THE FEED ENTHALPY COMPUTER

ABSTRACT: This study describes a generalized analog computer program for control of the feed stream enthalpy to a distillation column. It is based on the solution of a steady state heat balance equation written for the feed system to the column. Control is accomplished by feeding the solution from the computer to a conventional recording-controlling instrument which automatically manipulates a control valve in the stream line to a feed preheater.

The program developed is designed for solution with an EAI PC-12 Process Control Computer. The programming flexibility of this computer permits the use of standard, solid-state computing components. Scaling of the circuit is completely general, enabling the program to be utilized for a variety of columns having different operating conditions.

GENERAL

The importance of good regulation and control of the three major heat inputs to distillation columns in achieving improved operations is cited in the literature (1,2). Among the reasons presented therein are:

(1) the difficulty of separation in many columns

(2) the change in the dynamic character of columns

(3) the interaction of variables internal to the column, or external due to column auxiliaries

(4) the non-linear nature of significant variables in a column

(5) the change in demand upon column operation due to its dependency upon other parts of the process.

Even though control of distillation columns is a well established art, and is adequately documented (3,4), there are certain heat input disturbances which require more than conventional instrumentation for their control. One such disturbance is the change in enthalpy—heat content—of feed entering the column.

COMPUTER CONTROL OF FEED ENTHALPY

Although the heat supplied to a column by the feed is usually small in comparison to the total heat required for the separation, the importance to good column control of its being stabilized should not be overlooked. It is generally desirable that the feed enthalpy be controlled at a level which will result in the least operating costs while producing on-specification products. Regardless of whether the feed must enter at its bubble point temperature, partially vaporized, or subcooled, the problem of regulating it at a selected value becomes important to good column control.

One practical and economical method for regulating the feed heat content involves a special purpose analog computer, called a Feed Enthalpy Computer. This approach has been found, by simulation studies and extensive plant tests (1), to give excellent results where the feed enters at its bubble point temperature, partially vaporized.

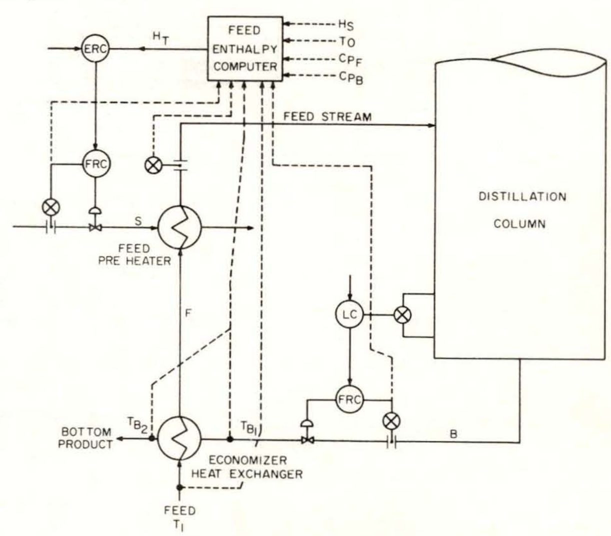

Figure 1. Feed Enthalpy Computer Control of Distillation Column.

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The concept of the Feed Enthalpy Computer is based on the inferential measurement of the total feed heat content by adding appropriate heat quantities; i.e., the initial heat content of the feed entering the economizer exchanger, the heat supplied to the feed by the economizer exchanger, and, the heat supplied by the steam feed preheater (refer to Figure 1). The computer continuously calculates the feed heat content in BTU per pound of feed at the column input. Its output serves as the measured variable to an enthalpy recorder-controller whose output cascades into a steam flow controller that modulates the preheater steam flow to maintain a constant feed enthalpy. Inputs to the computer are provided by conventional instrumentation in the form of signals from flow transmitters and thermocouples.

Benefits which accrue from improved column control through regulation of the feed enthalpy by computer control are (1):

(1) Improved primary control of the separation

(2) Lower operating costs

(3) Higher column throughputs

(4) Smoother terminal stream flows

(5) A more predictable operation with less human attention.

DERIVING THE EQUATION

Control of the feed stream heat content is based upon the computer solution of a steady state heat balance equation written for the column feed system. Referring to the schematic diagram of the feed portion of the distillation column (Figure 1) the total feed heat content per pound of feed, neglecting losses, is the sum of the following heat quantities.

$H_1 = c_{p_F}(T_1 - T_o)$ = Initial feed heat content above some reference temperature T_o – BTU per pound of feed.

$H_2 = \frac{B}{F} c_{p_B}(T_{B_1} - T_{B_2})$ = The heat given up by the bottom product stream to the feed in the economizer exchanger – BTU per pound of feed.

$H_3 = \frac{S}{F} H_s$ = The heat given up to the feed by the steam at the feed preheater – BTU per pound of feed.

The total heat content of the feed stream, per pound of feed, is then, in equation form;

$$H_T = H_1 + H_2 + H_3 \qquad (1)$$

or

$$H_T = c_{p_F}(T_1 - T_o) + \frac{B}{F} c_{p_B}(T_{B_1} - T_{B_2}) + \frac{S}{F} H_s \qquad (2)$$

ANALOG COMPUTER CIRCUIT

A suggested solution procedure outlining the mathematical operations required for solving equation 2 is shown in the information flow sheet of Figure 2. Using this diagram it is a relatively simple task to construct the computer circuit of Figure 3. Note that this circuit assumes that signals in the form of dc currents are available

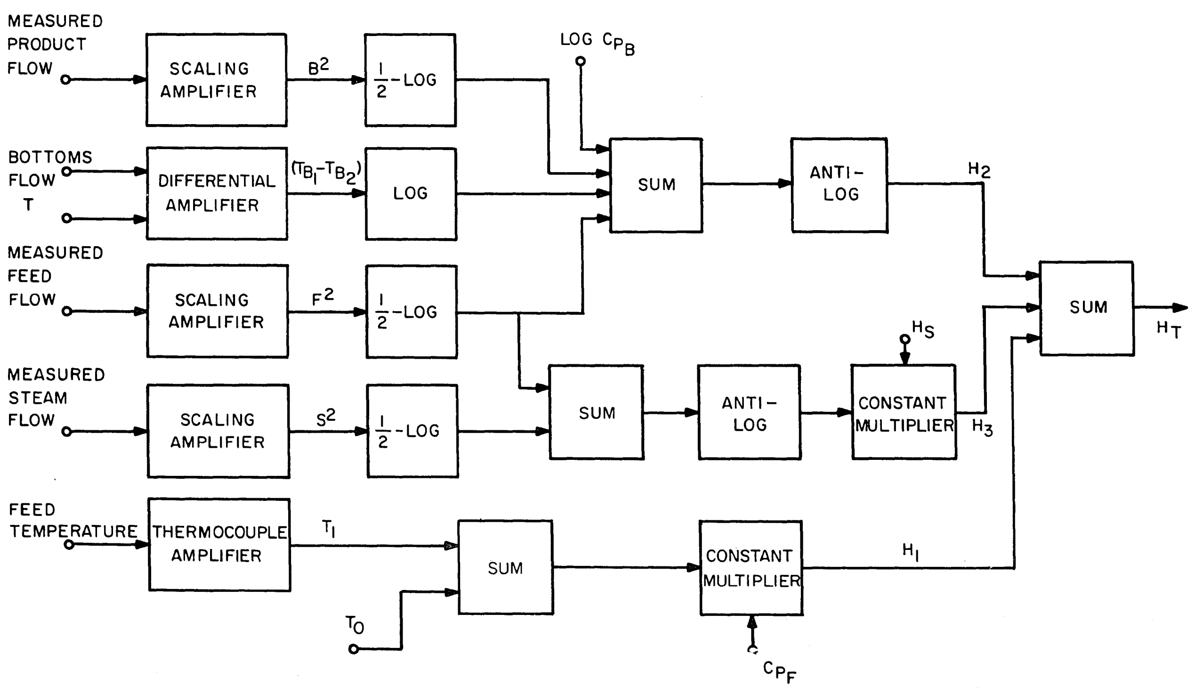


Figure 2. Calculation Scheme for Solving Steady-State Feed Heat Content Equation with an Analog Computer.

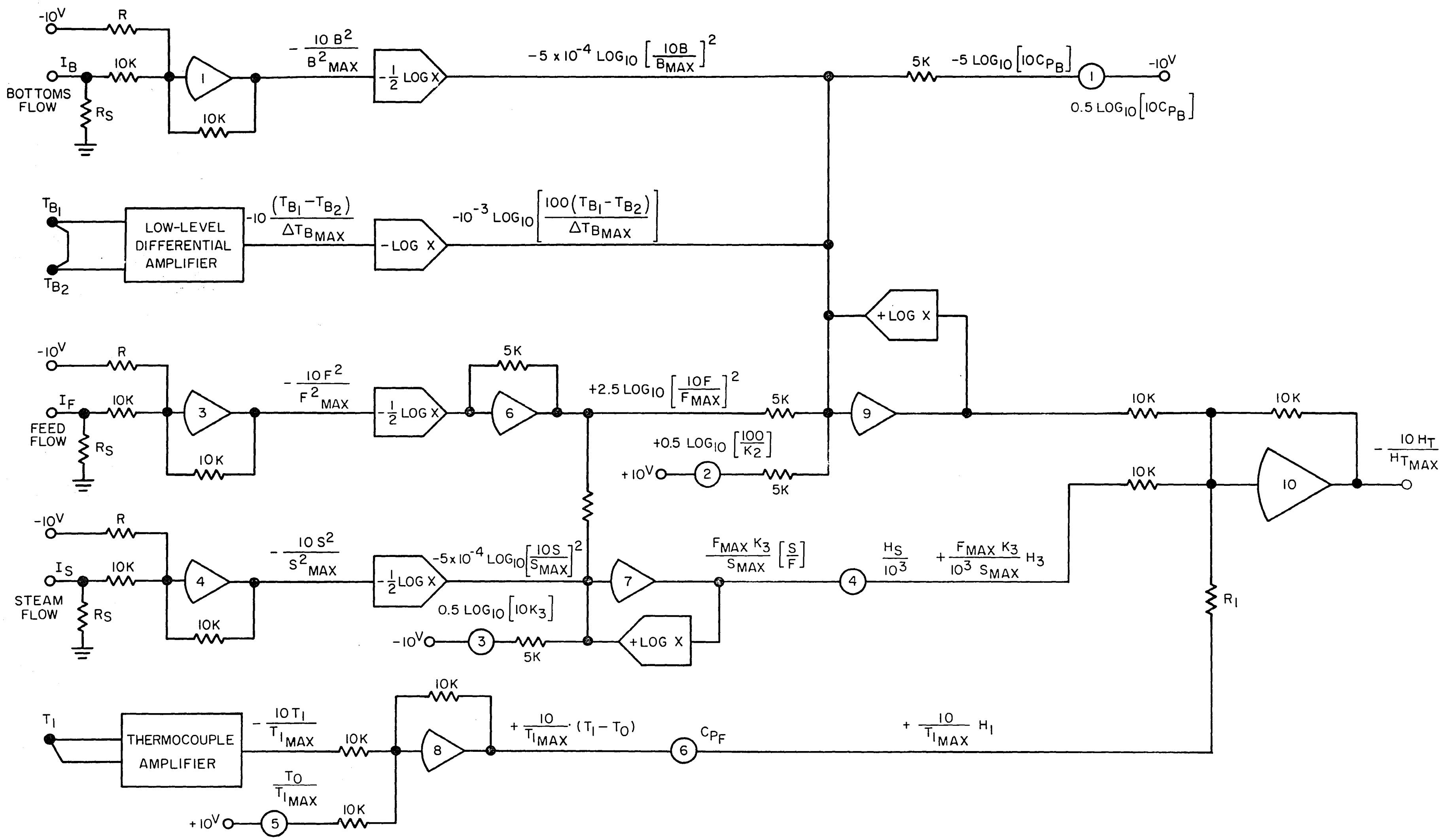


Figure 3. Scaled Analog Computer Circuit for Solving Feed Heat Content Equation, i.e., General Purpose Program for Feed Enthalpy Computer.

for representing the square of the three flow rates. Square root operations on these flow signals are performed automatically, being programmed into the computer circuits. Temperatures are assumed to be measured by thermocouples whose outputs may be fed directly to amplifiers internal to the computer. Although the computer output as shown in Figure 3 takes the form of a dc voltage which varies from 0 to -10 volts it is possible to arrange the amplifier input and output circuits such that a dc current acceptable by conventional instruments is obtained.

The circuit of Figure 3 employs the following types of standard PC-12 Computing Components.

DUAL OPERATIONAL AMPLIFIER (Type 6.368). Provides two high gain, chopper stabilized, transistorized operational amplifiers for the performance of linear and non-linear mathematical operations. Low drift, high accuracy, field-proven circuits are designed specifically for general purpose on-line computing applications. Compact, plug-in modules mount in vapor-tight industrial housings. Used in the computer circuit of Figure 3 for scaling of input signals and for summing operations. Four dual modules or a total of eight amplifiers are required.

LOW LEVEL DIFFERENTIAL AMPLIFIER (Type 6.422). A transistorized, low-level differential amplifier designed for amplification of low-level signals. Design features include AC input section for added stability, 0.01% gain accuracy, and input impedances greater than 10 megohms. Used in the computer circuit of Figure 3 to accept and amplify differential thermocouple inputs for measurement of the bottoms flow differential temperature. One required.

THERMOCOUPLE AMPLIFIER (Type 6.406). Transistorized, low-level amplifier designed for amplification of low level thermocouple signals. Has similar characteristics as Type 6.422 Low Level Differential Amplifier but is designed specifically for single-ended input signals. Used in the circuit to accept and amplify a thermocouple input for measurement of the input feed temperature. One required.

COEFFICIENT SETTING POTENTIOMETERS (Type 12.779). Provides four 10-turn, wire wound, 2000 ohm potentiometers with calibrated dials for setting of equation constants, constant inputs, and bias voltages. Six potentiometers required. Used in the circuit for introduction of scaling constants and for setting values for T_o, H_s, c_{pF}, c_{pB}.

1/2 LOG X DIODE FUNCTION GENERATOR (Type 16.215). Solid-state dual fixed diode function generator for generating logarithms, exponential functions, etc. When used with Amplifier 6.368 one generator will accept a positive voltage and generate a straight-line approximation of the logarithmic curve. The other generator accepts a negative voltage to perform the same function. Internal circuit components are sized to produce an output of 2.5 $\text{Log}_{10}(10X)$ for an input of X to facilitate the combined operations of square root and multiplication with a single amplifier. Current output for an input of X is $5 \times 10^{-4}\text{Log}_{10}(10X)$. Used in the circuit for forming the log of the signals representing the square of the flows. Three negative input generators are required.

LOG X DIODE FUNCTION GENERATOR (Type 16.214). Similar to the 1/2 Log X Generator but with internal circuit components sized to produce an output of 5.0 $\text{Log}_{10}(10X)$ when used with an operational amplifier. Current output for an input of X is 10^{-3} $\text{Log}_{10}(10X)$. Used in the circuit to perform anti-log operations and to take the log of the signal representing the bottoms differential temperature. Two positive input and one negative input generators are required.

These components, together with appropriate amplifier input and feedback resistances, system power supplies and control modules, patching system, etc., are mounted in an industrial housing to form the Feed Enthalpy Computer.

COMPUTER CIRCUIT SCALING

A generalized scaling scheme has been developed for the computer circuit used to solve the steady-state heat equation. All signals and circuit components are expressed in terms of the expected maximum values of the input variables. Thus, once the column operating conditions are known, the circuit components and the computed signals can be completely specified using the scaled computer variables shown on the circuit of Figure 3 and a design equation developed from the scaling procedure.

The Appendix presents a detailed development of the scaling.

EXAMPLE

Assume that the column operating conditions are given as follows:

B_{max} = 250,000 pounds per hour

$\Delta T_{B_{max}}$ = 300°F

F_{max} = 500,000 pounds per hour

S_{max} = 20,000 pounds per hour

$T_{1_{max}}$ = 200°F

c_{p_F} = 0.532 BTU per pound per °F

c_{p_B} = 0.424 BTU per pound per °F

H_s = 750 BTU per pound of steam

T_o = 75°F

From equation 2, the maximum value of H_T is calculated as

$$H_{T_{max}} = 0.532\ (200) + \frac{250{,}000}{500{,}000}(0.424)(300) + \frac{20{,}000}{500{,}000}(750) = 106.4 + 63.6 + 30 = 200.0$$

Through use of the design equation developed in the Appendix ....

$$\frac{1}{K_5} = \frac{F_{max} K_2}{\Delta T_{B_{max}} B_{max}} = \frac{F_{max} K_3}{10^3 S_{max}} = \frac{10}{H_{T_{max}}}$$

Then

$$\frac{1}{\ } = \frac{10}{H_{T_{max}}} = \frac{10}{200} = \frac{1}{20}$$

or

$$K_5 = 20$$

In addition

$$K_2 = \frac{\Delta T_{B_{max}} B_{max}}{20\ F_{max}} = \frac{(300)(250{,}000)}{(20)(500{,}000)} = 7.5$$

and

$$K_3 = \frac{10^3 S_{max}}{20\ F_{max}} = \frac{(1000)(20{,}000)}{(20)(500{,}000)} = 2.0$$

Potentiometer Settings become .....

#1 – $0.5\ Log_{10}(10\ c_{P_B}) = 0.5\ Log_{10}(4.24) =$

$(0.5)(.6274) = 0.3137$

#2 – $0.5\ Log_{10}(100/K_2) = 0.5\ Log_{10}(13.33) =$

$(0.5)(1.1248)$

$= 0.5624$

#3 – $0.5\ Log_{10}(10\ K_3) = 0.5\ Log_{10}(20) =$

$(0.5)(1.301) = 0.625$

#4 – $H_s/1000 = 750/1000 = 0.750$

#5 – $T_o/T_{1_{max}} = 75/200 = 0.375$

#6 – $c_{P_F} = 0.532$

Shunt resistors R_s are calculated to have the value . .

$$R_s = \frac{10}{I_{B_{max}} - I_{B_{min}}} = \frac{10}{(20-4)\ 10^{-3}} = \frac{10^4}{16} = 625 \text{ ohms}$$

Biasing resistors R are calculated to have the value ..

$$R = \frac{10}{R_s\ I_{B_{min}}}(10{,}000) = \frac{10^4}{(625)(4 \times 10^{-3})} = 40{,}000 \text{ ohms}$$

Scaling resistor R_1 has the value .....

$$R_1 = \frac{10\ K_5}{T_{1_{max}}}\ (10{,}000) = \frac{(10)(20)}{200}\ (10{,}000) = 10{,}000 \text{ ohms}$$

Amplifiers of interest have the following scaled computer variables as outputs .....

$$\#10 - \quad -\frac{H_T}{K_5} = -\frac{H_T}{20}$$

$$\#9 - \quad +\frac{F_{max} K_2}{T_{B_{max}} B_{max}} H_2 = +\frac{(500{,}000)(7.5)}{(300)(250{,}000)} H_2 = +\frac{H_2}{20}$$

... while potentiometers #4 and #6 have outputs scaled as follows .....

$$\#4 - \quad +\frac{K_3 F_{max}}{10^3 S_{max}} H_3 = +\frac{(2)(500{,}000)}{(1000)(20{,}000)} H_3 = +\frac{H_3}{20}$$

$$\#6 - \quad +\frac{10}{T_{1_{max}}} H_1 = +\frac{10}{200} H_1 = +\frac{H_1}{20}$$

-NOMENCLATURE-

T_1 = temperature of feed before entering economizer; °F.

T_o = arbitrary reference temperature used to compute H_T; °F.

T_{B_1} = temperature of bottoms product entering economizer; °F.

T_{B_2} = temperature of bottoms product leaving economizer; °F.

F = feed flow rate; lb/hour.

B = bottom product flow rate; lb/hour.

S = steam flow rate; lb/hour.

H_s = difference in enthalpy of steam entering preheater and condensate (assumed constant); BTU/lb of steam.

c_{P_F} = average specific heat of feed; BTU/lb – °F.

c_{P_B} = average specific heat of bottom product; BTU/lb – °F.

K_2, K_3, K_5 = scaling constants.

R_s = shunt resistors used to develop voltage from current inputs; ohms.

R = biasing resistors on input of flow scaling amplifier; ohms.

R_1 = input resistor for H_1 input to amplifier #10; ohms.

I = current representing square of input flows; millamperes.

SUBSCRIPTS

max = expected maximum value or range of variable.

- REFERENCES -

1. Lupfer, D.E., and M.W. Oglesby, "Automatic Control of Distillation Column Heat Inputs", Industrial and Engineering Chemistry, Dec. 1961.

2. Lupfer, D.E., and M. W. Oglesby, "Feed Enthalpy Computer Control of a Distillation Column", Control Engineering, Feb. 1962.

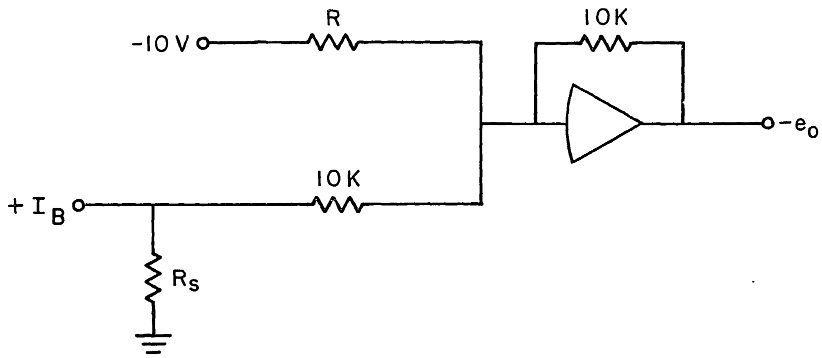
3. Lupfer D.E., and D.E. Berger, "Computer Control of Distillation Reflux", ISA Journal, Vol. 6, No. 6, June 1959.

4. Williams, T.J.; Harnett, R.T.; Rose, Arthur; Industrial and Engineering Chemistry, 48, 1008-19, 1956.

INPUT SCALING AMPLIFIERS. The components of the following circuit must be sized such that, for the range of currents between the minimum and maximum,

$$e_o = 0 \text{ for } I_{B_{min}}$$

$$e_o = 10 \text{ volts for } I_{B_{max}}$$



Summing currents at amplifier grid:

$$+\frac{R_s I_B}{10K} - \frac{10}{R} + \frac{e_o}{10K} = 0$$

Solving for resistance R:

$$R = \frac{100K}{e_o + R_s I_B}$$

Therefore, when $e_o = 0$ and $I_B = I_{B_{min}}$

$$\boxed{R = \frac{100K}{R_s I_{B_{min}}}}$$

The current summation equation then becomes

$$\frac{R_s I_B}{10K} - \frac{10}{100K} R_s I_{B_{min}} + \frac{e_o}{10K} = 0$$

so that when $I_B = I_{B_{max}}$, $e_o = -10V$

$$R_s I_{B_{max}} - R_s I_{B_{min}} = +10$$

or

$$\boxed{R_s = \frac{10}{I_{B_{max}} - I_{B_{min}}}}$$

e_o is to be made to represent the square of a flow, say B^2, so computer variable is defined as

$$-e_o = -k\, B^2$$

where k is an amplitude scale factor. But

$$k \cdot B_{max}^2 = 10$$

so

$$k = \frac{10}{B_{max}^2}$$

The scaled computer variable thus becomes

$$-e_o = -10 \frac{B^2}{B_{max}^2}$$

The Thermocouple Amplifier and the Differential Amplifier are scaled in exactly the same manner so as to restrict their maximum output to 10 volts. The circuits are more complex, however. Refer to the appropriate Service Manual for the exact procedure.

SCALING OF AMPLIFIER OUTPUTS

Amplifier #6: Summing Currents at grid (See Figure 3)

$$-5 \times 10^{-4} \operatorname{Log}_{10} \left[10 \left(\frac{10F^2}{F_{max}^2} \right) \right] + \frac{e_o}{5K} = 0$$

$$e_o = 2.5 \operatorname{Log}_{10} \left[\frac{100F^2}{F_{max}^2} \right]$$

Amplifier #7: Summing currents

$$-5 \times 10^{-4} \operatorname{Log}_{10} \left[\frac{100S^2}{S_{max}^2} \right] + \frac{2.5}{5K} \operatorname{Log}_{10} \left[\frac{100F^2}{F_{max}^2} \right] - \frac{10}{5K} \left(0.5 \operatorname{Log}_{10} \right) \left[10K_3 \right]$$

$$+ 10^{-3} \operatorname{Log}_{10} \left[10\, e_o \right] = 0$$

$$-2.5 \operatorname{Log}_{10} \left[\frac{10S}{S_{max}} \right]^2 + 2.5 \operatorname{Log}_{10} \left[\frac{10F}{F_{max}} \right]^2 - 5 \operatorname{Log}_{10} \left[10K_3 \right] + 5 \operatorname{Log}_{10} \left[10e_o \right] = 0$$

$$-5 \operatorname{Log}_{10} \left[\frac{10S}{S_{max}} \right] + 5 \operatorname{Log}_{10} \left[\frac{10F}{F_{max}} \right] - 5 \operatorname{Log}_{10} \left[10K_3 \right] + 5 \operatorname{Log}_{10} \left[10e_o \right] = 0$$

$$-5 \operatorname{Log}_{10} \left[\frac{10K_3\, F_{max}}{S_{max}} \left(\frac{S}{F} \right) \right] = -5 \operatorname{Log}_{10} \left[10e_o \right]$$

$$e_o = \frac{K_3\, F_{max}}{S_{max}} \left(\frac{S}{F} \right)$$

Amplifier #8: Summing currents

$$-\frac{10\,T_1}{T_{1max}}\left(\frac{1}{10K}\right)\left(+\frac{10\,T_o}{T_{1max}}\right.\left(\frac{1}{10K}\right)+\frac{e_o}{10K}=0$$

$$e_o=\frac{10}{T_{1max}}(T_1-T_o)$$

Amplifier #9: Summing currents

$$-5\times10^{-4}\,\mathrm{Log}_{10}\left[\frac{10B}{B_{max}}\right]^2-\frac{5}{5K}\,\mathrm{Log}_{10}\left[10\,C_{pB}\right]-10^{-3}\,\mathrm{Log}_{10}\left[\frac{100\,(T_{B_1}-T_{B_2})}{\Delta T_{B_{max}}}\right]$$

$$+\frac{2.5}{5K}\,\mathrm{Log}_{10}\left[\frac{10F}{F_{max}}\right]^2+\frac{5}{5K}\,\mathrm{Log}_{10}\left[\frac{100}{K_2}\right]+10^{-3}\,\mathrm{Log}_{10}\left[10e_o\right]=0$$

$$-5\,\mathrm{Log}_{10}\left[\frac{10B}{B_{max}}\right]-5\,\mathrm{Log}_{10}\left[10\,C_{pB}\right]-5\,\mathrm{Log}_{10}\left[\frac{100\,(T_{B_1}-T_{B_2})}{\Delta T_{B_{max}}}\right]$$

$$+5\,\mathrm{Log}_{10}\left[\frac{10F}{F_{max}}\right]+5\,\mathrm{Log}_{10}\left[\frac{100}{K_2}\right]+5\,\mathrm{Log}_{10}\left[10e_o\right]=0$$

$$-5\,\mathrm{Log}_{10}\left[\left(\frac{10B}{B_{max}}\right)\left(10\,C_{pB}\right)\left(\frac{100\,[T_{B_1}-T_{B_2}]}{\Delta T_{B_{max}}}\right)\right]+5\,\mathrm{Log}_{10}\left[\left(\frac{10F}{F_{max}}\right)\left(\frac{100}{K_2}\right)\right]$$

$$+5\,\mathrm{Log}_{10}\left[10e_o\right]=0$$

$$-5\,\mathrm{Log}_{10}\left[\frac{10^4\,B}{\Delta T_{B_{max}}\,B_{max}}\,C_{pB}\left(T_{B_1}-T_{B_2}\right)\frac{F_{max}\,K_2}{10^3\,F}\right]=-5\,\mathrm{Log}_{10}\left[10e_o\right]$$

$$e_o=\left(\frac{F_{max}\,K_2}{\Delta T_{B_{max}}\,B_{max}}\right)\frac{B}{F}\,C_{pB}\left(T_{B_1}-T_{B_2}\right)=\frac{F_{max}\,K_2}{\Delta T_{B_{max}}\,B_{max}}\,H_2$$

Amplifier #10: Summing currents

$$+\frac{F_{max}\,K_2}{\Delta T_{B_{max}}\,B_{max}}\,\frac{H_2}{10K}+\frac{F_{max}\,K_3}{10^3\,S_{max}}\,\frac{H_3}{10K}+\frac{10}{T_{1max}}\,H_1\left[\frac{1}{\frac{10K_5}{T_{1max}}\,(10K)}\right]+\frac{e_o}{10K}=0$$

$$+\left[\frac{F_{max}\,K_2}{\Delta T_{B_{max}}\,B_{max}}\right]H_2+\left[\frac{F_{max}\,K_3}{10^3\,S_{max}}\right]H_3+\left[\frac{1}{K_5}\right]H_1=-e_o$$

In order to sum these signals, all scale factors must be equal, or

$$\frac{F_{max}\,K_2}{\Delta T_{B_{max}}\,B_{max}}=\frac{K_3\,F_{max}}{10^3\,S_{max}}=\frac{1}{K_5}$$

The equation then becomes

$$+\frac{1}{K_5}\left[H_1+H_2+H_3\right]=-e_o=\frac{H_T}{K_5}$$

Representing e_o as a computer variable, and restricting the amplifier output to a 10 volts maximum . . .

$$k \cdot H_{T_{max}} = 10$$

$$k = \frac{10}{H_{T_{max}}}$$

or

$$\frac{1}{K_5} = \frac{10}{H_{T_{max}}}$$

Thus, the design equation becomes

$$\boxed{\frac{F_{max} K_2}{\Delta T_{B_{max}} B_{max}} = \frac{F_{max} K_3}{10^3 S_{max}} = \frac{1}{K_5} = \frac{10}{H_{T_{max}}}}$$