Prandtl Number x Reynolds Number, $dV\rho c_p/k$, dimensionless
Pr	Prandtl Number, $\mu c_p/k$, dimensionless
ppm	Parts per million
Q	Heat transferred, Btu per unit time
Re	Reynolds Number, $dV\rho/\mu$, dimensionless
r_1	Radius of return channel, ft
r_2	Radius of trap, ft
S	Solubility of sodium oxide in liquid sodium, weight percent, or parts per million, oxygen
S	Cross-section of fin, ft^2
T_{1L}	Temperature of fluid in return channel at L, ° F
T_{2L}	Temperature of fluid in annulus at L, ° F
T_{3L}	Temperature of coolant in jacket at L, ° F
T_{3x}	Temperature of coolant opposite entrance to the internal return channel, ° F

ABBREVIATIONS AND SYMBOLS (Continued)

$T_1(x)$	Temperature of fluid in return pipe, °F
$T_2(x)$	Temperature of fluid in annulus, °F
$T_3(x)$	Temperature of coolant in jacket, °F
T_b	Temperature of internal fluid at inside surface of bottom head, °F
T_c	Inlet temperature of coolant, °F
T_i	Trap or economizer inlet temperature, °F
T_o	Trap or economizer outlet temperature, °F
T_t	Trapping temperature, °F $= T_1(0) = T_2(0)$
t	Time, hr or sec
U_1	Overall heat transfer coefficient through wall between annulus and return channel, Btu/hr-ft^2-°F
U_2	Overall heat transfer coefficient through wall between trap and coolant jacket, Btu/hr-ft^2-°F
U_3	Overall heat transfer coefficient through bottom head, Btu/hr-ft^2-°F
U_e	Overall heat transfer coefficient through economizer internal wall, Btu/hr-ft^2-°F
V	Velocity, feet/sec or feet/hr
W	Mass of sodium in system, lb
W_c	Mass rate of flow of coolant, lb/hr
W_m	Mass rate of flow of trapped stream, lb/hr
w	Cold trap flow rate, lb/hr
x	Distance above lower end of trap, ft

ABBREVIATIONS AND SYMBOLS (Continued)

x_f	Length of fin, ft
z_p	Length of fin, ft
α	Trap efficiency, fractional
α	Dummy argument in mathematical notation
ΔT_m	Arithemetric mean temperature difference, °F
λ_1	Characteristic root of a differential equation
λ_2	Characteristic root of a differential equation
μ	Absolute viscosity of fluid, lb/hr-ft
ρ	Density, lb/ft^3

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APPENDIX

APPENDIX I

COLD TRAP THERMAL ANALYSIS PROGRAM

INTRODUCTION

The cold trap thermal analysis described in Section III has been programmed for computer calculation.

The program is written in FORTRAN II.

The computer used is a Raytheon 703. Computing time is in the order of a few seconds per case.

The program has two options. Option one calculates thermal profile and heat transferred in a basic cold trap with insulated ends. Option two performs the calculations of option one and considers the effect of coupling an economizer with the basic trap.

NOMENCLATURE

The following notation is used in the computer program:

Input Data

AE	Heat transfer surface area of economizer, ft^2
CC	Specific heat of coolant, Btu/lb-° F
CM	Specific heat of fluid in trap, Btu/lb-° F
DSTNCE	Axial length of trap section, feet (also called L in Section III).
NOCASE	Case Number

NOOPTN	Number of program option ∘ Option 1: basic trap configuration ∘ Option 2: trap with economizer
R1	Radius of return channel, feet
R2	Radius of trap, feet
TC	Inlet temperature of coolant, ° F
TI	Inlet temperature of sodium trap or economizer, ° F
U1	Overall heat transfer coefficient through wall between annulus and return pipe, Btu/hr-ft^2-° F
U2	Overall heat transfer coefficient through wall between trap and coolant jacket, Btu/hr-ft^2-° F
UE	Overall heat transfer coefficient through economizer wall, Btu/hr-ft^2-° F
WC	Mass flow rate of coolant, lbs/hr
WM	Mass flow rate through trap, lbs/hr

Other Notation Used in Program

C1	Constant No 1 C1 $= \frac{2\pi r_1 U_1 L}{W_m C_m}$
C2	Constant No 2 C2 $= \frac{r_2 U_2}{r_1 U_1}$
C3	Constant No 3 C3 $= \frac{W_m C_m}{W_c C_c}$
C4	Constant No 4 C4 $= \frac{U_e A_e}{W_m C_m}$
C5	Lambda factor 1 in solution of differential equation

C6	Lambda factor 2 in solution of differential equation
E1	Exp (C5 * C1) or Exp (C5 * C1 * x/L)
E2	Exp (C6 * C1) or Exp (C6 * C1 * x/L)
F1	Factor in calculating Trapping Temperature
F1L	Factor 1 with arguments (C_1, λ_1, λ_2) at L
F2L	Factor 2 with arguments (C_1, λ_1, λ_2) at L
QECON	Economizer duty, Btu/hr
QJAC	Coolant duty, Btu/hr
T1(X)	Temperature of fluid in return channel at position X, °F
T2(X)	Temperature of fluid in annulus at position X, °F
T3(X)	Temperature of coolant in jacket at position X, °F
T1L	T1(X) at L, °F
T2L	T2(X) at L, °F
T3L	T3(X) at L, °F
TO	Temperature of fluid leaving trap or economizer, °F
TT	Trapping temperature (T1(0) = T2(0)), °F
TITO	TI - TO
TTTC	TT - TC
X	Axial distance above entrance to return channel, feet

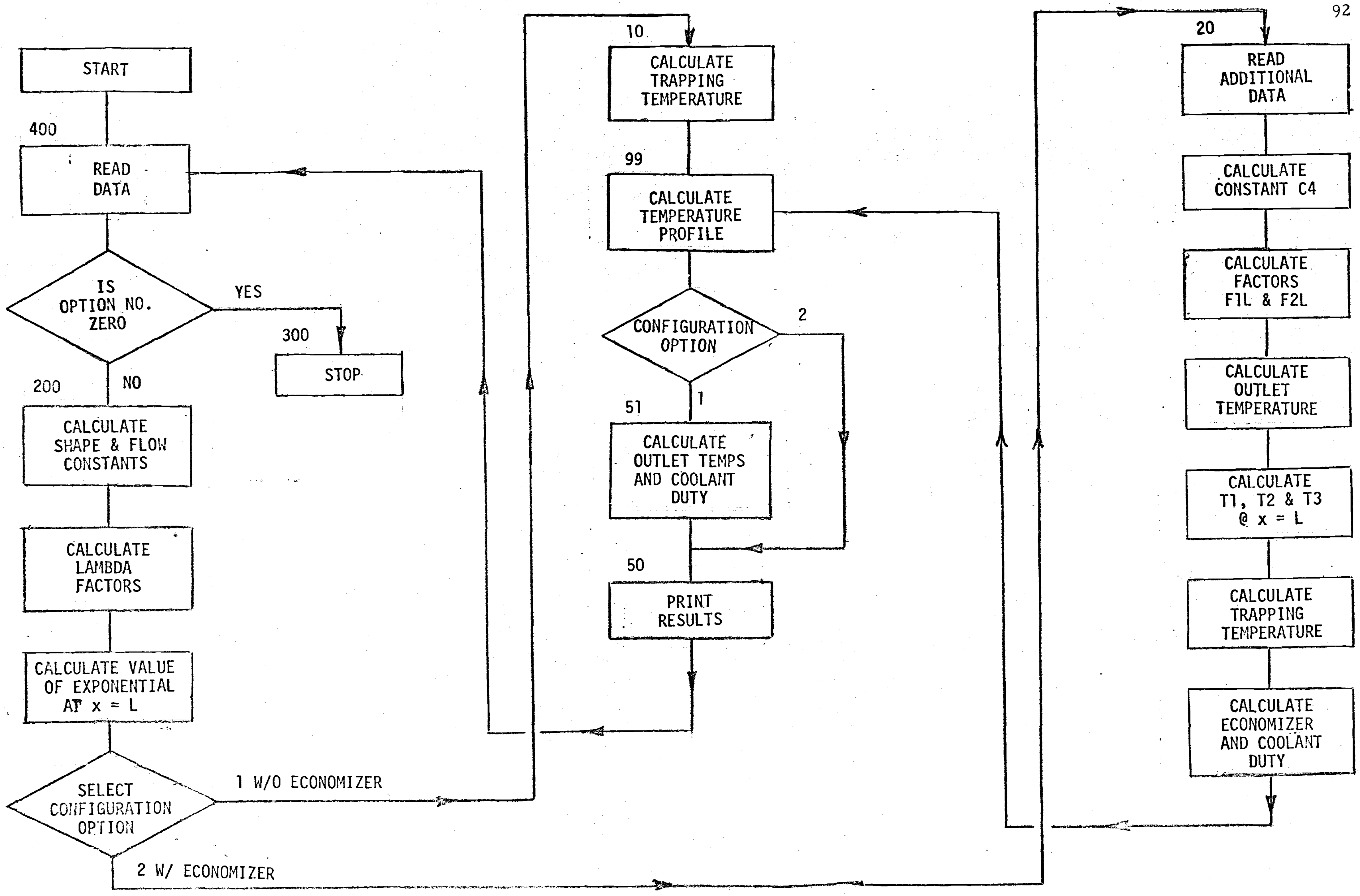

FIGURE 8 COMPUTER PROGRAM LOGIC DIAGRAM

PROGRAM LISTING

```
C      COLD TRAP THERMAL ANALYSIS PROGRAM
C                BY M O ROTHWELL
C                  MAY    1970
C
      DIMENSION T1(21), T2(21), T3(21), X(21)
C
    1 FORMAT (I5, I1, F5.2, F6.2,F6.2, F6.3, F6.3, F6.0,
     1F6.0, F6.3, F6.3, F5.0, F5.0)
    2 FORMAT (F8.2, F8.2)
    3 FORMAT (26X,20HRESULTS OF COLD TRAP/ 28X,
     116HTHERMAL ANALYSIS//)
    4 FORMAT (10X, 11HCASE NUMBER, 30X, I5 /)
C
    5 FORMAT (10X,21HTEMPERATURES   DEG F ,7X,5HINLET,7X,
     16HOUTLET /14X,11HMAIN STREAM,13X,F5.0,8X,F5.0/ 14X,
     27HCOOLANT,17X,F5.0,8X,F5.0/10X,20HTRAPPING TEMPERATURE,
     321X,F5.0,8H   DEG F / 2H  /)
    6 FORMAT (10X,15HCOOLANT    DUTY,22X,F9.0,9H   BTU/HR /
     110X,15HECONOMIZER DUTY,22X,F9.0,9H   BTU/HR //)
    7 FORMAT (10X,14HLENGTH OF TRAP,27X,F5.2,7H   FEET /
     110X,16HDIAMETER OF TRAP,25X,F5.2,7H   FEET /
     210X,23HDIAMETER OF RETURN PIPE,18X,F5.2,7H   FEET //)
C
    8 FORMAT (10X,29HTEMPERATURE PROFILE     DEG F  /
     115X,1HX,9X,6HRETURN,6X,7HANNULUS,6X,7HCOOLANT )
    9 FORMAT (13X,F5.2,8X,F4.0,9X,F4.0,9X,F4.0 /)
   11 FORMAT (10X,17HFLOW THROUGH TRAP,21X,F8.0,3X,5HLB/HR /
     110X,12HCOOLANT FLOW,26X,F8.0,  3X,5HLB/HR //)
C
   12 FORMAT (10H          , / 10H          , /)
   13 FORMAT (10X, 13HCONFIGURATION, 10X,
     123HTRAP WITHOUT ECONOMIZER//)
   14 FORMAT (10X, 13HCONFIGURATION,13X,
     120HTRAP WITH ECONOMIZER //)
C
   16 FORMAT (10X, 34HINTERIOR HEAT TRANSFER COEFFICIENT,
     15X,F7.2 / 10X,34HEXTERIOR HEAT TRANSFER COEFFICIENT,
     25X,F7.2 //)
   17 FORMAT (10X, 32HECONOMIZER HEAT TRANSFER SURFACE,
     18X,F6.2,3X,5HSQ FT/ 10X,
     236HECONOMIZER HEAT TRANSFER COEFFICIENT,3X,F7.2 //)
   18 FORMAT (10X,15HCOOLANT    DUTY,22X,F9.0,9H   BTU/HR /
     13H   /)
```

```
C     READ DATA
  400 READ (7,1)NOCASE,NOOPTN,DSTNCE,U1, U2, R1,R2,WM,WC,CM,
     1CC,TI,TC
      IF (NOOPTN) 300, 300, 200
C
C     CALCULATE SHAPE  AND FLOW CONSTANTS
  200 C1 = (6.283 *R1 *U1 *DSTNCE) / (WM * CM)
      C2 = (R2 * U2) / (R1 * U1)
      C3 = (WM * CM) / (WC * CC)
C
C     CALCULATE LAMBDA FACTORS
      SUM1 = ((C2**2)*((1.0 -C3)**2))+ 4.0*C2
      SUM1 = SQRT (SUM1)
      C5 = 0.5*(C2*( 1.0 - C3)  + SUM1)
      C6 = 0.5*(C2* (1.0 - C3) - SUM1)
C
C     CALCULATE VALUE OF E AT L
      ARG1 = C5 * C1
      ARG2 = C6 * C1
      E1 = EXP (ARG1)
      E2 = EXP (ARG2)
C
C     SELECT CONFIGURATION OPTION
      GO TO (10, 20), NOOPTN
C
C     OPTION 1 BASIC TRAP CONFIGURATION
C          NO ECONOMIZER
C
C     CALCULATE TRAPPING TEMPERATURE
   10 F1 =-(C6*(1.0 +C5)* E1) +(C5* (1.0 + C6)* E2)
      TT = ((TI - TC)*((C5 - C6)/ F1 )) + TC
C
C     CALCULATE TEMPERATURE PROFILE
   99 DO 100   I = 1, 20
      A = I
      X(I) = 0.05 * A* DSTNCE
      ARG1 = (C5* C1*X(I)) / DSTNCE
      ARG2 = (C6* C1*X(I)) / DSTNCE
      E1 = EXP  (ARG1 )
      E2 = EXP  (ARG2 )
C
      T1(I) = ((TT - TC)*(((C5/(C5-C6))*E2) - ((C6/(C5-C6))
     1*E1))) + TC
C
      T2(I) = (TT - TC) * (-(( C6 * (1.0+C5)) / (C5 - C6 ))
     1*E1 + ((C5*(1.0+C6)) /(C5-C6)) *E2) + TC
```

```
 100  T3(I)  = ( TT - TC ) * (( C5 + C6 + C5*C6)  /
     1(C5 - C6)) * (-E1 + E2)  + TC
      GO TO (51, 50), NOOPTN
C
C     CALCULATE OUTLET TEMPERATURES AND COOLANT DUTY
   51 TO = T1(20)
      T3L = T3(20)
      QJAC = WC*CC*(T3L - TC)
      GO TO 50
C
C     PRINT RESULTS
   50 R1 = 2.0 * R1
      R2 = 2.0 * R2
C
      WRITE (8,12)
      WRITE (8,3)
      WRITE (8,4) NOCASE
C
      GO TO (70, 71), NOOPTN
   70 WRITE (8,13)
      GO TO 73
   71 WRITE (8,14)
      GO TO 73
   73 WRITE (8,5) TI, TO, TC, T3L, TT
C
      WRITE (8,16) U1, U2
      WRITE (8,11) WM, WC
C
      GO TO (81, 82), NOOPTN
   81 WRITE (8, 18) QJAC
      GO TO 83
   82 WRITE (8,6) QJAC, QECON
   83 WRITE (8,7) DSTNCE, R2, R1
C
      GO TO (75, 74), NOOPTN
   74 WRITE (8,17) AE, UE
   75 WRITE (8,8)
C
      DO 101 I = 1 , 20
  101 WRITE (8,9) X(I), T1(I), T2(I), T3(I)
C
      GO TO 400
C
C     OPTION 2 TRAP WITH COUPLED ECONOMIZER
C
C     READ ADDITIONAL DATA
   20 READ (7,2) AE, UE
C
C     CALCULATE CONSTANT
      C4 = (UE * AE) / (WM * CM)
```

```
C     CALCULATE FACTORS F1L AND F2L
      F1L = (1.0/(C5 -C6)) *(-(C6*E1) + (C5*E2))
      F2L = (-(C5*C6)/(C5 - C6)) * (E1 - E2)
C
C     CALCULATE TO
   21 TITO = ((TI- TC)* F2L) / (F1L + ((1.0 + C4) * F2L))
      TO = TI - TITO
C
C     CALCULATE T1L, T2L, AND T3L
      T1L = TI - (TITO* (1.0 + C4))
      T2L = TI - (C4 * TITO)
      T3L = TC + (C3 * TITO)
C
C     CALCULATE TRAPPING TEMPERATURE
      F1 = -(C6*(1.0 + C5) *E1) + (C5*(1.0 + C6) *E2)
      TT = ((T2L - TC) * ((C5 - C6) / F1)) + TC
C
C     ECONOMIZER AND JACKET DUTY
      QECON = WM*CM*(TI - T2L)
      QJAC = WC*CC*(T3L - TC)
C
C     TRANSFER TO TEMPERATURE PROFILE ROUTINE
      GO TO 99
C
  300 STOP
      END
```