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USE OF HYBRID SIMULATION TECHNIQUES IN THE NUCLEAR ROCKET PROPULSION PROGRAM*

MASTER

Hugh S. Murray　　Charles P. Milich
Thomas E. Springer　　J. Douglas Balcomb
University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87544
U.S.A.

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INTRODUCTION

Hybrid simulation is being used at the Los Alamos Scientific Laboratory to predict the dynamic behavior of nuclear rocket propulsion systems. Hybrid computer models of the nuclear reactor and its associated propellant feed-system are used for studying possible accidents during a test to determine proper emergency shutdown procedures. These simulations are run in real time. Transfer function data are also obtained at various operating points for designing the control systems.

To obtain reactor heat exchanger models that are accurate over a wide range of operating levels, the properties of the hydrogen propellant must be generated. Since any property is a function of two other properties, this task requires the capability of two-dimensional non-linear function generation. Since the digital computer is much better able to solve this problem than the analog computer, the need for hybrid rather than pure analog computation is obvious.

THE HYBRID FACILITY AT LOS ALAMOS

The hybrid computer facility used in the nuclear rocket program consists of two Electronic Associates, Inc. 100-volt analog computers (Models 231-R and 221-R) with a total of 220 amplifiers, and of a Honeywell, Inc. DDP-116 digital computer with 8192 words of memory. The word length in the DDP-116 is sixteen bits. Communication between the two types of computers is provided by a Raytheon 40-channel analog-to-digital multiverter (ADC) and by 40 digital-to-analog converters (DAC). Conversion is to twelve bits, including sign, which will resolve analog voltages as low at 50 millivolts.

The digital-to-analog converters are variable-reference devices in which the 100-volt reference of a DAC may be replaced by an analog voltage. This configuration allows two-quadrant multiplication of a digital voltage by an analog voltage.

*Work performed under the auspices of the U. S. Atomic Commission

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DISCLAIMER

The digital computer is thought of, in this facility, as a "black box" function generator which independently generates non-linear functions of analog voltages and has no control over the analog computers. The digital computer performs its tasks continuously, regardless of the mode of the analog computer.

HYBRID SOFTWARE

The rate at which the digital computer reads analog voltages, calculates functions, and outputs analog voltages is controlled by three separate interrupt clocks. For the nuclear rocket system considered, the clock rates for the three groups of functions were 500, 125, and 62.5 generations per second, respectively. In general, digital multiplications and one-dimensional table lookups were executed at the faster two rates, whereas hydrogen properties were executed at the slow rate.

A special computer program was written for the Los Alamos hybrid computer. The program, called HOP (Hybrid Operating Program), is basically a macro-compiler which combines machine-language instructions to generate a particular function with the addresses of the corresponding analog input and output channels. For example, the following lines of information read by HOP from a typewriter or cards will compile and then execute a code to: (1) multiply ADC channel 4 by ADC channel 6 and place the result on DAC channel 2; and (2) put ADC channel 5 through a one-dimensional digital function generator whose output will appear on DAC channel 1.

```
INIT    FAST
        MPY     M4, M6, D2
7       DFG     M5, D1
        END
INIT    DATA
7       DFG     .1, .12, .2, .25, .3, .4, .45, .3, .2, .1, 0
        END
        XEQ
```

These functions will be executed at the fast clock rate.

The data statement allows the required data for the DFG to be read into the machine. The number 7 refers the DFG function to data table number 7.

It is not the intent of this paper to describe HOP in detail but rather to convey its capability. HOP has successfully provided a means of communication with the hybrid system for the analog-oriented user. In particular, HOP has made it unnecessary for the user to learn the digital computer assembly language in order to use the hybrid computer.

NON-LINEAR FUNCTION GENERATION ON THE DIGITAL COMPUTER

Enthalpy (H) and pressure (P) are used to describe the state of the coolant in the rocket heat exchanger model. These two properties are then used by the digital computer to look up the other properties which are used in the model. Three additional properties are required in a nuclear rocket model: temperature, the density correction factor for the ideal-gas relationship (compressibility), and the property-dependent factor in the heat-transfer correlation. The heat-transfer coefficient which is generated is:

$$h = \frac{k^{.6}\, c_p^{.4}}{\eta^{.4}}$$

where k is the conductivity, c_p is the specific heat, and η is the viscosity of the coolant.

The coefficient h is required for describing the heat transfer from the walls of a heat-exchanger section to the coolant. The dynamic relationship between the material temperature and gas temperature is given by:

$$\dot{H}_m = Q - \frac{K}{M} h \,(T_m - T_g)$$

where

T_m = the material temperature, a function of the material enthalpy, H_m

M = material mass

K = geometric portion of the heat transfer coefficient

T_g = average coolant temperature

h = property-dependent heat transfer coefficient--a function of gas enthalpy and pressure

Q = heat generated

The steady-state enthalpy rise of the coolant in a heat-exchanger section is given by:

$$\Delta H_g = \frac{K}{\dot{w}} h \left(T_m - T_g\right)$$

where $\dot{w}$ is the coolant mass flow rate.

The gas temperature T, as well as h, is seen to be a function of gas enthalpy and pressure. However, whereas h is looked up directly, the quantity, T/H + CONST, is looked up instead of T. The constant is 150 BTU/lb. In this way, the value H + 150, which is an analog variable, may be used as the DAC reference to obtain T. T/(H + 150) is an extremely well-behaved function for hydrogen. Therefore, it may be looked up relatively slowly while T retains the bandwidth of H.

The functions h, T, and T/(H + 150) are shown in Figures 1, 2, and 3, respectively. A partial mechanization diagram for an analog-hybrid heat exchanger calculation is shown in Figure 4.

The compressibility factor is generated in the same manner as temperature. Instead of compressibility, Z, the property

$$\frac{ZT}{H + 150}$$

is generated. This is done because the fluid continuity equation for a heat-exchanger section

$$\dot{\rho} = \frac{1}{V} \left(\dot{w}_{in} - \dot{w}_{out}\right)$$

is written in terms of density, ρ. V is the coolant passage volume. Pressure is obtained from density by multiplication by ZT. Again, the desired function, ZT, is modified by dividing by (H + 150) so that a slowly-varying function may be generated. Figure 5 shows a diagram for obtaining pressure from the continuity equation.

The actual hydrogen property determination is made by means of a four-point linear interpolation scheme. The formulation is given in Figure 6. The hydrogen property grid used for the three properties in nuclear rocket simulations is shown in Figure 7. The data points are generated by a larger code* which has access to detailed properties of hydrogen.

*O. A. Farmer, T. E. Springer, and B. B. Fisher, Los Alamos Scientific Laboratory Report LA-3381, 1965.

Although hydrogen property generation is one of the most important tasks performed by the digital computer, several other types of functions are required in a nuclear rocket simulation. Most of the necessary one-dimensional functions are generated digitally, for example. These include material temperatures versus enthalpies, reactivity versus control drum position, and temperature reactivity functions. The general elimination of non-linear analog devices has greatly increased problem reliability and reproducibility of results.

Many arithmetic functions are performed on the digital computer. These include multiplication, division, and square-root extraction and are generally repeated at the faster clock rates. The approximate timing for a few of the digital functions used is given below.

Function	Time, Microseconds
Hydrogen Property Lookup (H2PR)	760
Multiply (MPY)	16
Divide (DIV)	30
Square-Root (SQRT)	130
One-Dimensional Table Lookup (DFG)	60

A typical rocket simulation uses 11 DFG's, 6 H2PR's, 2 SQRT's, 4 MPY's, and 9 DIV's.

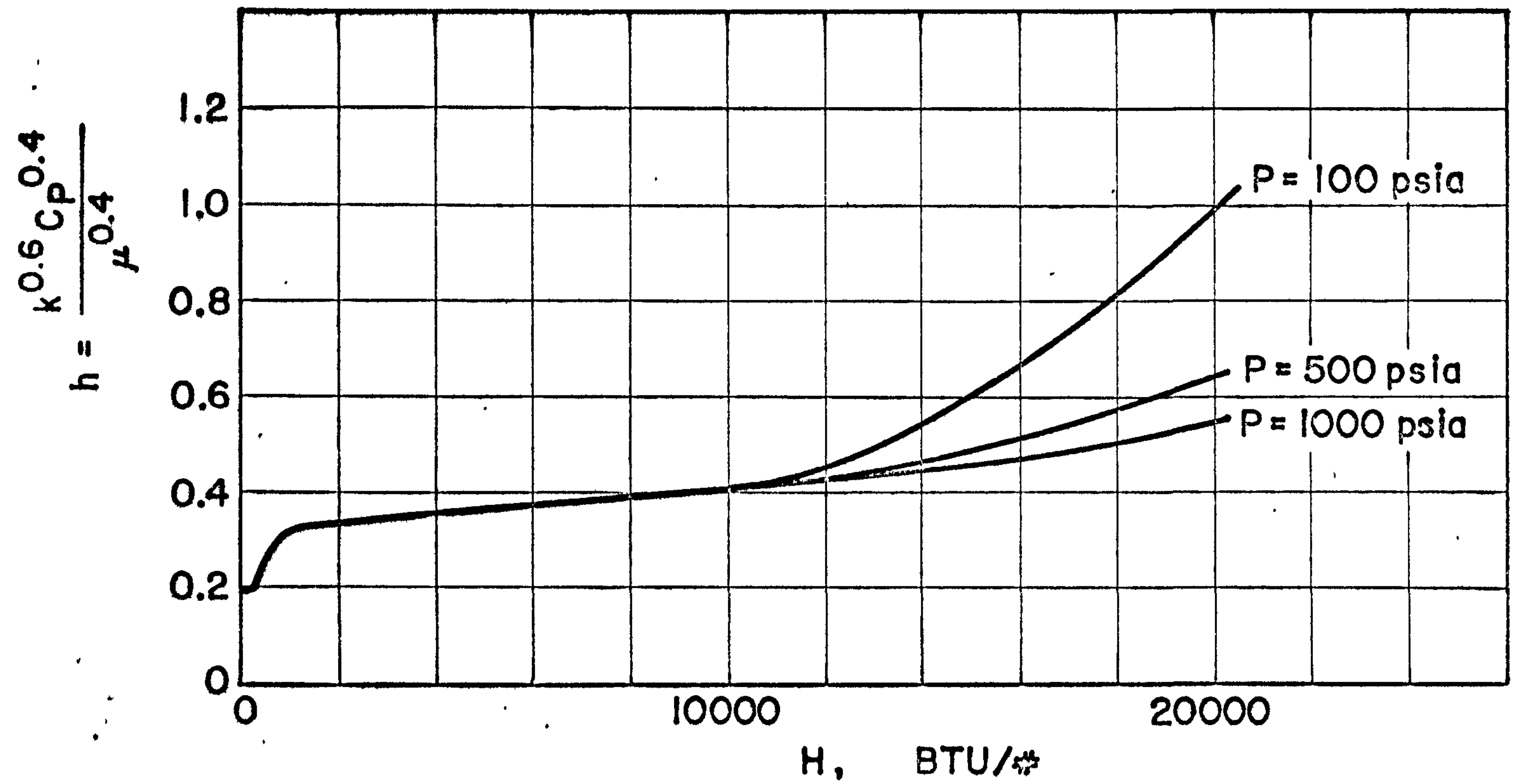


FIGURE I h vs H

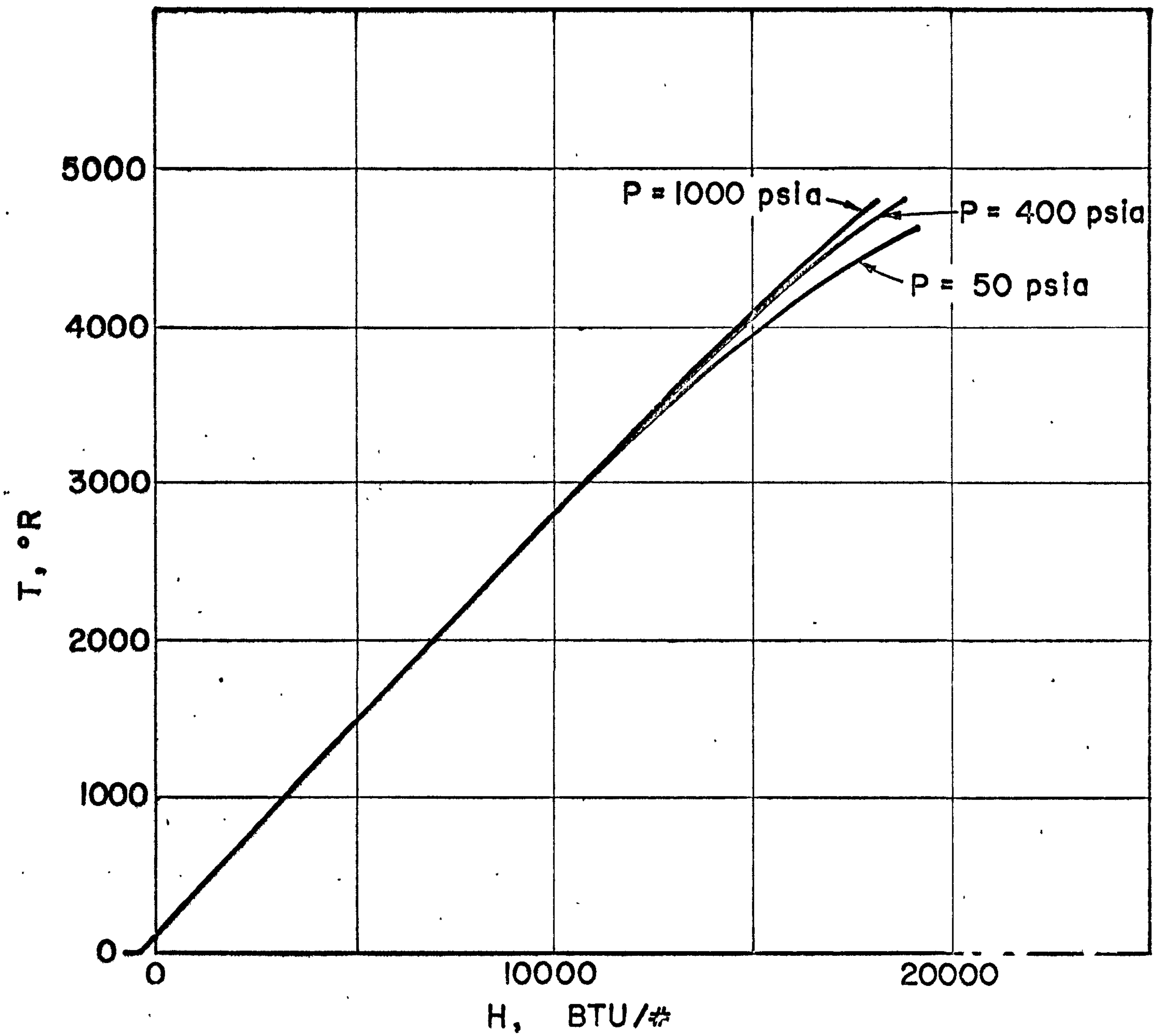


FIGURE 2 T vs H

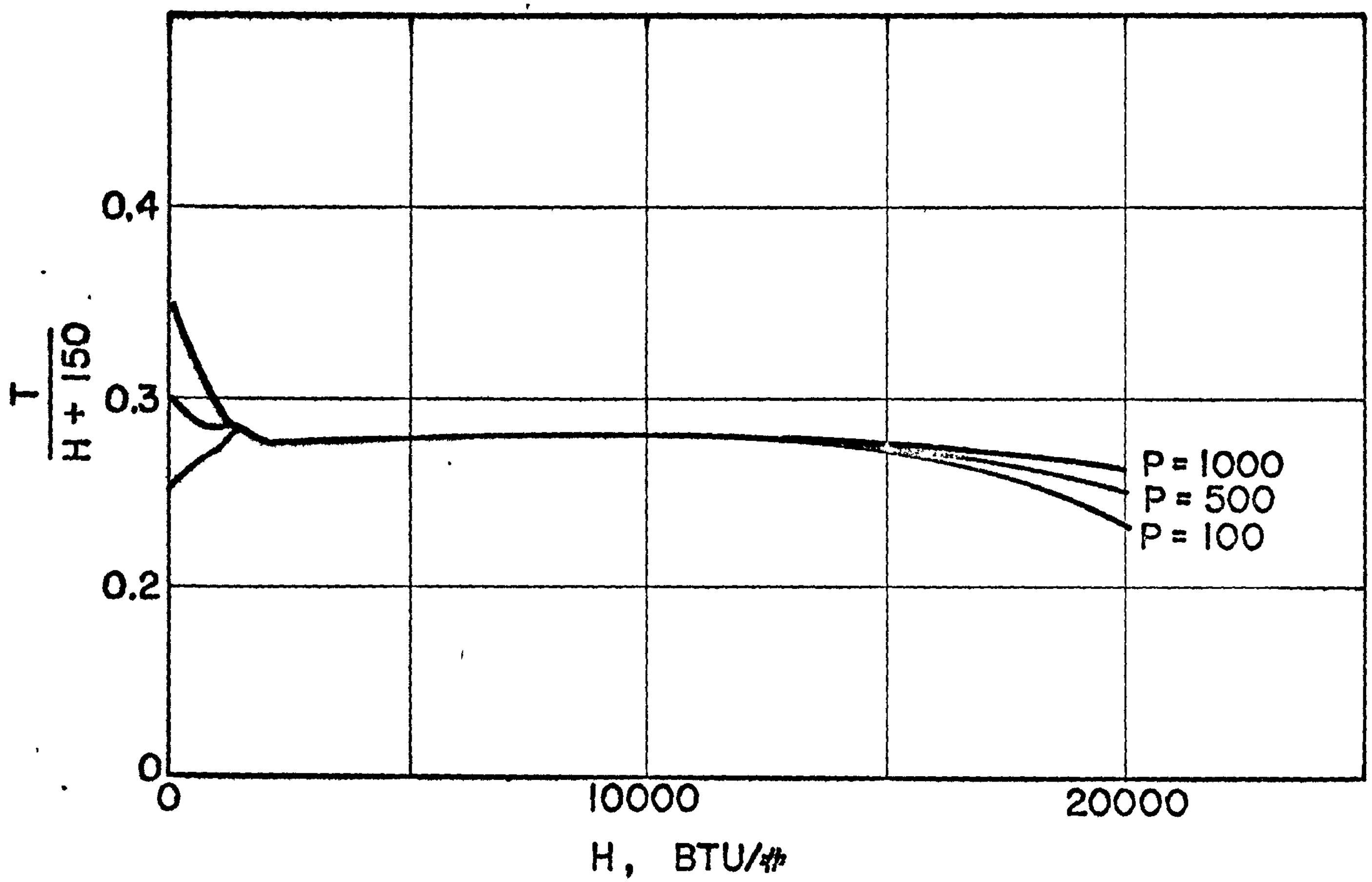


FIGURE 3 $\frac{T}{H + 150}$ vs H

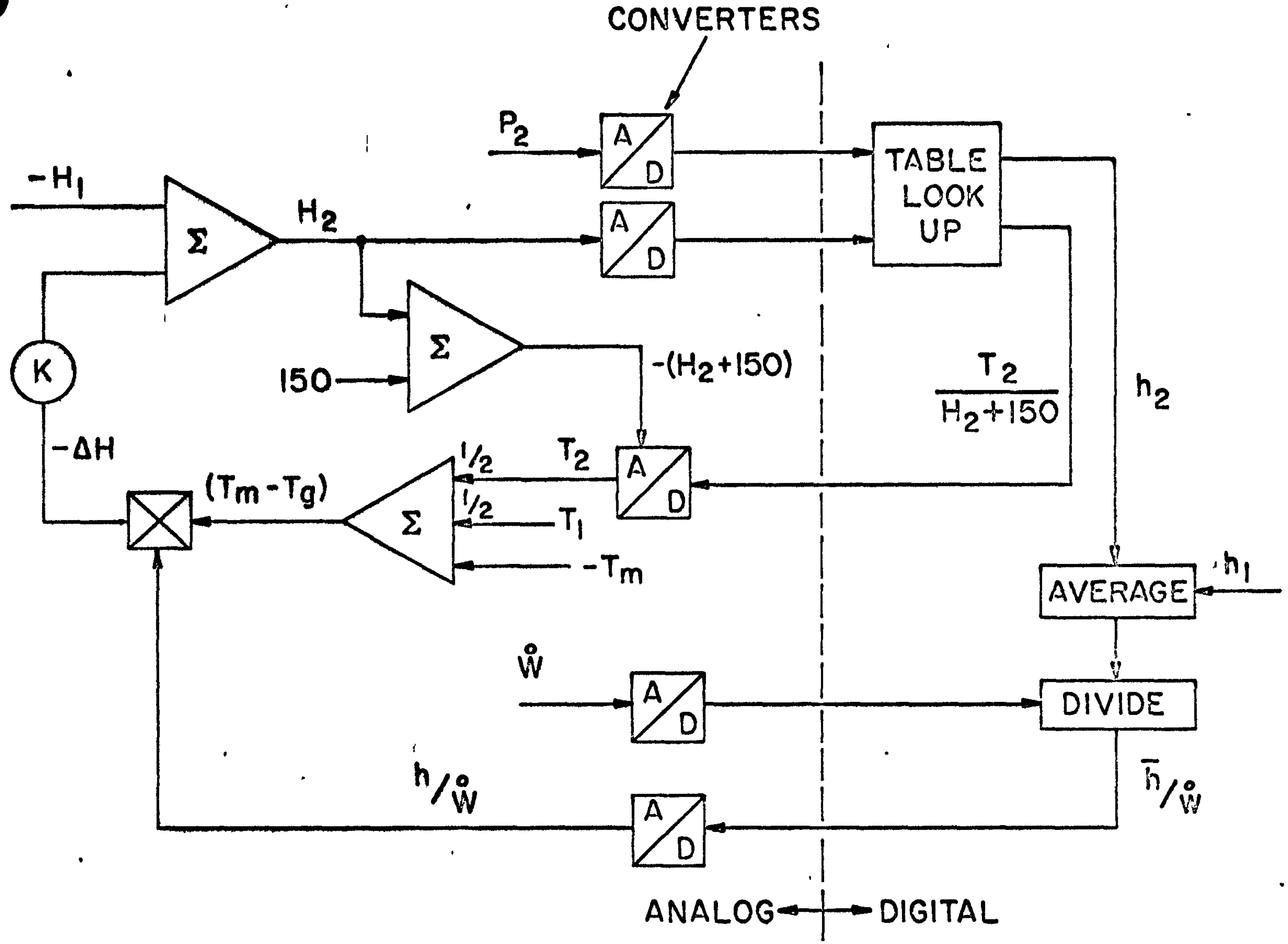


FIGURE 4

STEADY STATE PORTION OF HEAT TRANSFER CALCULATION

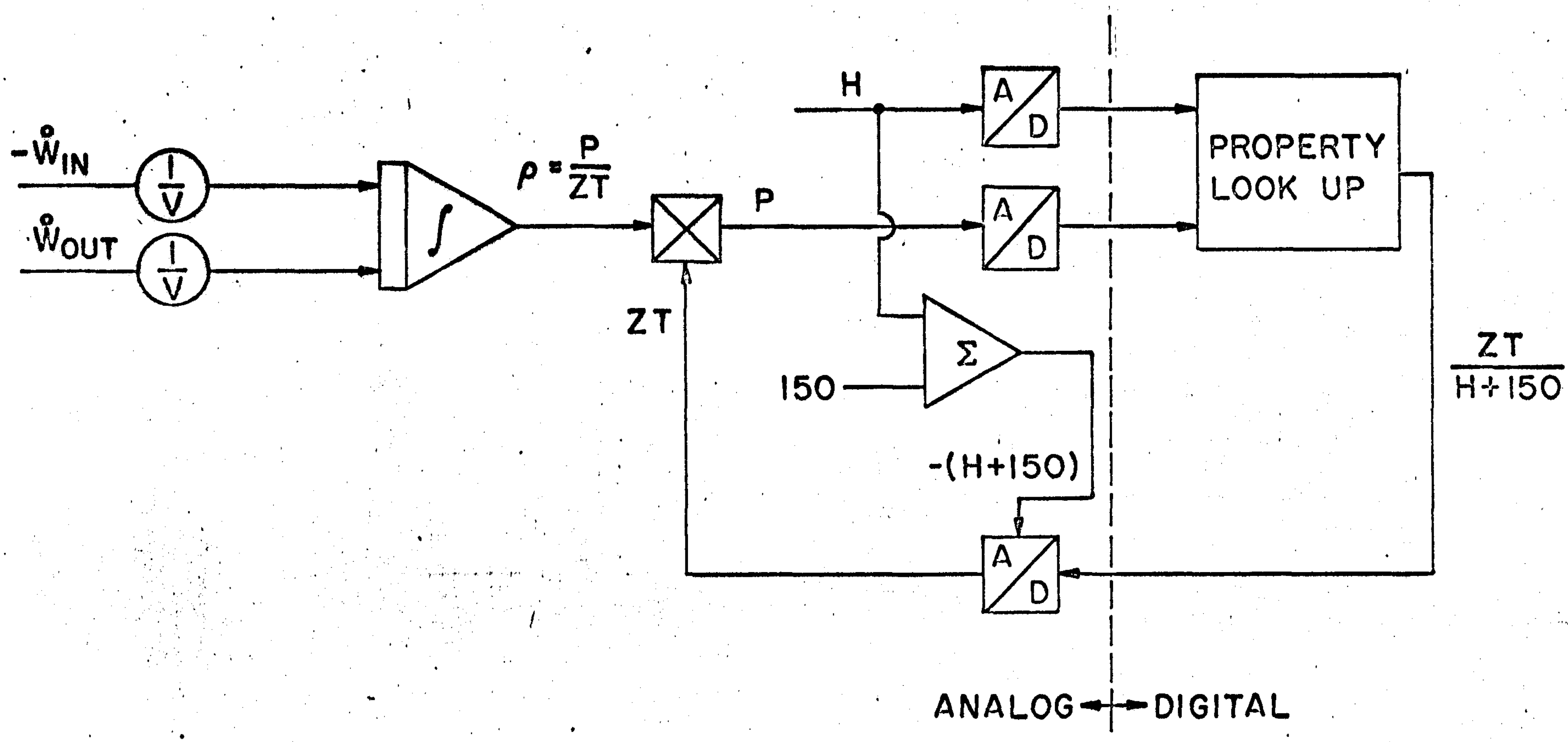
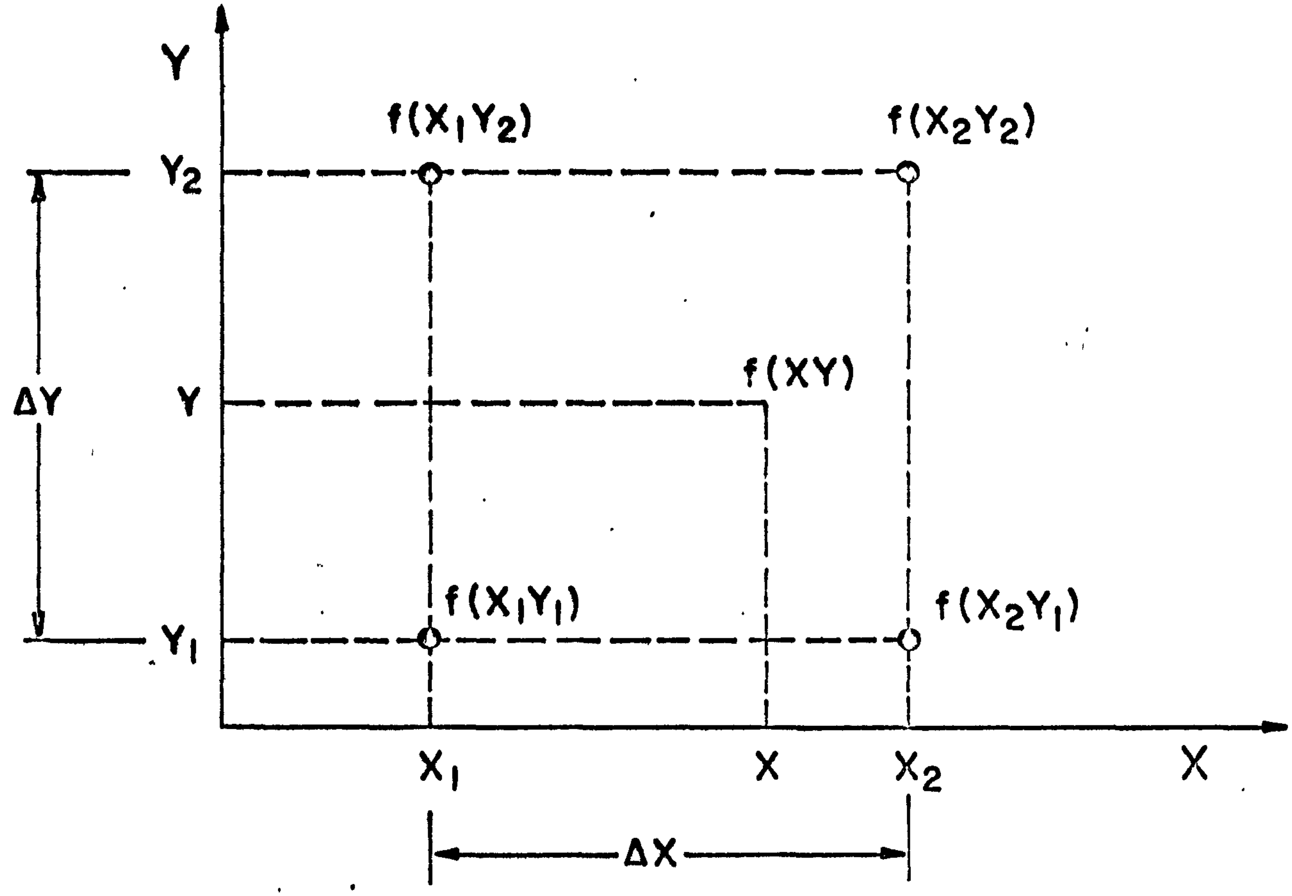


FIGURE 5
OBTAINING PRESSURE
FROM DENSITY



$$f(XY) = f(X_1Y_1) + \frac{(Y-Y_1)}{\Delta Y}\left[f(X_1Y_2) - f(X_1Y_1)\right]$$

$$+ \frac{(X-X_1)}{\Delta X}\left[f(X_2Y_1) - f(X_1Y_1)\right] + \frac{(X-X_1)(Y-Y_1)}{\Delta X\,\Delta Y}\left[f(X_2Y_2) - f(X_2Y_1) - f(X_1Y_2) + f(X_1Y_1)\right]$$

FIGURE 6

FOUR - POINT LINEAR INTERPOLATION

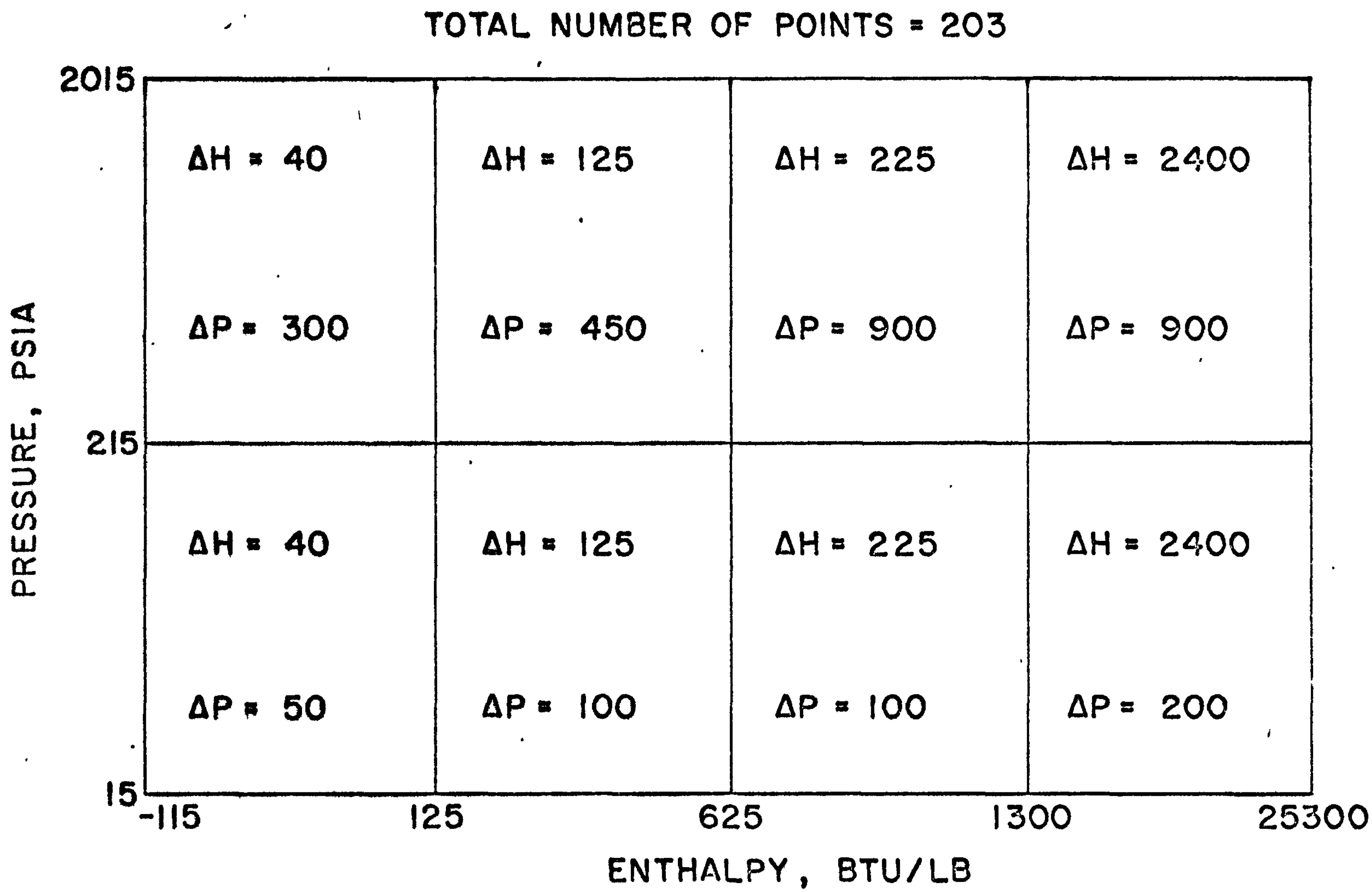


FIGURE 7

HYDROGEN PROPERTY GRID