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NL-339 (3/77)

# EXPERIMENTS ON SURGE TANK PRESSURE TRANSIENTS

By

William W. L. Ng

THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES
OF THE UNIVERSITY OF OTTAWA AS PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF
APPLIED SCIENCE IN MECHANICAL ENGINEERING

## CONTENTS

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# ABSTRACT

With the advent of nuclear reactor power plants the development of a rigorous theoretical model for predicting the surge tank pressure transients during prescribed changes in liquid level history has been a subject of great interest. Due to the coolant expansion and contraction in primary loop of a reactor, there are three distinct modes of surges, namely, 'pure' insurge, 'pure' outsurge and multiple surges (a series of insurge and outsurges). The purpose of this project is to construct a simple experimental apparatus and to study the experimental aspect of multiple surge transients. It concentrates mainly in some of the measurement techniques in a laboratory size surge tank and attempts are made in experimental procedure for different modes of simulation of pressure transients.

Experimental data from numerous tests on the laboratory size surge tank for both insurge and outsurge are included. With available analytical models to simulate pressure transient prediction, the results are exceedingly good and are in close agreement with experimental data. One important parameter which has been discovered in this experiment is the transient rate surge. For example, in the pure outsurge case, a fast or slow transient rate has a considerable difference in pressure drop for a given experimental run.

Since no heat transfer is being assumed in the derivation of outsurge governing equation, a rapid transient flow rate is required for good prediction of the pressure drop. However, in the pure insurge case, a slow transient rate should take place to allow heat transfer to occur. For multiple surges, in general a good agreement has been obtained between predicted and experimental pressures. Some discrepancy at the second stage of the outsurge process does exist. This is due to the fact that computational switches of governing equations which are employed in the analytical model do not allow thermodynamic equilibrium. In reality, this is not true.

Another type of multiple surges, outsurge followed by insurge, which involves more violent transition between fast outsurge and slow insurge produces a consistent trend in pressure prediction using the existing model. Modification of governing equation is needed to accommodate fast transient of this mode of multiple surge. Recommendation for future improvement of surge tank apparatus which will facilitate verification of any changes in analytical models is also included.

# LIST OF SYMBOLS

| | | |
|---|---|---|
| A | Area of surge tank wall | |
| a | Volume of the hemispheric portion of the pressurizer | $m^3$ |
| b | Cross-sectional volume of the pressurizer per cm displacement | $m^3/cm$ |
| D | Diameter of the pipe | in |
| E | Voltage source | volt |
| h | Specific enthalpy | BTU/lbm |
| J | Mechanical equivalent of heat | |
| K | Isentropic expansion coefficient | |
| L | Water level of the liquid | cm |
| P | Pressure | bar |
| Q | Amount of heat transfer | Joules |
| R | Resistance | ohm |
| t | Time | sec |
| U | Temperature | |
| v | Specific volume | $ft^3/lbm$ |
| Vd | Total pressurizer volume | $m^3$ |
| $\Delta x$ | Incremental distance in x-direction | |
| Z | Input impedance | ohm |

## LIST OF SUBSCRIPTS

| | |
|---|---|
| 1 | Water at constant height reference leg |
| 2 | Water between the top and the bottom reference point |
| 3 | Water between the bottom reference point and the input port of differential pressure transucer |
| cm | Common mode |
| in | Normal mode |
| cw | Cold water |
| o | Outside |
| i | Internal |
| N2 | Nitrogen |
| sas | Saturated steam |
| sus | Superheated steam |
| saw | Saturated water |
| suw | Sub-cooled water |
| t | The surge tank |

# LIST OF FIGURES

# Chapter I

## INTRODUCTION

### 1-1 General

Any closed liquid system, subject to changes in temperature and hence in colume, must be protected against excessive pressure variations. The Canadian designed line of power reactors named CANDU which use deuterium (heavy water) as a moderator and natural (unenriched) uranium as a fuel incorporate a pressurizer in the primay circulation loop. This pressurizer is a vapor-filled chamber capable of cushioning the volume transients. The lower portion of the tank is filled with liquid acting as a reservoir to excessive coolant while the upper portion contains vapor. The schematic diagram Fig. 1-1 shows the primary and secondary cooling circuits of a closed-cycle type nuclear power plant using pressurized heavy water as the coolant.

Heavy water is heated in the reactor core and flows through a steam generator, where secondary steam is generated for the turbine system, the primary coolant returns to the reactor vessel through a circulation pump. Fluctuation of primary coolant temperature due to changes of turbine load causes volume transients and pressure transient is resulted. The pressurizer chamber has its additional function of maintaining the coolant pressure within pres-

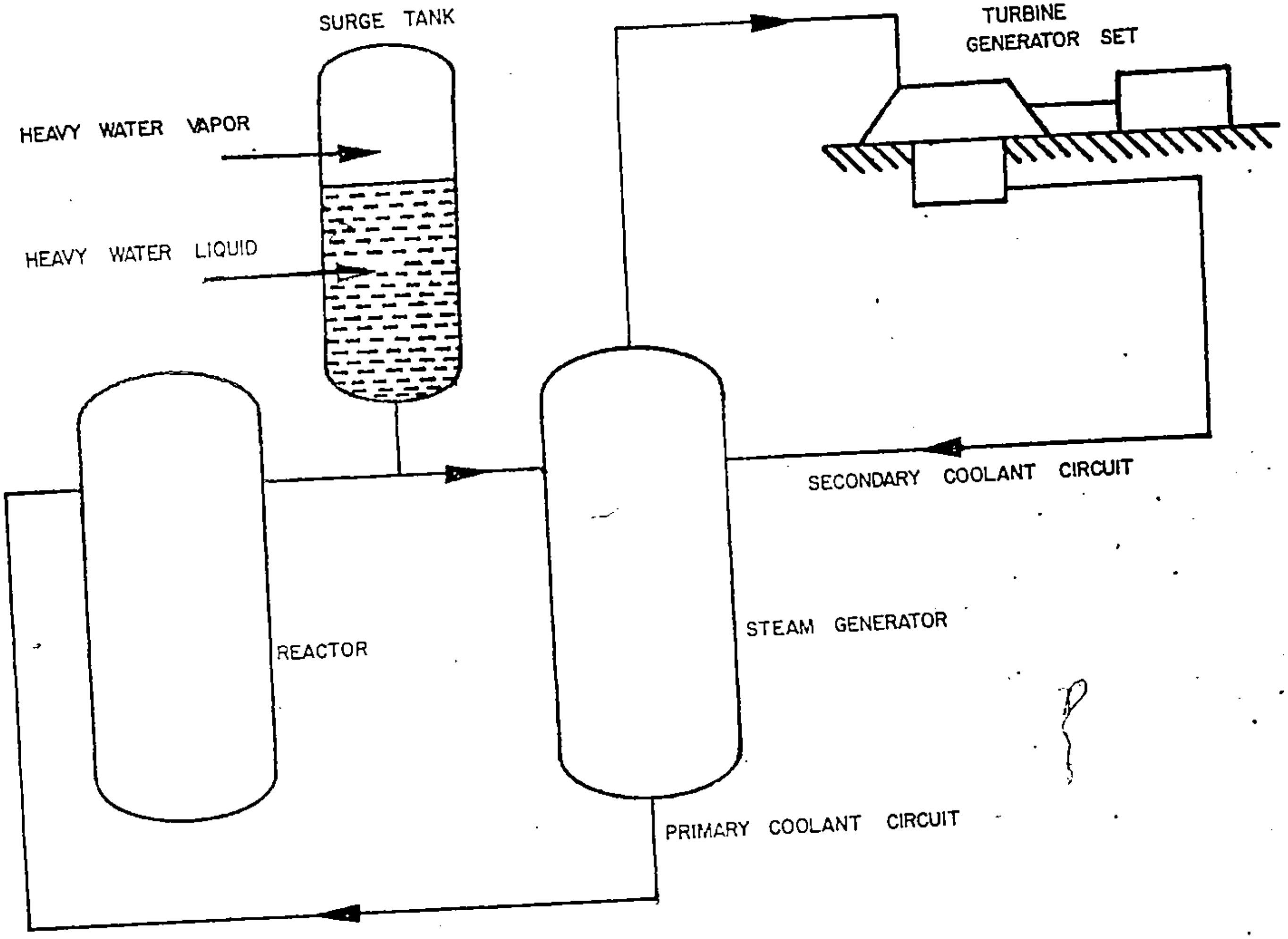


Fig. 1-1 SIMPLIFIED SKETCH OF A REACTOR

cribed limits by means of heaters immersed in the liquid.

A pressurizer or surge tank in CANDU reactor power generation plant plays a very important role both in design and performance. Optimum dimension of such a pressurizer will not only cause a considerable saving in containment cost, but it would also become an attractive proposition for naval power plant. Manoeuvrability requirements for ships impose stringent performance criteria for the pressurizer in terms of the pressure limits to be maintained upon load changes.

There are three modes of pressure transients that would likely to occur. These pressure transients are brought about by volume changes in the primary coolant - the 'pure' insurge, 'pure' outsurge and multiple surges of coolant into or out of the pressurizer. During steady state operation of the reactor plant the amount of energy supplied by the reactor equals the amount of energy extracted from the steam generator by the secondary system, so the total energy content of the primary water and hence its volume remains constant. A decrease of turbine load causes a rise in average temperature of the primary cooling water and consequently, an increase of its volume. Coolant rushes into the surge tank and the pressure increases - pure insurge. On the other hand an increase of turbine load results a fall in average temperature of the primary cooling water. This brings about a decrease of its volume. Coolant rushes out the surge tank and the pressure decreases - pure outsurge.

However, the occasion which may be expected from failure of secondary circuit pump arrives when there is a turbine load excursion. The coolant surges into the pressurizer then it is followed by coolant surges out. The cycling effect can also be brought about in a ship propulsion plant by a sudden manoevre. In the exact opposite fashion, the coolant surges out first and then it surges into the pressurizer again. This is caused by an increase of turbine load and next followed by a decrease of load. Pressure rises and falls in accordance to decrease or increase of load. This mode of pressure transient is called multiple surge.

Since nuclear power plants are designed for steady state operation of base load, this undesirable adverse phenomena of multiple surges requires a clear understanding of its mechanism involved and at the same time it is necessary to predict pressure transient.

## 1-2 The Scope and Motivation of this Project

Accurate prediction of pressure transients in a surge tank is very important to the safety of reactor operation. In recent years liquid cooled nuclear power reactors have placed particular emphasis on the need for an analytical method of predicting pressure change. And the third mode of multiple surges presents another challenge for accurate prediction.

Some of the available analytical models such as Ref. (1, 2 & 3) have been tested with actual reactor loop data. The results are exceedingly good and are in close agreement with experimental data. Laboratory scale set-up which is presented below has not been tried out at pressures higher than 200 psi. The purpose is to simulate insurge and outsurge experimentally. It is the intention of the author to establish a small size tank with facility to measure pressure and water level as a mean to verify the analytical models for pure insurge and pure outsurge. The scope of this project is to build the surge tank together with full instrumentation to measure water level, pressure and temperature information. These serve as inputs to the analytical models. The predicted pressure is then compared with experimental results in the designed pressure range.

In light of completion of this system set-up, initial test runs were performed. The third mode of multiple surge (insurge followed by outsurge) which is the primary function of this exercise was also simulated. Verification of these experimental results with existing multiple surge analysis and some modifications were performed.

This project concentrates mainly in some of the measurement techniques in a laboratory size surge tank and therefore attempts were made in establishing experimental procedures for different modes of simulation of pressure transients.

## 1-3 Survey of the Literature

### General

A number of theoretical models have been proposed for predicting the pressure transients during insurge and outsurge (1)(2). Yet the important flashing phenomenon associated with the outsurge and the condensation phenomenon associated with the insurge is not adequately investigated. The theoretical analysis and the experimental information for the multiple surges is almost non-existent in the available literature.

### Steam Compression

When the vapor-liquid interface rises due to an insurge of water into the pressurizer, the vapor phase is compressed. The initially saturated steam becomes superheated. In the beginning the content of the pressurizer is at the saturated temperature corresponding to the saturated pressure. When the vapor is being compressed due to insurge, heat transfer from the vapor to the vessel wall starts. Vapor starts condensing on the cooler boundaries of the wall and the liquid. The vessel surface which covers with condensate will necessarily follow the saturated temperature. Hence the temperature of the outside boundary of the vapor volume must also have the saturation temperature corresponding to the pressure at any particular instant.

The conclusion is that the vapor phase is nonhomogeneous during insurge and is composed of inner volume of the superheated vapor and a surrounding volume of vapor with a temperature going to the saturation temperature at the boundary of the vessel wall. The thickness of this 'Boundary Layer' is similar to filmwise condensation on a vertical surface. The film growth along the vessel wall is generally small. In most of the cases, it is, therefore, allowable to approximate this nonhomogeneous vapor volume by a homogeneous one.

All the previous investigations agree at one point that the isentropic model for the insurge is highly inappropriate and the pressure predicted on the basis of this model is excessively high compared to those measured during experiments. This discrepancy is related to the fact that an additional amount of energy from the steam will be removed due to the heat transfer from the vapor to the pressurizer wall, which is at a relatively low temperature.

Nahavandi and Makkenchery (4) developed a theoretical model based on the concepts of bubble rise and condensate drop velocity. The pressurizer is divided into two controlled volumes or so called stratified elements separated by a water vapor interface. The bottom element contains subcooled or boiling liquid and the top element contains superheated or condensing vapor. Between these two controlled volume, the authors formulate four kinds of state which would likely be recognized during the operation of a pressurizer. With appropriate assumptions the four kinds of state that complete the description of pressurizer insurge and outsurge, the continuity and enerfy equations were then applied. The resulting model so formulated is used to predict pressure transient based on certain criteria that would help to recognize the four states inside the pressurizer.

Drucker and Tong (5) conducted a series of experiments on a low pressure laboratory model of a surge tank and tried to obtain a mathematical correlation between the level and pressure. They used a step by step time increment and conducted the energy balance at the end of each time increment. The heat flow from the vapor is calculated from an empirical relation and heat sink constant for the vessel walls and liquid, which was obtained experimentally.

Drucker and Gorman (6) described an iterative procedure for the pressure prediction which was similar to the one described by Drucker and Tong (5), except that no empirical constants were required. Good agreement between the experimental and predicted values were obtained. Gorman and Gupta (7) extended the work of Drucker and Gorman for higher pressure ranges. Excellent agreement was obtained between the experimental and analytical pressure prediction.

Van den Honert (8) described the results of experiments carried out on a 1 cubic meter water steam pressurizer at 125 atm. and studied the effects of outsurge, insurge, electrical heating, and use of a spray injection system.

Kendall (9) used the continuity and energy approach and studied the surges of a surge tank in the Gentilly Reactor Power Plant.

Moeck (10) continued his work and studied both the insurge and outsurge. However, the adiabatic model described by him for the insurge leads to somewhat high pressure prediction.

### Steam Expansion

In the event that the liquid surges out of the pressurizer, the vapor volume increases and expansion takes place. The saturation temperature drops with the pressure, but the phases remain in thermodynamic equilibrium. Condensation process, if present, stops and the evaporation of initially saturated liquid starts. Very little work has been done on the pressure transients during outsurge.

Van den Honert (8) has described a complex model involving the sub-cooling of the vapor. A relatively simpler model has been utilized by Gorman (11) to predict the pressure transients during an outsurge from an actual reactor surge tank at the usual operating pressures and the known surge rates. He has clearly demonstrated the inadequacy of the closed isentropic expansion model.

Gorman and Gupta (7) have used the 'stepped open system' for the pressure prediction. The outsurge is considered to be broken up into small increments of water level drop. The system which consists of the initial tank conetent undergoes a closed isentropic expansion with the associated first increment of the level drop.

A pressure prediction is obtained at the end of this expansion. A new system consisting of the liquid and vapor in the tank is next considered at the beginning of the second increment. A closed isentropic expansion is again assumed to obtain a pressure prediction. This analytical procedure is repeated until the pressure associated with the entire level history during outsurge is obtained. Good agreement between the experimental and the analytically predicted values is obtained.

Moeck (10) used the same energy and continuity equations and obtained an expression relating the pressure and level history. His work is mainly related to drum configuration of Gentilly BLW-250. In his analysis he assumed that water flashing and steam condensation are assumed to be instantaneous.

He also pointed out that when the pressure in a large vessel containing steam and water is disturbed, a reaction follows a situation which lies between the two extremes of (i) infinite heat transfer between the steam and water phases (thermodynamic equilibrium), (ii) no heat transfer between the phases (thermodynamic non-equilibrium). Mathematical expression based on either of these two extremes, the pressure transient predictions were adequate to describe the dynamic behaviour of the two phases in a drum. Very good agreement between the experimental and predicted pressure history was observed.

## Chapter II

## SIMULATION OF PRESSURE TRANSIENTS USING CSMP TECHNIQUE

### 2-1 General

The Continuous System Modeling Program (CSMP) is a problem-oriented program package specifically designed to facilitate simulation studies of continuous systems on digital computer (12). Because of its flexibility, power, and relative ease of use, CSMP has gained wide acceptance as an important tool in the design of engineering systems whose dynamic behavior is governed by differential equations.

### 2-2 Pressure Prediction - Pure Insurge

The governing equation in pure insurge is based upon a steam drum (9, 10) (a generalised pressurizer). By considering a special case which yields a relationship between the history of the liquid-level rise and the corresponding vapor-pressure rise, the analysis is closely related to the work done by Kendall et al (9) and Moeck (10). The only difference is that it is a broader in scope because it includes the heat transfer between the system and the wall. The detailed discussion and derivation of the governing equation are given in (1).

The governing equation in pure insurge for rate of change of pressure is as follows:-

$$\frac{dP}{dt} = \frac{PKb\dot{L} + PK\left(\left.\frac{\partial v_{sus}}{\partial h_{sus}}\right|_{p}\right)\left(\frac{dQ}{dt}\right)}{V_d - a - bL} \qquad \text{-------- Eqn. 2.2.1.}$$

or written in computer variable name with consistent units

```
PDOT = AM/(VD-A-B*L)
AM   = PCON-M
M    = P*K*DRDH*DQDT*1.E-6
```

where

$V_d$ = total volume of the pressurizer ($m^3$)

$a$ = volume of the hemispheric portion of the pressurizer ($m^3$)

$b$ = cross-sectional volume of the pressurizer per cm displacement ($m^3/cm$)

$\dot{L}$ = rate of water level change (cm/sec)

$\left.\frac{\partial v_{sws}}{\partial h_{sws}}\right|_P$ = partial derivative of change of volume with respect to change of enthalpy of superheated steam for a constant pressure (c.c./joules)

$\frac{dQ}{dt}$ = rate of heat transfer (joules/sec)

$K$ = isentropic expansion coefficient (1.26)

$P$ = gage pressure in the pressurizer (BAR)

$L$ = water level measured from a fixed reference point (cm)

In Continuous System Modeling Programme the physical dimension of the pressurizer is first specified in the initial segment of the programme. They are converted into suitable units and are only evaluated once. Since this computer package simulates the counter-part of an analog computer, it contains integral and derivative statements. These statements are Y = INTGRL (I.C.,X) and Y = DERIV (I.C.,X) respectively. Utilising these powerful subroutines the governing equation can therefore be evaluated with proper input and initial conditions.

Inputs to this simulation are level history of the insurge, thermodynamic property of $\left.\frac{\partial \upsilon_{sws}}{\partial h_{sws}}\right|_p$ as a function of pressure, initial pressure of the pressurizer and initial slope of the water level. DRDH is the variable name for thermodynamic property of $\left.\frac{\partial \upsilon_{sws}}{\partial h_{sws}}\right|_p$ and the formulation of this property is presented in Section 2-5. Water level history in the programme is called FUNCTION LE

FUNCTION LE = to, lo, $t_1$, $l_1$ ..... ti, li, ..... etc.

where

to = time at start of insurge

lo = water level at start of insurge

ti = time at ith seconds after start of insurge

li = water level at ith seconds

Although the nature of this water level history is written in discrete form, CSMP has incorporated such provision of function generator capability. This, therefore, allows interpolation of water level automatically when the specific integration time increment calls for such evaluation. Thermodynamic property or DRDH is written in explicit form for the range of pressure where insurge is about to take place. The obtained coefficients of the polynomial are presented in later section of this chapter. Since the governing equation involved the rate of change of water level this information is extracted by DERIV statement via FUNCTION LE with specified initial slope.

The rate of the heat transfer to the wall, $\frac{dQ}{dt}$ is found by taking the derivative of Q using DERIV statement. The heat content Q is computed by $Q = At\ Cp\ \rho_t \int_0^L U\ dx$ __Eqn. 2.2.2.

where

At = area of the inside wall of the pressurizer tank

Cp = specific heat@constant pressure for the material used for the pressurizer

$\rho_t$ = density of the material used for the pressurizer

U = temperature distribution in the wall

In order to obtain the temperature distribution U, Fourier transient heat conduction equation is required,

$$\frac{\partial^2 U}{\partial x^2} = \frac{1}{\alpha}\frac{\partial U}{\partial t} \qquad \text{-------Eqn. 2.2.3.}$$

where x is the co-ordinate along the thickness of the wall

$\alpha$ = coefficient of thermal diffusivity

$\frac{\partial U}{\partial t}$ = partial derivative of temperature change w.r.t. time

To solve this Fourier equation, initial and boundary conditions are needed. These initial conditions are (i) $U(0,t) = \phi$ The inner surface of the pressurizer wall follows the saturation temperature history at all time.

(ii) $U(x,0) = 0$

At the on-set of the insurge, the pressurizer wall is at uniform temperature and the initial temperature is taken as the reference value.

(iii) $\left.\frac{dU}{dx}\right|_{x=L} = 0$

This boundary condition assumes there is no temperature gradient at the outer surface of the pressurizer. This is to say the insulation material behaves in an ideal fashion.

This principle used for solving this partial differential equation is based on discretizing the independent variable $x$ , and treating the other independent variable t as a 'continuous' variable within the CSMP package. This will reduce the partial differential into a set of ordinary differential equations.

$$\left.\frac{dU}{dt}\right|_{i} = \alpha\,\frac{U_{i-1}-2U_i+U_{i+1}}{\Delta x^2}$$

where

i = 1,2,.......10, corresponding to 10 nodal points within the thickness of the pressurizer wall

$\Delta x$ = the increment thickness of variable x

When the above mentioned initial and boundary conditions are applied to this set of ordinary differential equations, the imaginary temperature $U_{11}$ at nodal point 10 is eliminated. Temperature Uo at nodal point 1 becomes o at time o and is equal to $\phi$ at other time. In the programme presented in App. 3 , the variable name is PHIM which in turn equal to the difference between the saturation temperature corresponding to the pressure at that time and initial saturation temperature.

The INTGRL statement is then implemented to perform integration at each nodal point. The temperature is summed over the thickness of the wall by Simpson's rule to obtain numerical value of $\int_0^l U dx$.

---

+in here it means that the computer programme will automatically simulates the T variable by specifying the increment of time.

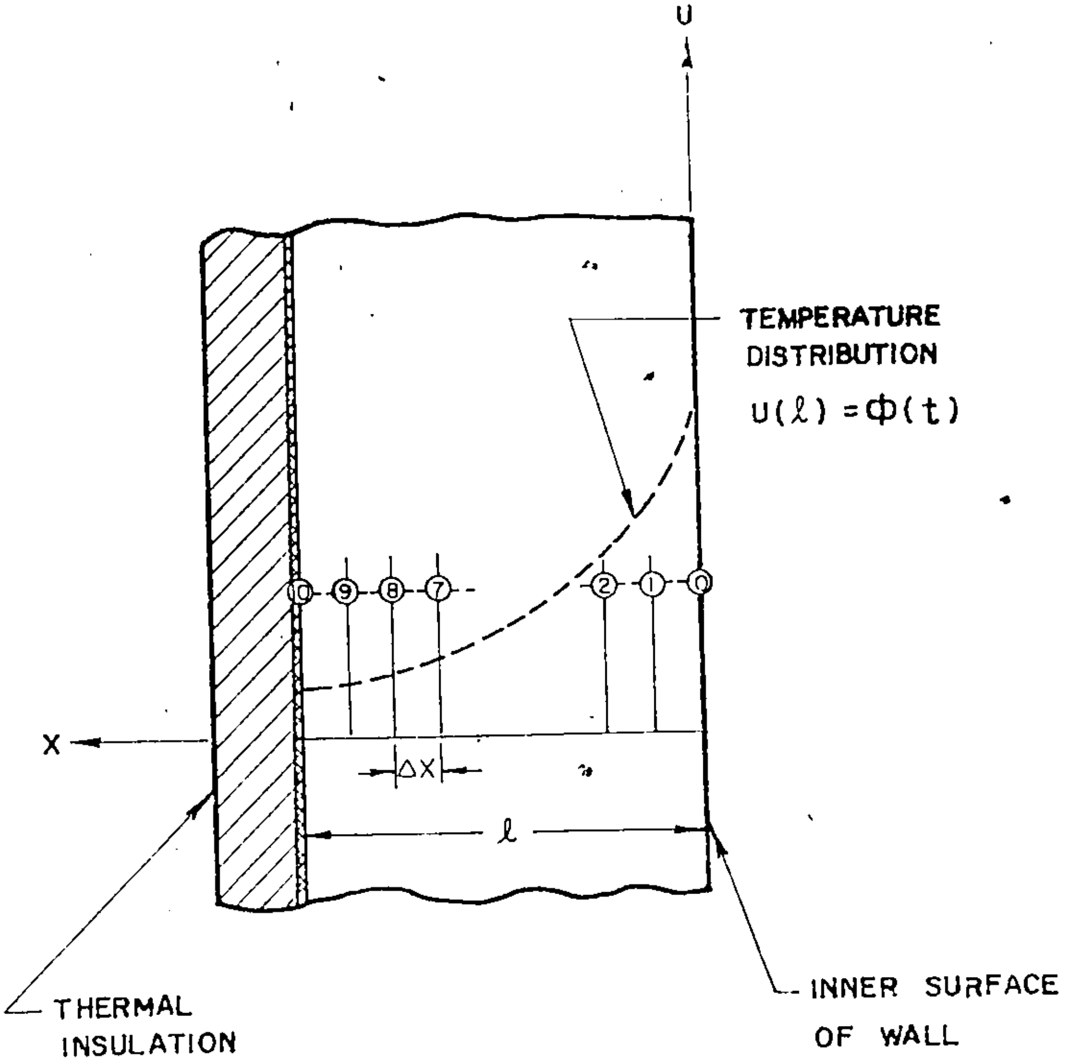


Fig.2-2-1 PRESSURIZER VESSEL WALL

## 2-3 Pressure Prediction - Pure Outsurge

The relationship between the liquid level history drop in a surge tank and the corresponding vapor pressure drop can be found from Moeck's work (10).

The governing equation in this case is

$$\frac{dP}{dt} = \frac{1}{1/b(F_1 a + V_d F_2) + F_1 L} \cdot \frac{dL}{dt} \quad \text{--------Eqn.2.3.1.}$$

where

$$F_1 = \left[ \frac{v_{sas}}{v_{saw}} \frac{dh_{saw}}{dp} - \frac{dh_{sas}}{dp} \right] \frac{1}{h_{sas} - h_{saw}} + \frac{1}{v_{sas}} \cdot \frac{dv_{sas}}{dp}$$

$$F_2 = \left[ \frac{dh_{sas}}{dp} - \frac{v_{sas}}{J} \right] \frac{1}{h_{sas} - h_{saw}} - \frac{1}{v_{sas}} \cdot \frac{dv_{sas}}{dp}$$

or in computer variable name

DLDP = (A* $F_1$ + VD * $F_2$)/B + $F_1$ * L

DPDL = 1/DLDP

PDOUT= DPDL * LDOT

The procedure in programming this equation is similar to pure insurge. In this outsurge case, there is no heat transfer term involved, except formulation of thermodynamic properties as a function of pressure. Most of these properties are linear functions within the range of the pressure drop. Level history is then programmed as the input to the CSMP and the derivative of water level is obtained by the DERIV statement. All the thermodynamic properties such as $\frac{dh_{sas}}{dp}$, hsaw, $\upsilon_{sas}$, $\upsilon_{saw}$ are formulated and presented in Section 2-5.

where

$V_{sas}$ = specific volume of saturated steam cu.ft/$lb_m$

$V_{saw}$ = specific volume of saturated water cu.ft/$lb_m$

$h_{sas}$ = specific enthalpy of saturated steam BTU/$lb_m$

$h_{saw}$ = specific enthalpy of saturated water BTU/$lb_m$

## 2-4 Pressure Prediction - Multiple Surge (insurge followed by outsurge)

Insurge followed by outsurge can be easily visualised by noticing the water level rises inside the surge tank, and then drops abruptly after the maximum level has been attained. Take an ideal situation of sinusoidal rise and fall of water level as shown in Fig. 2-4-1. The first half of the cycle of water level history the pressure rise is exactly the same as pure insurge. It is therefore can be described by pure insurge governing equation namely Eqn. 2.2.1. During this process the vapor is superheated, the water becomes subcooled and the wall takes on a non-uniform temperature distribution. With the help of a T-S diagram for the vapor in the surge tank (Fig. 2-4-2) its trajectory 1-2 is shown by dotted line. Although the exact path from state 1 to state 2 is yet to be determined, the governing equation (Eqn. 2.2.1) gives the pressure transient corresponding to water level excursion a-b.

During the subsequent outsurge part of the cycle vapor and liquid try to attain thermodynamic equilibrium and it can be shown thermodynamically that the vapor reaches the saturation temperature associated with pressure before liquid, and hence the process can be divided into three stages:

(1) outsurge of superheated vapor and subcooled liquid,
region bc, fig. 2-4-1 ; path 2-3, fig. 2-4-2

(2) outsurge of saturated vapor and subcooled liquid,
region cd, fig. 2-4-1 ;

(3) outsurge of saturated vapor and saturated liquid,
region de, fig. 2-4-1 ; path 3-1, fig. 2-4-2

The outsurge starts with the superheated vapor and subcooled liquid. During the course of the first stage of outsurge they tend to reach the saturated condition. This resembles the pure insurge phenomenon in the reverse direction and therefore Eqn. 2.2.1 can be used to describe the process with a slight modification in the heat transfer term.

During the second stage, the temperature of subcooled liquid is very close to the saturation temperature and hence it can be assumed that thermodynamic equilibrium is attained at point e, thus eliminating the second stage completely. The rest of the process follows the pure outsurge case.

The governing equations are essentially the same for pure insurge and outsurge cases. In this situation a switching criteria is involved as the pressure rises and drops during the excursion of water level fluctuation. The switching criteria is presented in a flow chart form

(Fig. 2-4-3) and is realised by employing flags called KEYIN & KEYOUT. They are complementary to each other and can only have value of either zero or one. Water level rises at the beginning of the cycle. Pressure will increase due to the decrease of the volume and thus compresses the vapor. With all the appropriate assumptions in force the pressure prediction equation is identical to pure insurge case.

Equation is switched in by flag KEYIN = 1. As the water level reaches the top, or as the rate of change ALDOT becomes a certain specified value, heat transfer term is switched off (i.e. M = 0). Pressure prediction, [illegible] a negative change of water level will follow a tre[illegible] reduction. Water level drops and it will eventually reaches a state such that the temperature of vapor falls below the initial starting temperature TEMPIN. This causes the KEYIN = 0 and KEYOUT = 1. Outsurge governing equation (Eqn. 2.3.1) is required for pressure prediction.

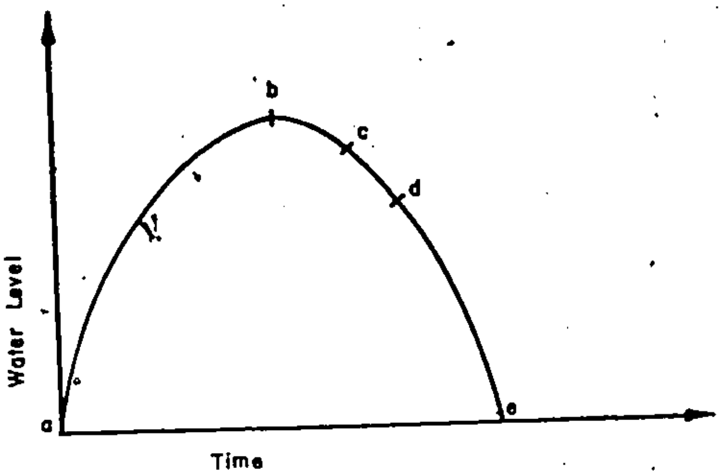


Fig.2-4-1 Sinusoidal Water Level History

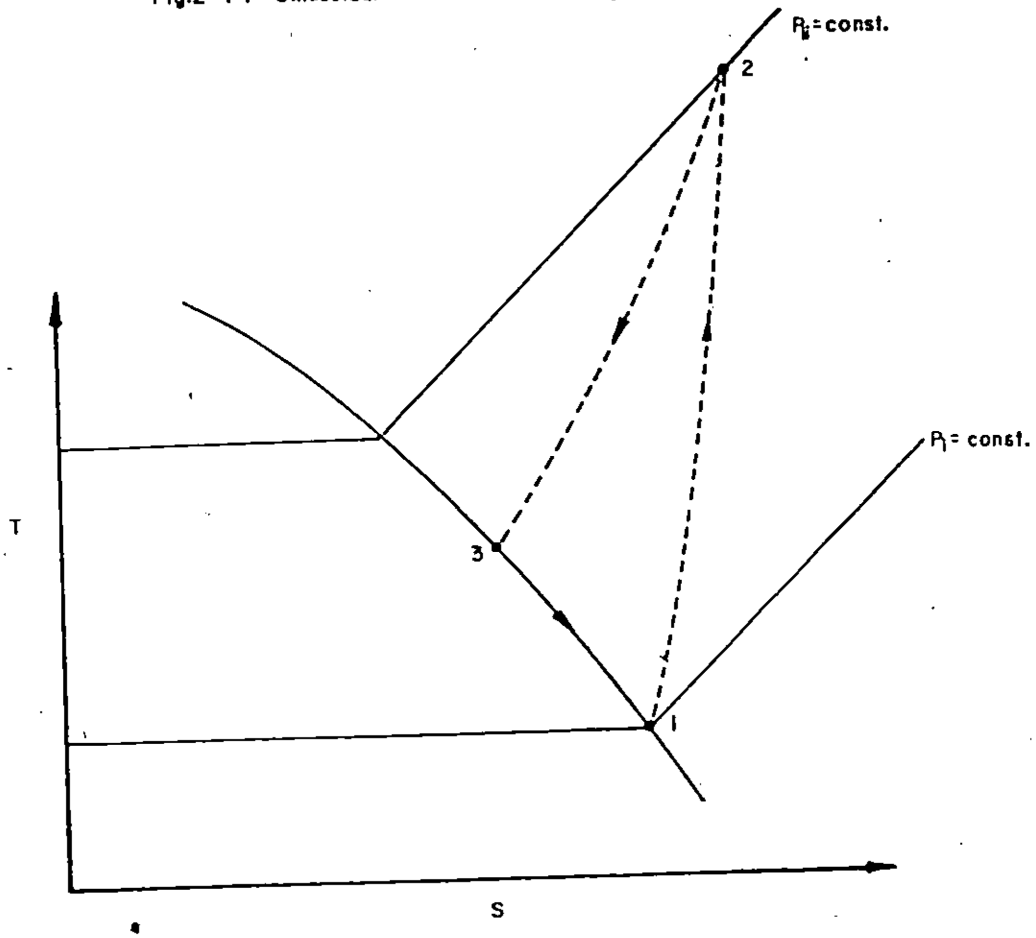


Fig.2-4-2 Multiple surge trajectory in T-S diagram for steam

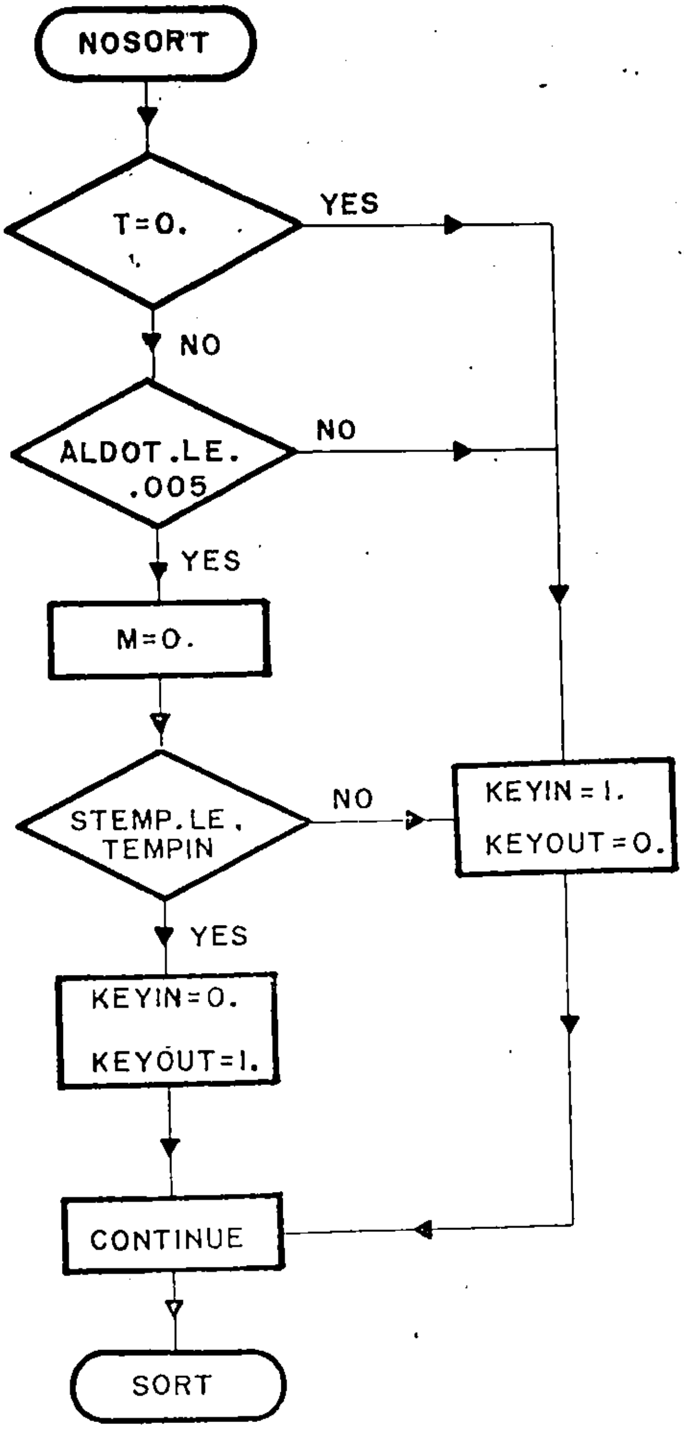


Fig. 2-4-3 Flow chart for switching creteria in multiple surge

## 2-5 Thermodynamic Properties Formulation

To obtain all thermodynamic properties as a function of pressure Least Square Curve-fitting technique is employed. This is a method which is generally used and it is believed to be suitable for the approximation of all properties encountered in the model. The range of pressure which is valid for these approximated functions is confined to the following specifications in each presentation. Thermodynamic properties are presented in British Units unless otherwise specified. Pressure at all times is in BAR.

### Presentation of DVG$\left(\frac{dv_g}{dp}\right)$ and VG($v_g$) as a function of Pressure

(188 p.s.i.a.) $12.97\text{BAR} < P < 13.79\text{BAR}$ (200 p.s.i.a.)

$VG = a_0 + a_1 * P$

$a_0 = 4.64061$

$a_1 = -0.17059$

$DVG = -0.17059$ (Derivative of VG)

Approximate Error = ± .082%

### Presentation of DHG$\left(\frac{dh_g}{dp}\right)$ and HG($h_g$) as a function of Pressure

(188 p.s.i.a.) $12.97\text{BAR} < P < 13.79\text{BAR}$ (200 p.s.i.a.)

DHG = 1.09 (using the slope of the plot of HG VS P)
or using Polynomial Function

$DHG = b_o + b_1 * P + b_2 * P * 2$

where

$b_o = 0.22155604E02$

$b_1 = -0.32286957E01$

$b_2 = 0.12321145$

## Presentation of DRDH $\left(\frac{\partial v_s}{\partial h_s}\Big|_p\right)$ as a function of Pressure

(195 ps.i.a.)13.45BAR<P<14.83BAR (215 p.s.i.a.)

$t_{sat} < t < t_{sat} + 25^{\circ}F$

To find $\frac{\partial v_s}{\partial h_s}$ as a function of pressure, specific volume ($v_s$) versus enthalpy ($h_s$) of steam at one particular pressure is plotted over a temperature starting at saturated temperature up to 25°F of superheat. Similar plot of $v_s$ vs $h_s$ is then repeated over the pressure range as specified above in the same range of degrees of superheat. This family of plot is shown in Fig.2-5-3. The slope of each graph is the value of $\frac{\partial v_s}{\partial h_s}$ at that particular pressure. Function DRDH* is next curve-fitted by Least Square technique after slopes from $v_s$ and $h_s$ plot are evaluated.

---

*Due to model requirement DRDH is given in cc/joules, this is done by multiplying a conversion factor of 2.68389E01 to the standard British Unit.

## Presentation of HFG($h_{fg}$) as a function of Pressure

(188 p.s.i.a.)$12.97\text{BAR} < P < 13.79\text{BAR}$ (200 p.s.i.a.)

$HFG = Co + C_1 * P$

$Co = 0.920282E03$

$C1 = -0.555449E01$

Approximate Error = ± .007%

## Presentation of VF($v_f$) as a function of Pressure

(188 p.s.i.a.) $12.97\text{BAR} < P < 13.79\text{BAR}$ (200 p.s.i.a.)

$VF = do + d_1 * P$

$do = 0.172335E-01$

$d_1 = 0.836843E-04$

Approximate Error = ± .005%

## Presentation of DHF ($\frac{dh_f}{dp}$) as a function of Pressure

(188 p.s.i.a) $12.97\text{BAR} < P < 13.79\text{BAR}$ (200 p.s.i.a.)

$DHF = 6.74$ (using the slope of the plot of HF VS P)
or using Polynomial Function

$DHF = e_o + e_1 * P + e_2 + e_3 * P ** 3$

where

$e_o = 0.23574630\ E03$

$e_1 = -0.30107910\ E02$

$e_2 = 0.70606716$

$e_3 = 0.19700072\ E-01$

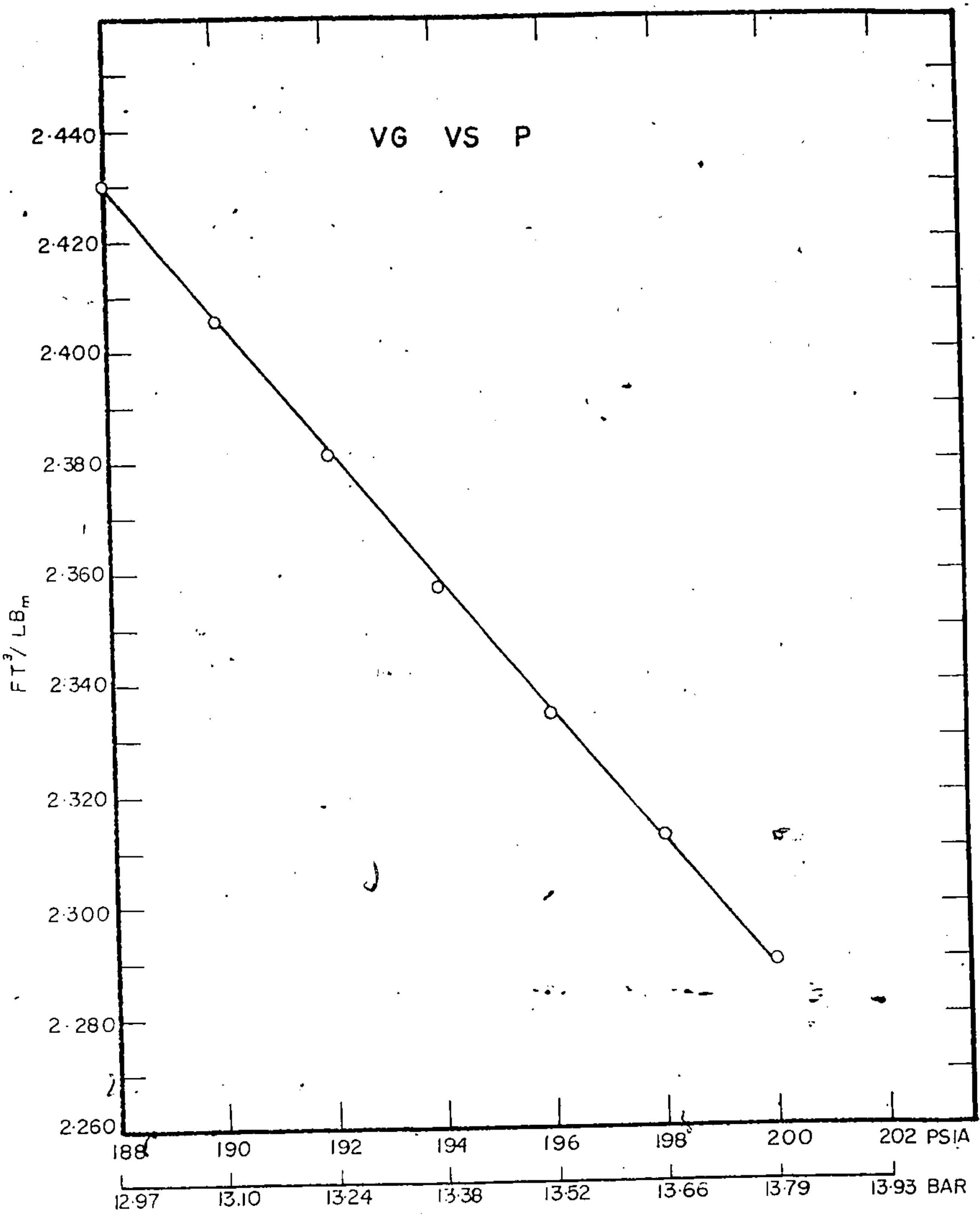


Fig. 2-5-1 PLOT OF SPECIFIC VOL. OF STEAM VS PRESS.

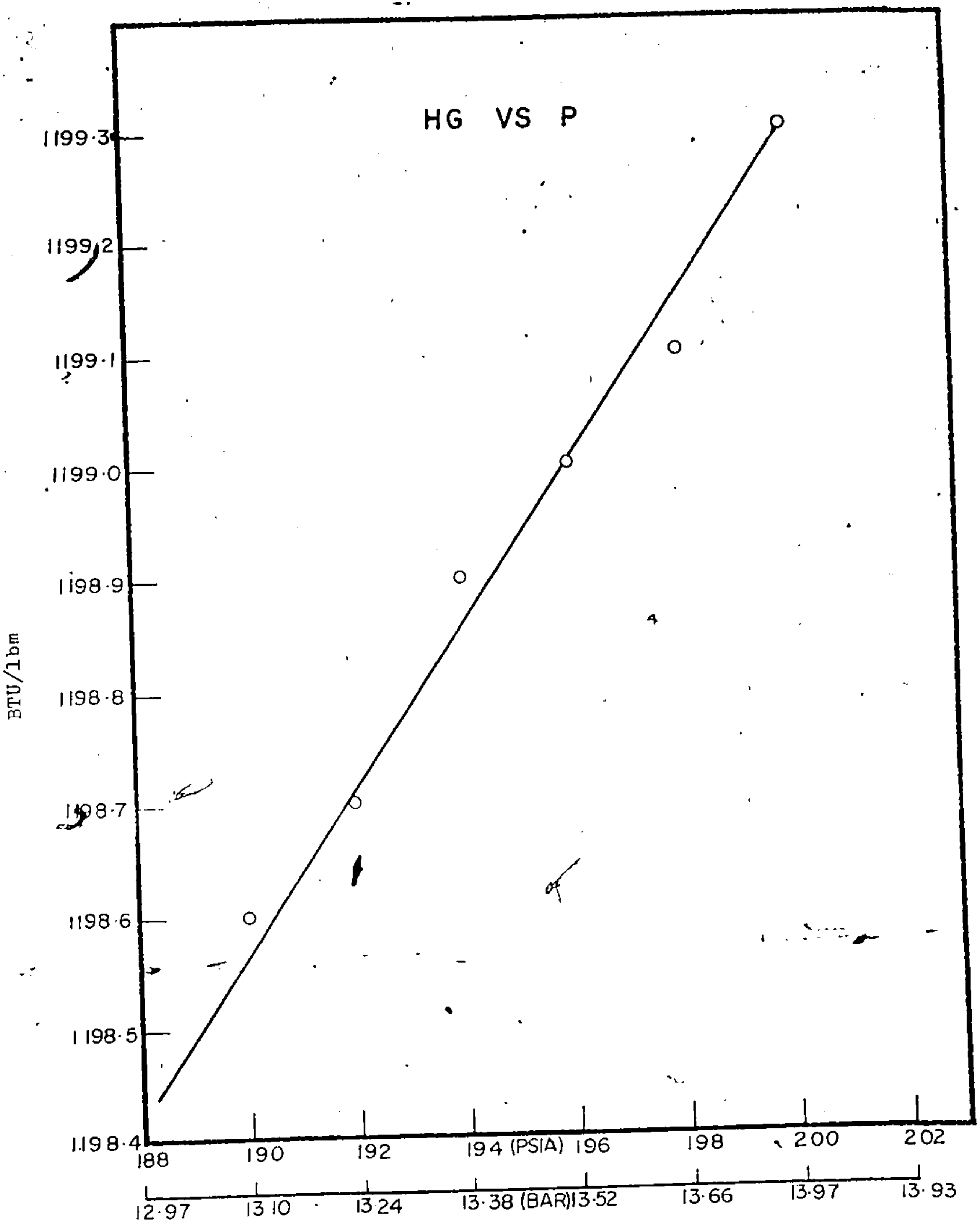


Fig. 2-5-2 PLOT OF ENTHALPY OF STEAM VS PRESSURE

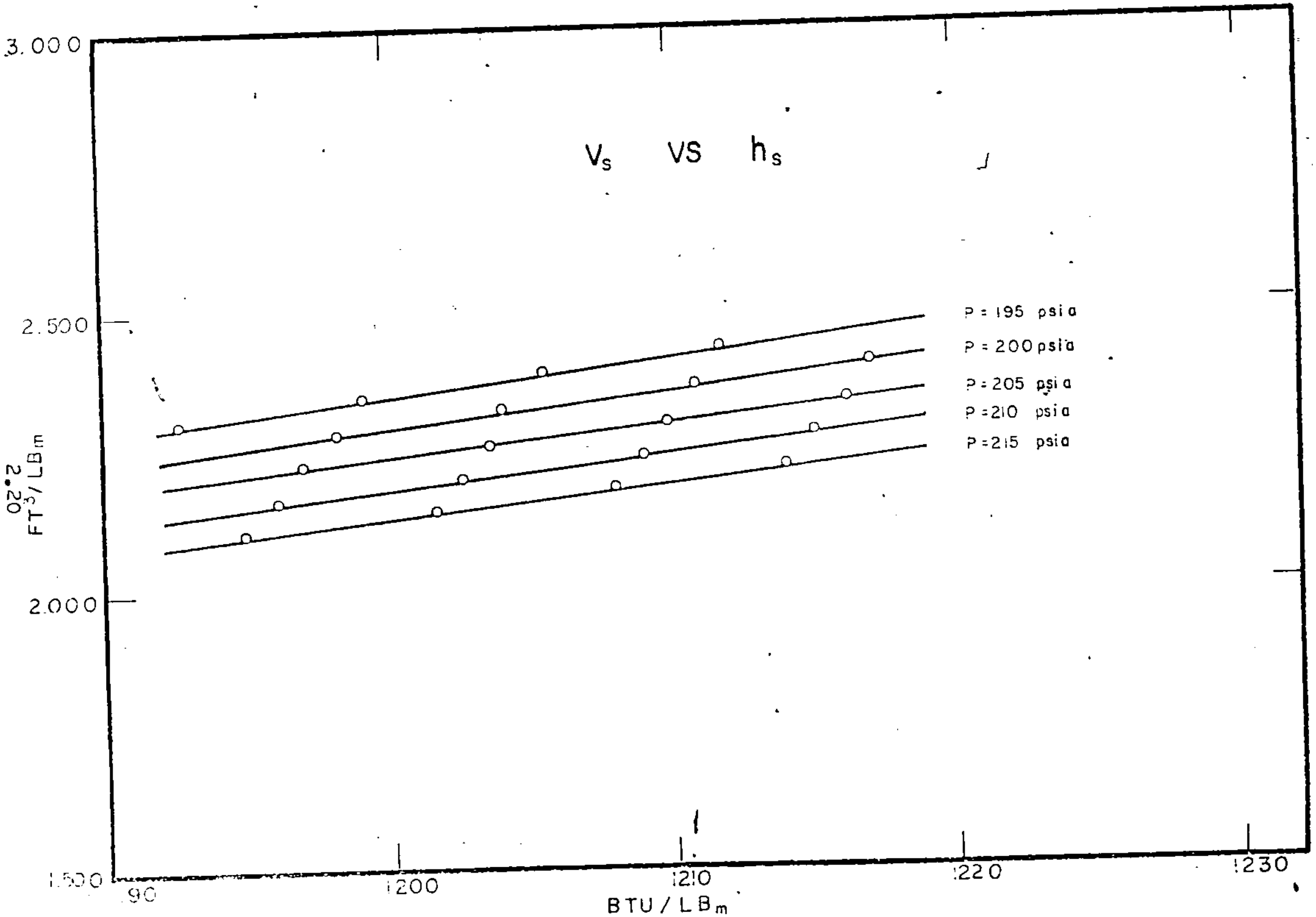


FIG. PLOT OF SPECIFIC VOLUME VS ENTHALPY OF STEAM

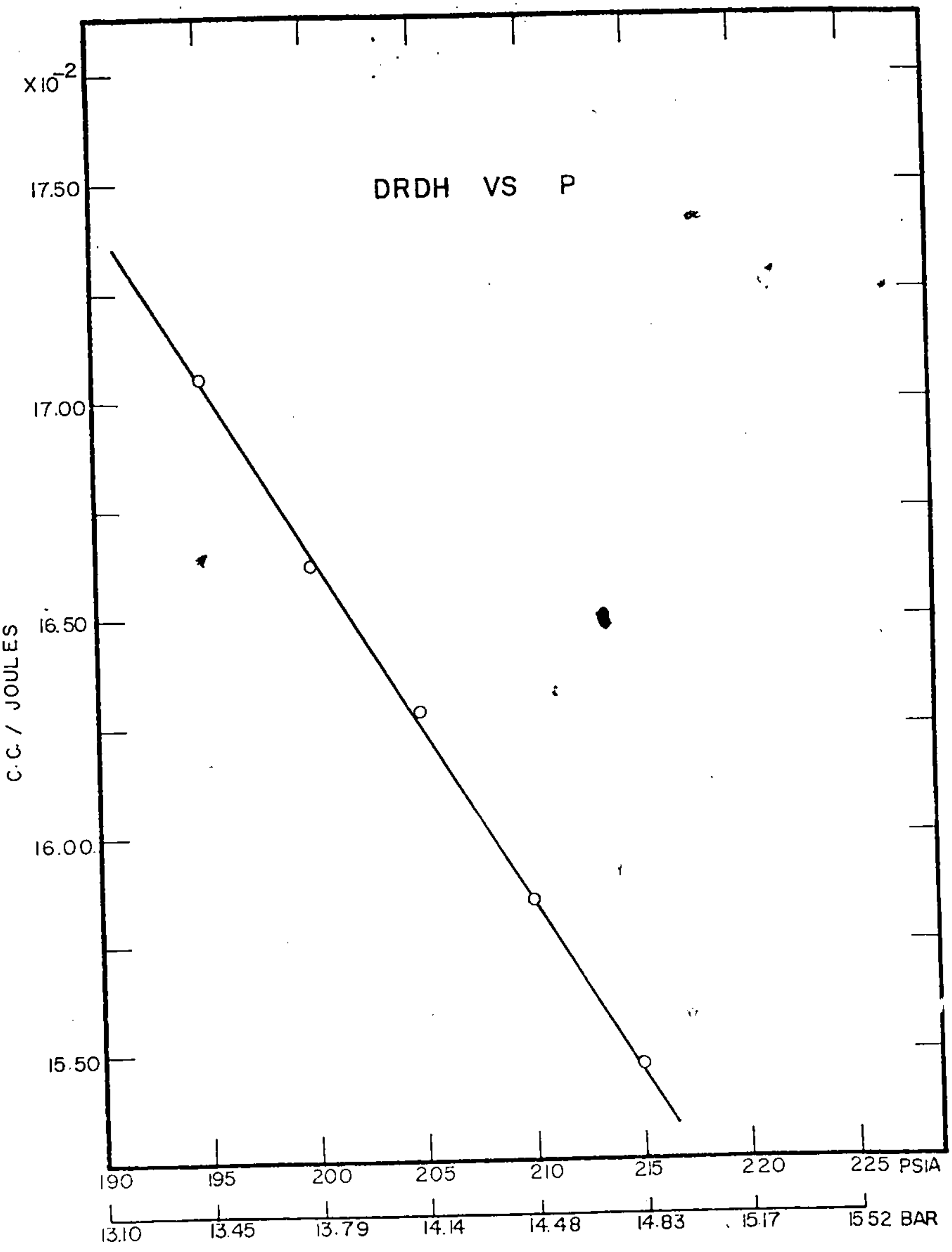


Fig. 2-5-4 PLOT OF DRDH VS PRESSURE

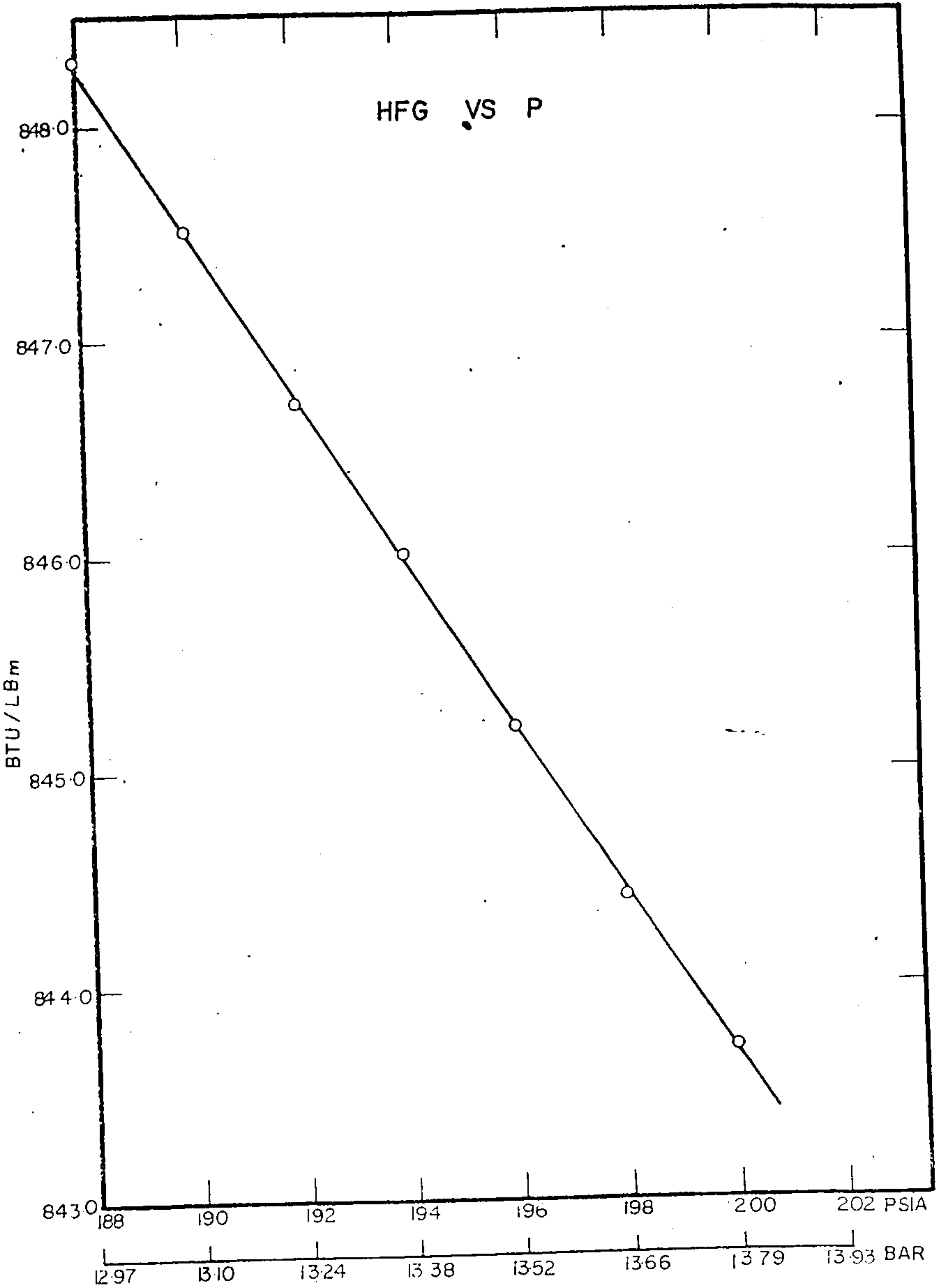


Fig. 2-5-5 PLOT OF LATENT HEAT OF STEAM VS PRESSURE

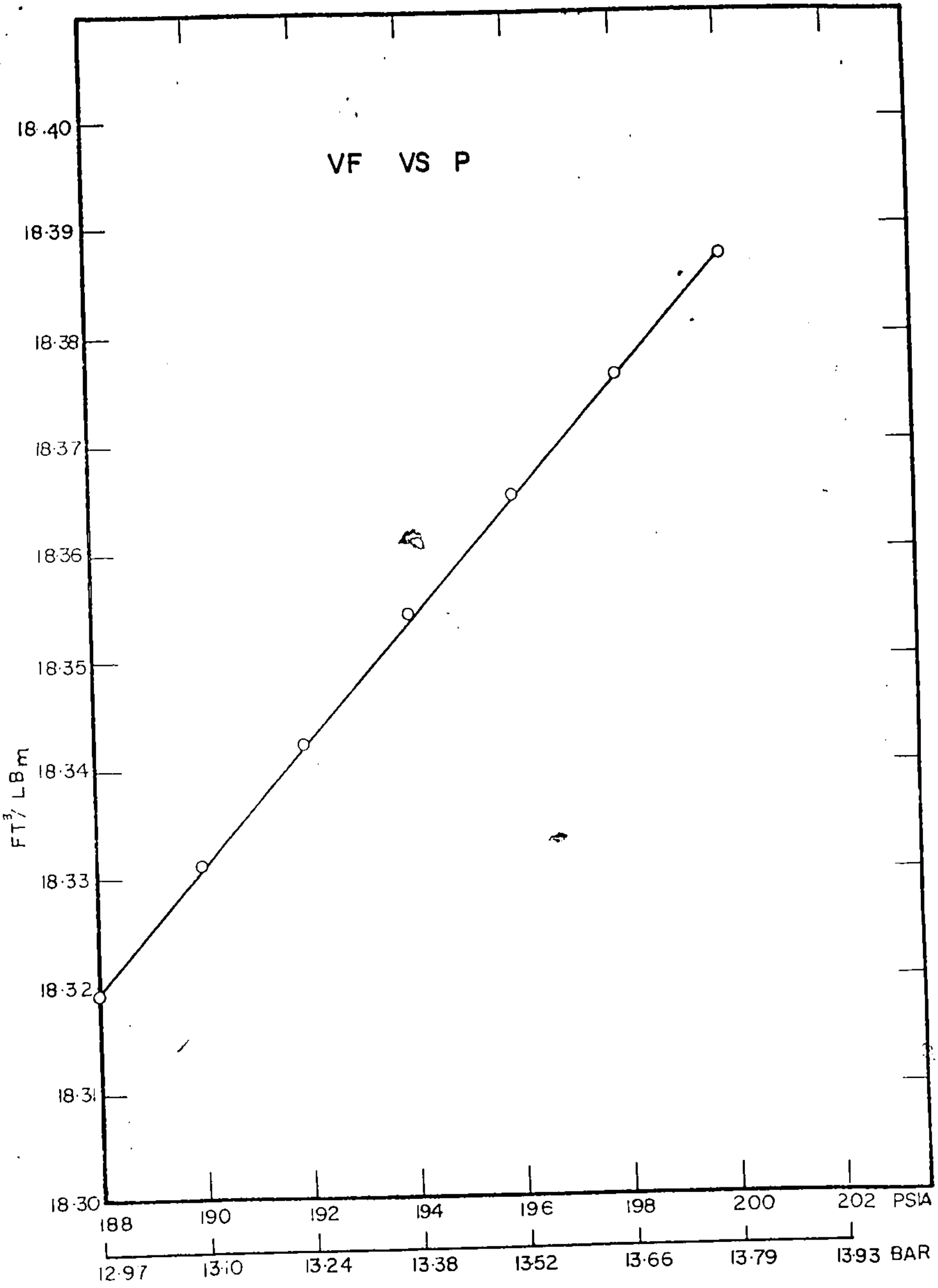


Fig. 2-5-6 PLOT OF SPECIFIC VOLUME OF WATER VS PRESSURE

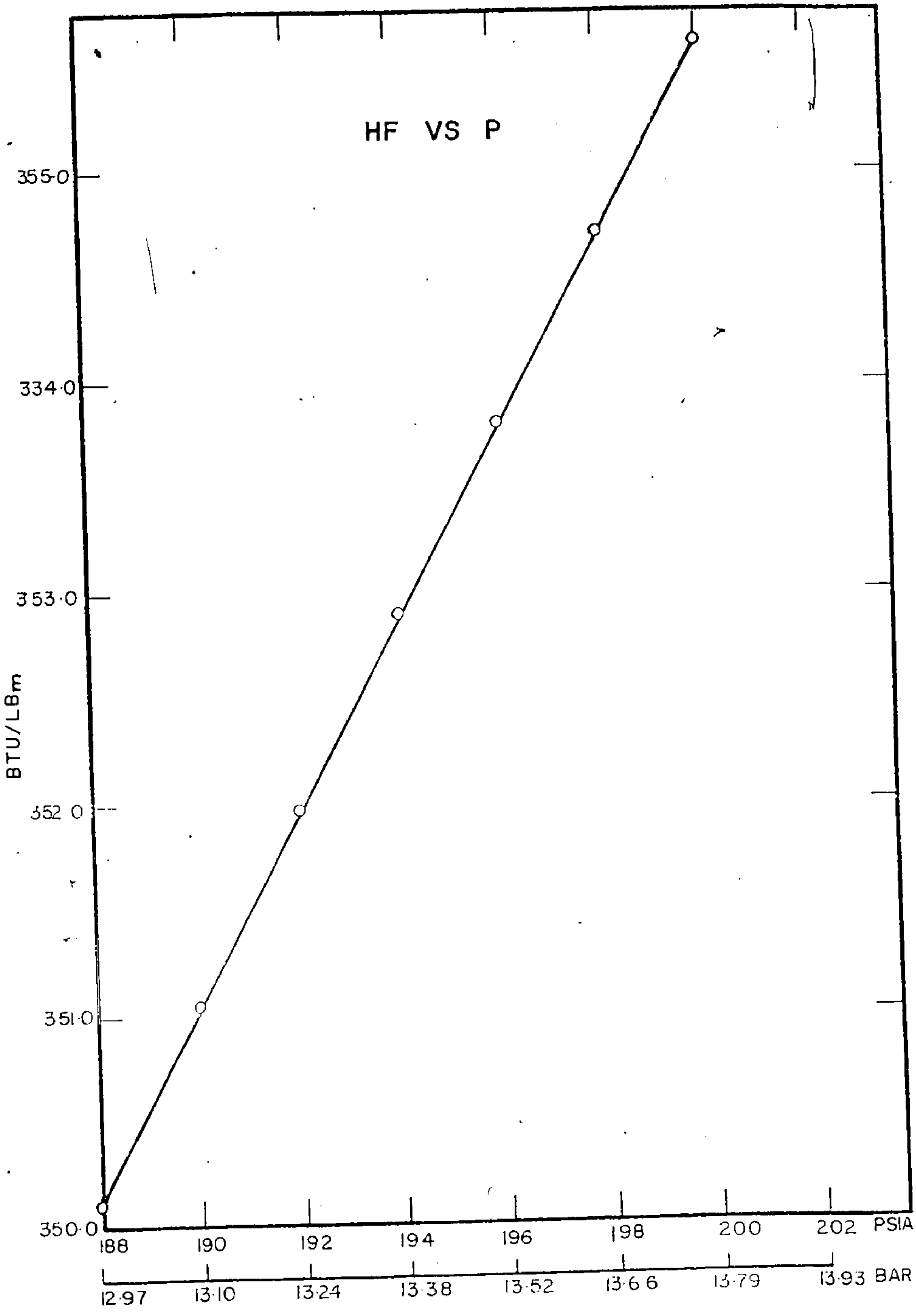


Fig. 2-5-7 PLOT OF ENTHALPY OF WATER VS PRESSURE

# Chapter III

## EXPERIMENTAL ASPECTS OF THE APPARATUS

### 3-1 General Description and Design of the Apparatus

Schematic diagram of surge tank, Fig. 3-1-1 shows all the important components that complete the apparatus. Two identical stainless steel tanks are of 5 gallons capacity. They are rated to withstand a maximum pressure of 2,000 psia. The overall dimension is about 35 inches high and 7 inches in diameter. Each cylinder weighs approximately 85 lbs. To facilitate ease of mounting, the two cylinders are placed about 4 feet apart and are secured to a strong wooden frame. Their vertical positions are maintained by two additional horizontal members which allow adequate space for insulation material.

All the connecting pipings are of ½ inch diameter 304 stainless steel tube of 0.040" thickness. The choice of pipings are in accordance to ANSI Pressure Piping Code to withstand maximum operating pressure of 700 psia and temperature 600°F.

Straight pipe under internal pressure in the above mentioned Code suggests that minimum wall thickness should be calculated as follows:-

$$tm = \frac{PDo}{2(SE + py)} + Am \qquad \text{------- Eqn.3.1.1.}$$

where tm = minimum required wall thickness inches

P = internal design pressure, psi gage

Do = outside diameter of pipe in inches

SE = maximum allowable stress in meterial due to internal pressure at the design temperature

Am = an additional thickness, in inches to provide for mechanical strength

y = coefficient having values of 0.4 as given in Table 104.1.2, A in ANSI B31 Power Piping Code

In this application, maximum allowable stress of 304 s.s. tube is taken from table as $9.7 \times 10^3$ psi at maximum operating pressure of 600°F. With an additional thickness of .010" to provide for mechanical strength, the minimum required wall thickness comes to .028". Therefore tubes of ½ inch diameter of 0.040 thickness are used in all the connecting pipings.

Other components such as valves and tube fittings are of Swagelok design, SWAGELOK® Tube Fittings provide a leak-proof, torque-free seal at all tubing connections. The seal consists of two, front and back ferrules. They grasp tightly around the tube regardless of wall thickness by ferrule inter-action and since this inter-action moves along the tube axially instead with a rotary motion - free of torque that might otherwise impart onto tubings, ferrules provide a leak-proof seal under pressure up to the burst of the tubing. Valves and fittings are rated by manufacturer to a higher limit than at present operating conditions. Through out the cold water testing of the apparatus, they are found to be functioning satisfactorily up to a much higher pressure than design

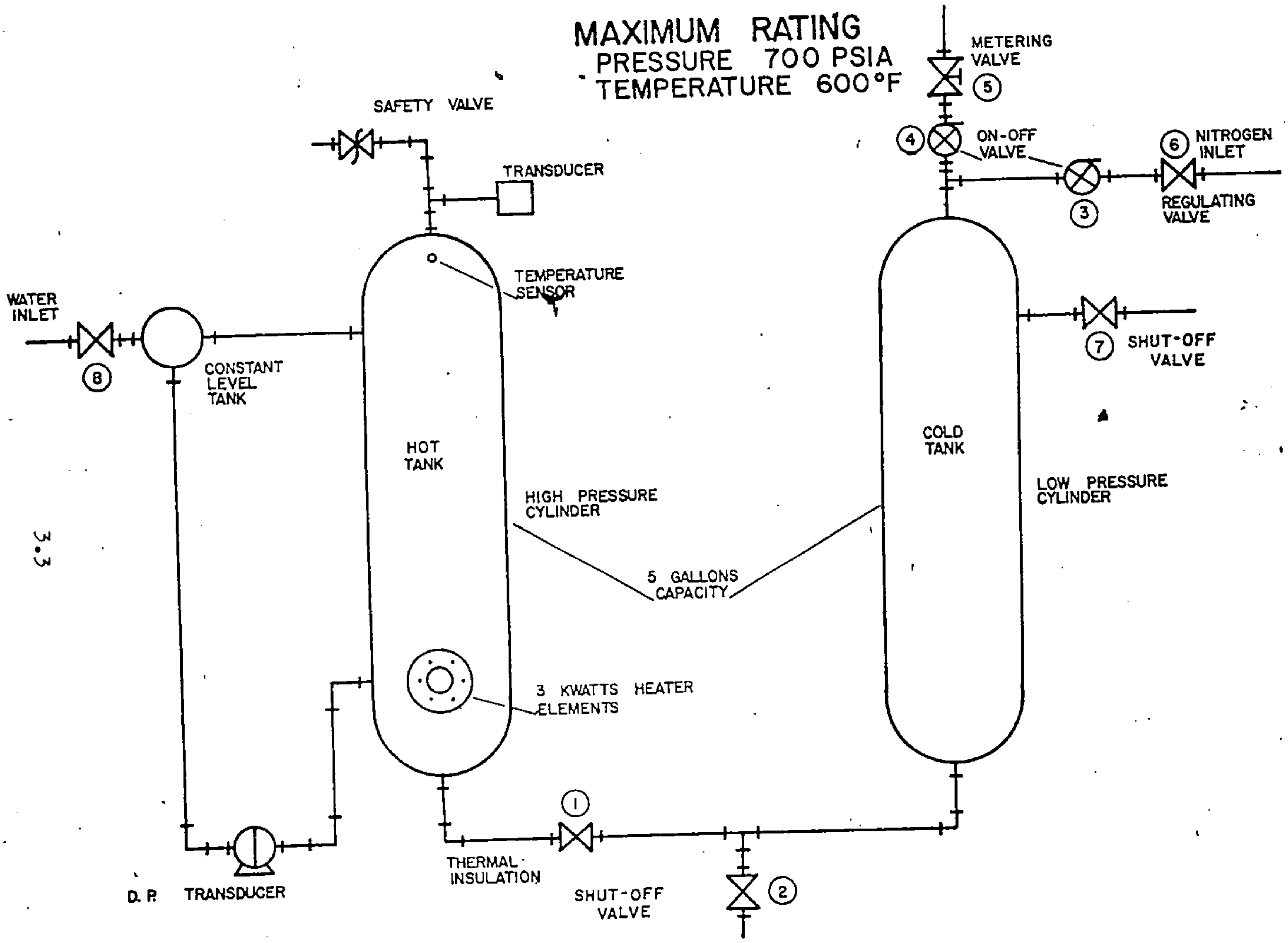


Fig.3-1-1 SCHEMATIC DIAGRAM OF SURGE TANK

Ill.3-1-1 The Surge Tank Apparatus

Ill.3-1-2 Water Level Measurement

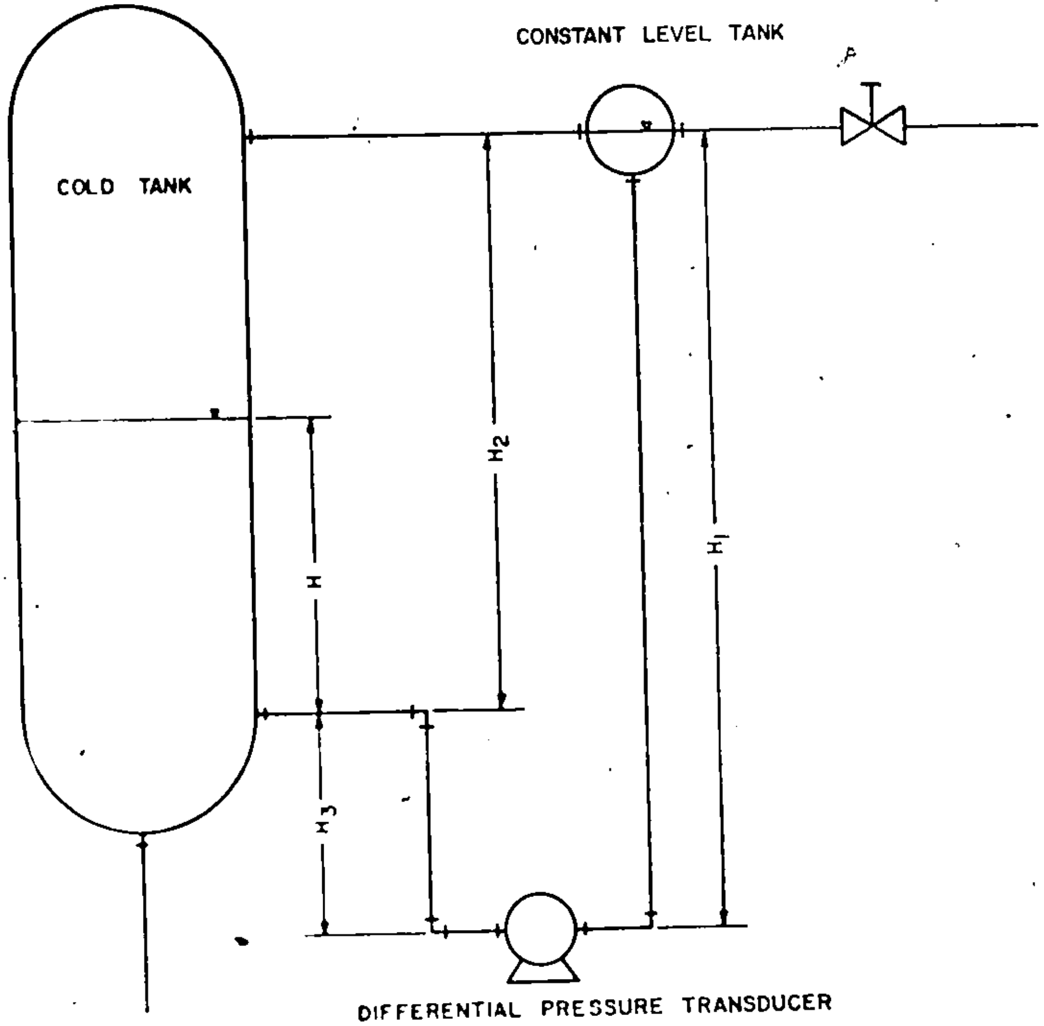


Fig. [illegible] WATER LEVEL MEASUREMENT USING DIFFERENTIAL PRESSURE TRANSDUCER limit.[4]

Constant water level tank is situated at the pressurizer side. This is of a better arrangement than putting it on the cold tank side. When the apparatus was first put together, the differential transducer was placed on the cold tank. Fig. 3-1-2 shows schematically the principle on which the measurement is based. An uninsulated reference leg outside the cold tank is filled with water. This leg is connected to the cold-tank gas space through a small reservoir, thus ensuring a constant reference level. The water level inside the tank serves a variable leg, the pressure difference between the two legs is measured by means of a differential pressure transducer (Kayowa type PD-200GA). The pressure difference detected by the transducer is:-

$$\Delta P = H_1\rho_1 - H_3\rho_3 - H\rho - (H_2 - H)\rho_{N2}$$

$$= H_1(\rho_1 - \rho_3) + H_2(\rho_3 - \rho_{N2}) - H(\rho - \rho_{N2})$$

The expression for the water level

$$H = \frac{-\Delta P + H_1(\rho_1 - \rho_3) + H_2(\rho_3 - \rho_{N2})}{\rho - \rho_{N2}} \quad \text{-------- Eqn. 3.1.2.}$$

But $\rho_1 = \rho_3$

$$\text{Therefore } H = \frac{-\Delta P + H_2(\rho_3 - \rho_{N2})}{\rho - \rho_{N2}} \quad \text{-------- Eqn. 3.1.3.}$$

To obtain the level in the pressurizer (hot tank), the water level in both tanks is allowed to seek its own level initially. With the assumption that the two tanks are physically identical, a change in water level in one would result a change in the other. In this way the water level in the pressurizer can be recorded. This indirect method of obtaining water level information is inherently introduced erroneous result for a simple reason that the diameter of the two tanks cannot possibly be exactly the same. This in turn gives an over-estimation of water level change in the pressurizer depending on the fact that the pressurizer is having a larger or smaller diameter than the cold tank. Nevertheless, the main source of inaccuracy of this method of measuring water level in the hot tank can be attributed by the change of specific volume of water between the hot and the cold tank. A decrease of water level in the cold tank results in a bulk of water entering the hot tank. Although this mass of water will quickly assume the temperature of main bulk of water in the hot tank because of mixing. Specific volume of the liquid in the hot and the cold tank can be differed by as much as 15%. Thus the water level in the hot tank estimated by this indirect method cannot be too reliable. However, this is later being modified to the existing version as shown in Fig. 3-1-1. The expression for water level namely Eqn. 3.1.3 remains essentially unchanged, except the density $\rho_{N2}$ now becomes $_{SUS}$ (density of superheated steam). Densities of $\rho_1 = \rho_3$ still remain a valid assumption, which can be readily explained by the fact that conduction of heat through water without circulation is poor. The temperature of water at the two input ports of the D.P. transducer is essentially the same. And this has been experimentally verified. Fig. 3-1-3 shows the thermal insulation for the pressurizer consists of two types of material. The inner most layer is asbestos cloth while the second layer is fibre glass insulation. Asbestos cloth can stand up to temperature of 1,000°F without greatly affecting the value of coefficient of conductivity while fibre glass would only be suitable if the temperature is below 400°F. This arrangment does not present too much difficulty in determining the thickness of insulation. It is estimated that two layers of asbestos cloth wrapping of about $\frac{3}{16}''$ is required while 2 inches of fibre glass is adequatefor thermal insulation. Other parts of the apparatus such as valves, fittings and connecting tubes are also insulated to reduce heat loss. The material used is of commercial type of piping insulation.

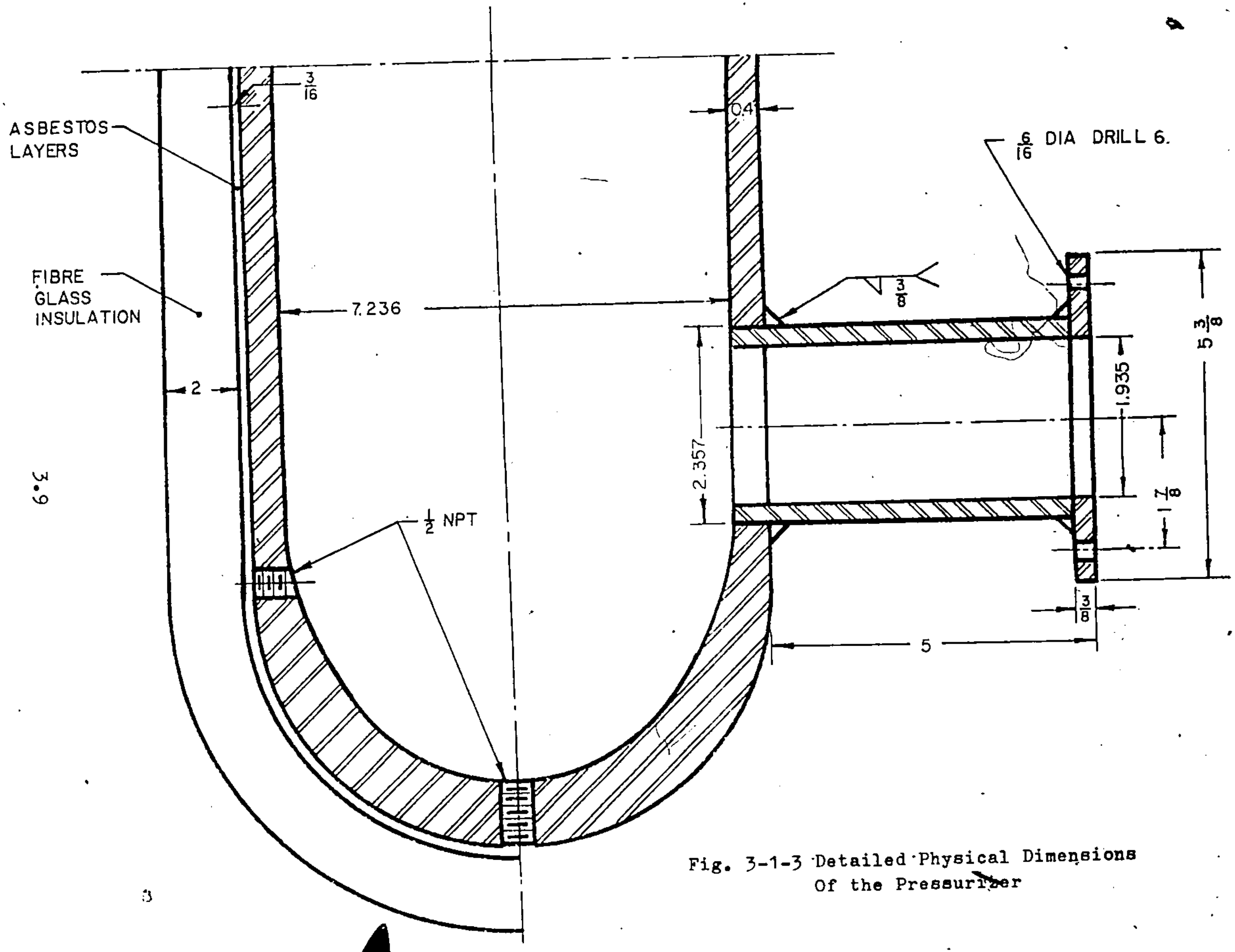


Fig. 3-1-3 Detailed Physical Dimensions
Of the Pressurizer

## 3-2 Process Operation

Before start up of the experiment pressure transducer amplifiers are adjusted to predetermine gain and nulled to prevent any thermal drift or offset during instrument warm-up period. All the adjustment is verified against a high precision digital voltmeter which is incorporated in the data acquisition system. A block diagram of instrumentation shows the general scheme of measurement Fig. 3-2-1. To achieve the desired initial conditions the heater elements are switched in via temperature controller. The temperature controller derives its input from thermocouple probe which is situated in the vicinity of the heater element and is immersed in the liquid. The output of this unit varies proportionally from 4-20 ma. depending of the temperature difference between the set-point and the controlling temperature. This signal is the input to the driver stage which supplied power proportionally to the heater element. This arrangment of wiring the heater element is essentially a closed loop negative feedback systems. This error signal being the temperature difference between set-point and liquid provided corrective action to the supply driver. In this way satisfactory initial conditions can be accomplished.

Water level measurement is done by means of a differ-

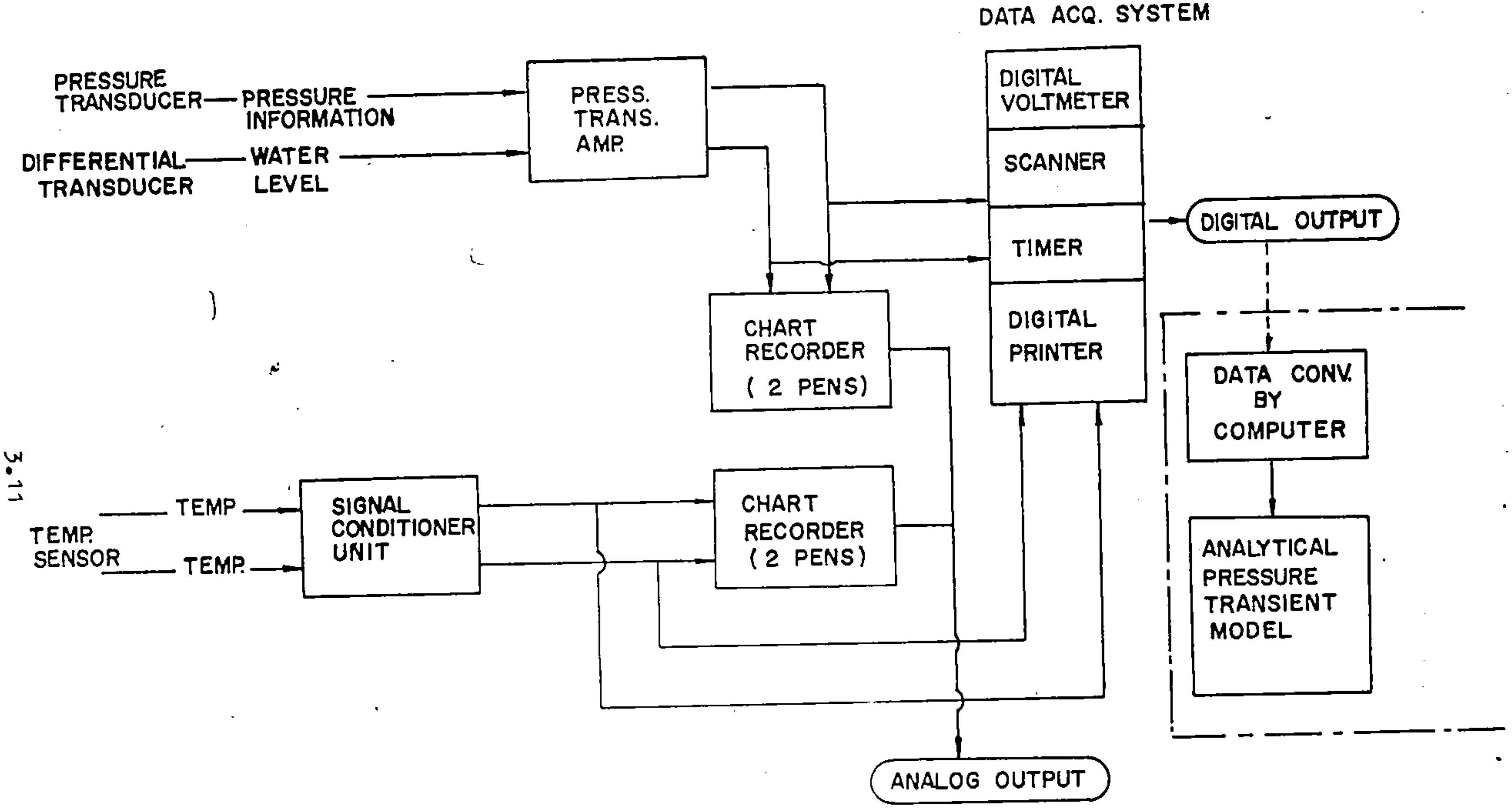


Fig. 3-2-1 BLOCK DIAGRAM OF INSTRUMENTATION

ential transducer situated at the hot tank. One port of the transducer is subjected to a constant water level leg while the water in the tank serves as avariable leg. Thus by keeping track of the water level in the hot tank, water insurge and outsurge of the pressurizer can be recorded. In adopting this set-up, water in both tanks is first filled to the same level. Hereafter the valve which connects between the hot and the cold tank is closed until pressurizer reaches the starting state.

Nitrogen that is introduced through a regulated valve from storage cylinder is applied to the cold tank to induce transient flow. For insurge case regulator supply valve is turned on thus achieving the sudden transient effect to the pressurizer. For outsurge case reverse procedure takes place. Nitrogen is vented out through metering valve. Pressure in the hot tank will force water out and it is to be collected in the cold tank. At all times pressure and water level readings are recorded.

The bulk temperature of the vapor above the water level inside the pressurizer is also recorded via signal conditioner unit onto one of the channels of the strip chart recorder. The recorded temperature gives the degree of superheat of the vapor and it contains the valuable information in the input for switching criteria in the case of multiple surge.

To simulate pure insurge the procedure of introducing nitrogen is as followed:-

(1) The water in the hot tank is brought to initial specific condition by switching on the 3 K watts heaters. Water level in the tank is maintained at about half full by closing valve No.1 during the start up of the hot tank.

(2) As soon as initial pressure is reached nitrogen supply is introduced into the cold tank via valve No.6 and No.3. The pressure gage in the cold tank should show approximate reading as in the hot tank.

(3) Valve No.1 is then slowly opened to allow the water to seek equilibrium inside the two tanks while at the same time the heaters should be under the regulation of the temperature controller. In this fashion the starting pressure is maintained in the hot tank.

(4) After equilibrium has been achieved, valve No.3 is closed while regulator valve No.6 is adjusted to a bigger opening. At this stage, insurge simulation is ready to start.

(5) To begin the insurge run, valve No.3 is quickly

cracked open. This introduces nitrogen into the cold tank via the regulating valve No.6. For fast or slow insurge, the amount of nitrogen can be controlled by the adjustment on the regulating valve before the start of the run. Service valves No.2, 7 and 8 are remained close all the time while valve No.4 and 5 remain unoperative.

To simulate pure outsurge, steps (1), (2) and (3) are repeated. This time metering valve No.5 is adjusted to suitable size orifice. When ON-OFF valve No.4 is opened, outsurge begins by venting the nitrogen into the atmosphere.

Multiple surge simulation is achieved by first opening valve No.3 followed by valve No.4. However, at no time the two valves are opened simultaneously.

### 3-3 De-airing Procedure for the Pressurizer

Initial start up of the pressurizer, de-airing procedure is necessary to get rid of the air (and moisture) in the space above the water level. This is achieved by first bringing the water to boil. Steam is then allowed to escape through valve No.7 which is used for introducing water into the system. It is noticed that for best result of de-airing, the valve should be opened and shut in succession. This will allow the pressure to build up and subsequently release it. Upon opening of the valve the steam under pressure will create a partial vacuum which helps to suck out the air trapped inside the tank. Built-up steam eventually displaces the air to a negligible amount. A repetition of five or six crackings of the valve will be suffice while at all time the valve No.1 connecting the two tanks remains close.

The other method which involves a connection of a vacuum pump to get rid of the air has also been experimenting on. It is found that there is no significant improvement to the degree of vacuum that one can achieve. For simplicity, the former de-airing procedure is adopted throughout the rest of the experiment.

## 3.4 Instrumentation and Measurement Technique

### (i) Data Acquisition System

Input Scanner Unit HP 2901A essentially consists of a stepping switch, control circuits, output delay switching circuits and front-panel pushbuttons. This scanner unit performs the main function to scan selected channels one at a time by action of a stopping switch. When the control circuit receives an appropriate command, the stepping switch advances one channel position. The output delay switching circuits remove Scanner input signals from output connectors which are used to deliver information to the digit printer. This output delay function is vital while the stepping switch is advancing so that inputs from different channels will not be crossing each other. If front-panel pushbuttons for the new selected position has been self-latched, the control circuit directs the output delay circuits to enable the program contact closures at output connector, to select the proper output connector, and, after a delay, to connect the input signal for that channel to that output connector. In this way the control circuits perform the major functions of starting the scanner's stepping switch from "Home" to the first preselected channels via front-panel pushbuttons and of advancing the stepping switch from channel to channel.

Digital Recorder has a digital clock incorporated in the unit so that the output of different channels being scanned will have the time information and channel identification. The unit accepts up to 20 columns of 4-line-binary-coded electrical inputs from one or two data sources and will print at maximum rate of 20 lines per second. At the rate of printing out, this is found to be adequate for this present investigation.

Measurement resolution is mainly dictated by the auto ranging features in the digital voltmeter unit. Transducer outputs will then have a measuring accuracy of ±.005 mv.

### (ii) Floating Measurement and Guarding

In making floating measurement such as an output from a bridge circuit, care should be taken to eliminate common mode source error. Pressure transducer utilising the strain gage bridge arrangement is an example of floating measurement. The output of the transducer is to be measured as accurately as possible because it is the pressure variation information in voltage form.

Common mode source error arises from having the different ground at the measuring instrument and the ground at the source. This situation may be caused by voltage drops in the ground lines or currents induced into them. An example of this situation is grounded measurement Fig. 3-4-ii(a). A new source, Ecm, the difference between grounds is called the "common mode source". This voltage source is "common" to both the high and the ground lines. Common mode current can go either through Rb or through Ra and Z1. Since Z1 is usually much larger than Ra, and since they are both in parallel with Rb, most of the voltage across Rb will also appear across Z1. All of the common mode voltage will be dropped across Rb, so the instrument will respond to most of it causing a change in reading - an error.

Measurements with differences between grounds, or common mode voltage, are called floating measurements and are said to "float" by the amount of common mode voltage. The circuit found in transducer has both sides of the bridge above ground, so no matter how the voltmeter is connected there will be a common mode voltage, and the measurement will be floating.

During this experimental investigation, instruments used for pressure transducer measurement are digital voltmeter and chart recorder. These instruments have an extra terminal called "guard" besides the HI, LO and ground. This feature provides the facility to shunt off this common mode error so that the output voltage is measured as [illegible] only as the instrument would permit. The guard connection for the bridge circuit is as shown in Fig. 3-4-11(b).

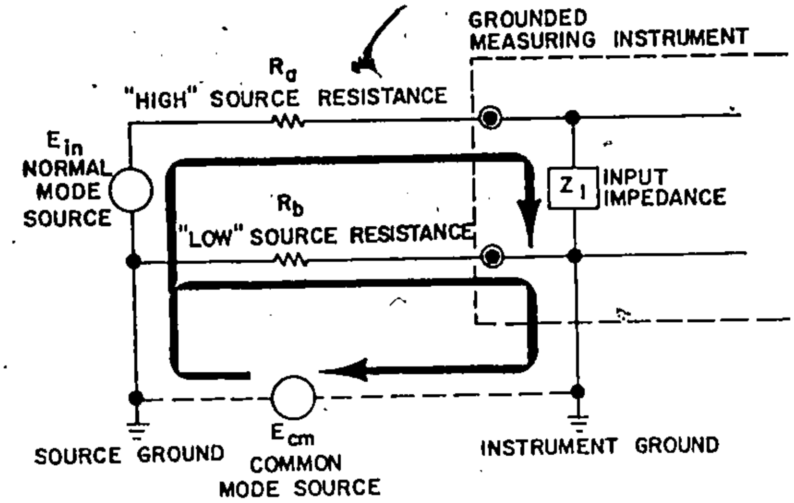


Fig.3-4-ii(a)

Grounded Measurement with a Common Mode Voltage

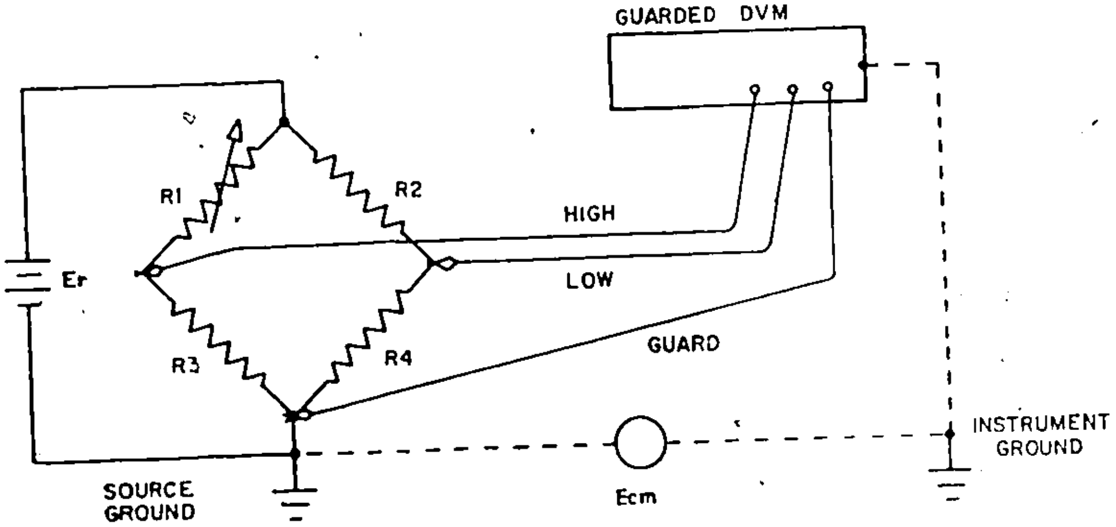


Fig.3-4-ii(b)

Guard Connection for the Bridge Circuit

### (iii) Thermocouple Connections

There are two common ways of connecting thermocouples. The first method of connecting thermocouples is to make use of an extra wire of a type of material (say metal B) forming a reference junction with metal A. The thermocouple wires are connected directly to the voltmeter as shown in sketch (i). This method may be practical if the thermocouples and the voltmeter are close to each other.

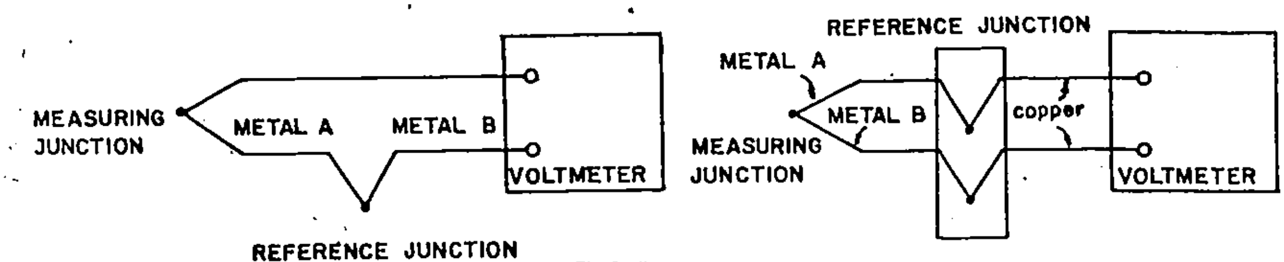


Fig.3-4-iii

SKETCH (i) THERMOCOUPLE CONNECTIONS SKETCH (ii)

The second method is used in this experiment. Reference to sketch (ii), the voltmeter is some distance from measuring junction and therefore copper extender wires are used to bridge the gap. The connections between the copper wires and the thermocouple wires from thermal junctions. These junctions are held at a constant, uniform temperature and together from the reference junction for the measurement. The voltmeter responds to the temperature difference between the measurement and reference junction.

### (iv) Reference Junctions

A commonly used reference temperature is 32°F and most thermocouple reference tables use this temperature as a reference point. This temperature is reproduced easily and accurately with a crushed ice bath (a mixture of ice and distilled water). Throughout this investigation and actual experiment set-up, this simple means in obtaining reference junction is used. A mixture of crushed ice and water is kept inside a thermo-flask and thus it maintains a reference point of 32°F for a long time.

Measurement of temperature, however, with signal conditioning device such as HONEYWELL ACCUDATA 106 Thermocouple Control and Suppression Unit provides one of the most important features. Electrical compensation for changes in cold junction temperature, referencing the thermocouple to 32°F (0°C). The unit has a stablised reference point for use with various thermocouples. It uses a temperature sensitive resistor and a bias circuit to provide electrical compensation for ambient changes in cold junction temperature.

Thermocouple leadwires from the hot junction are brought to a compensation block where a conversion to copper occurs. Block temperature variation affect the cold junction, causing an erroneous output signal. A changed resistance produces a voltage equal and opposite to that generated at the reference junction, thus cancelling it and keeping the reference junction electrically at 0°C.

This type of reference junction is called a self-compensation reference. It does not require an ice bath or constant temperature oven, but generates an appropriate corrective voltage to compensate for variation in the reference junction temperature. The combined voltage generated by the reference junction and the self-compensating reference closely duplicates the voltage of an ice point reference over an ambient temperature of approximately 32°F to 122°F.

Beside the above mentioned feature the unit provides positive and negative d-c calibration for recorder. It gives an accurate +1mv or -1mv signal at +1%. This signal is applied in series with the input signal, and is switched in an out of the circuit with a front panel control.

The last but not the least feature, the unit provides stepped and find d-c suppression of thermocouple input. This facility is made available by suppression circuitry, and thus permits expansion of temperature measurements to provide a more accurate view of the area of interest.

Suppression is provided by "coarse" and "fine" (step and continuous) adjustments. Coarse (step) suppression precise current is applied to the compensation resistor. This resistor changes with temperature variations creating a potential at the reference junction output which returns the reference junction to an electrcal 0°C and cancels the error signal.

Reference to the simple schematic compensation circuit sketch, ambient temperature changes at the reference junction are sensed by the compensation resistor enclosed in the temperature block RT1. In the diagram the reference junction, measurement junction and the compensation resistance are represented as e.m.f. sources. If the block temperature varies, a voltage is generated by the thermocouple reference (cold) junction, creating an erroneous reading at the control unit output. The compensation resistance RT1, located in the same environment as the reference junction and subjected to the same temperature variation, changes resistance in direct proportion to ambient temperature variations. The bias voltage applied across this

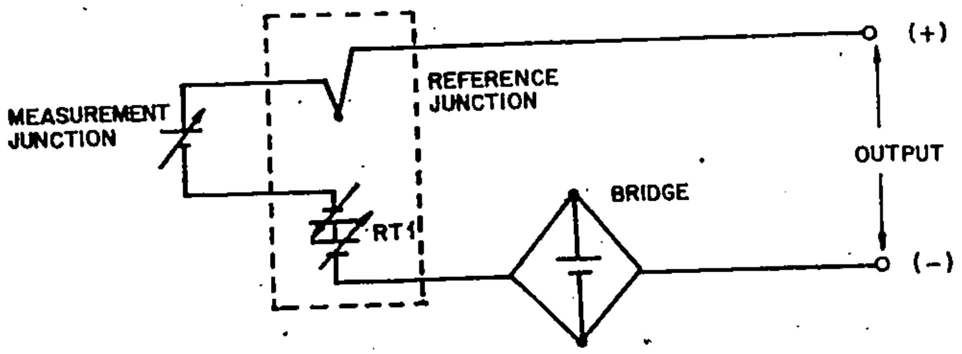


Fig.3-4-iv(a) COMPENSATION CIRCUIT SIMPLIFIED SCHEMATIC is adjustable in 10mv steps between +0 and +50mv for temperature measurements, and between -40 and +50mv for other inputs. Fine suppression is controlled with a 22-turn potentiometer, adjustable from 0 to 10mv, thus giving a full range of control between the step suppression settings, and extending the total range of suppression from -50 to +60mv.

In this investigation of insurge runs accurate temperature in terms of degrees of superheat is estimated of the order of 50° at starting initial pressure of 200 p.s.i.g. With this suppression feature, the input signal going to the chart recorder is suppressed and therefore the whole span of the chart is utilized for degrees of superheat recording. This magnifies the temperature resolution of particular area of interest. This temperature measurement clearly indicates the magnitude of superheat of compressed steam. The temperature history which is measured by this method is mainly used in the switching criteria in the analytical model for multiple surge.

# Chapter IV

## 4-1 Pure Insurge

Both experimental and theoretical pressure transients are plotted vs time for duration of 30 seconds and the result is presented in Fig. 4-1-1, 4-1-2 and 4-1-3. These simulation runs are typical experimental value obtained under the same initial condition of about 200 p.s.i.g. Although the initial change of water level for each run is different, the amount of water in the beginning of the insurge is maintained approximately the same. The slope of water level at the start of the test run is a variable parameter for these simulation runs. Steeper is the initial slope of water level signified higher transient flow fate. The numerical value of the initial slope and starting pressure for each run is presented as followed:-

```
RUN 22   ALDOT = DERIV (0.065, ALI)
         PRESG = 203.87
RUN 23   ALDOT = DERIV (0.097, ALI)
         PRESG = 197.34
RUN 24   ALDOT = DERIV (0.030, ALI)
         PRESG = 198.67
```

Experimental data of water level and pressure are recorded in digital form in mv with the corresponding time information. Experimental readings are next changed to the correct units by Conversion Program ( App. 1 ). In essence the program incorporates all the conversion factors of the pressure transducer to convert mv into p.s.i.g. for the pressure information while water level data is transformed into inches of water via Eqn. 3.1.3. Sample of the Conversion Programme print-out is included in App.2 .

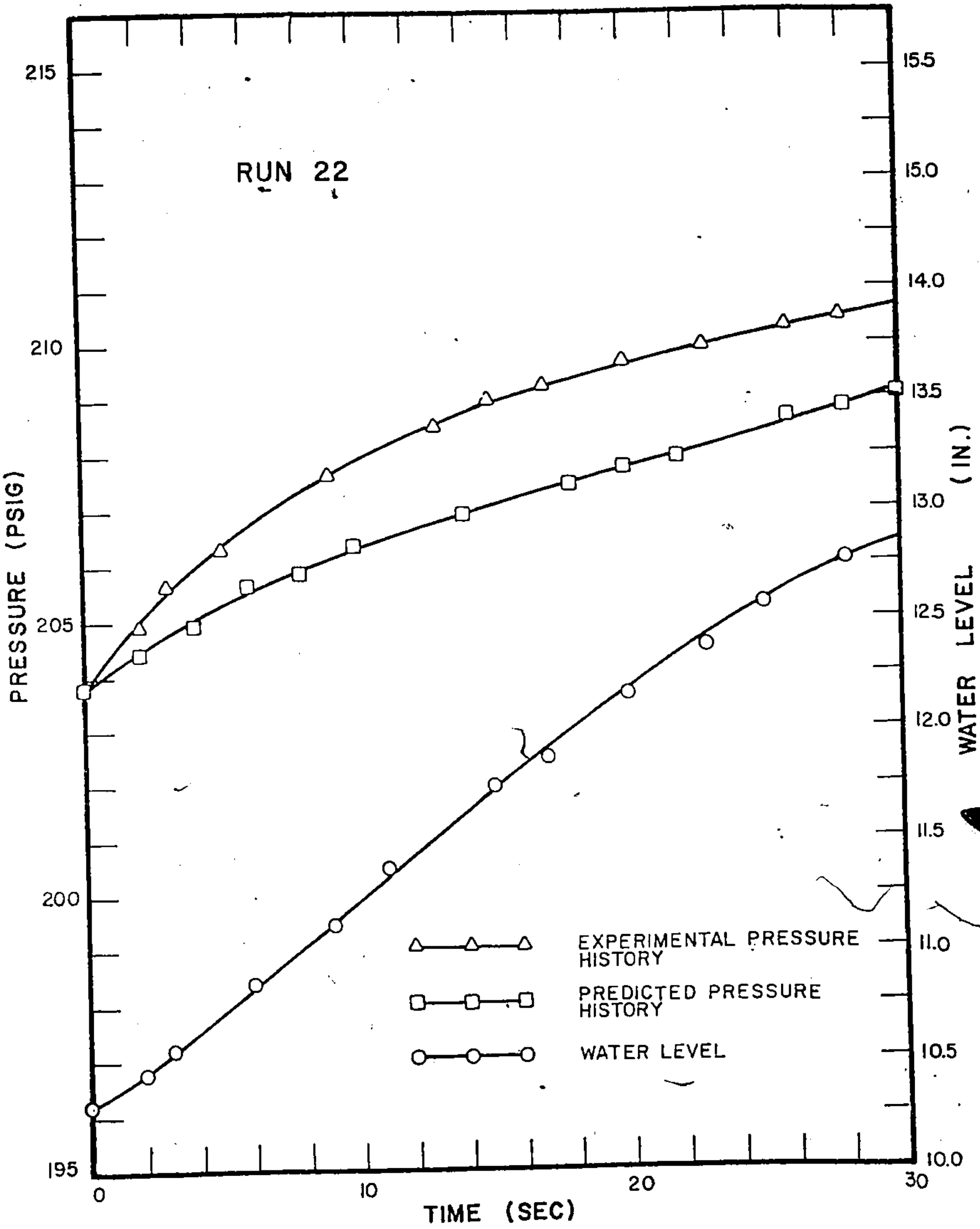


Fig. 4-1-1 Plot of pressure and water level history for pure insurge

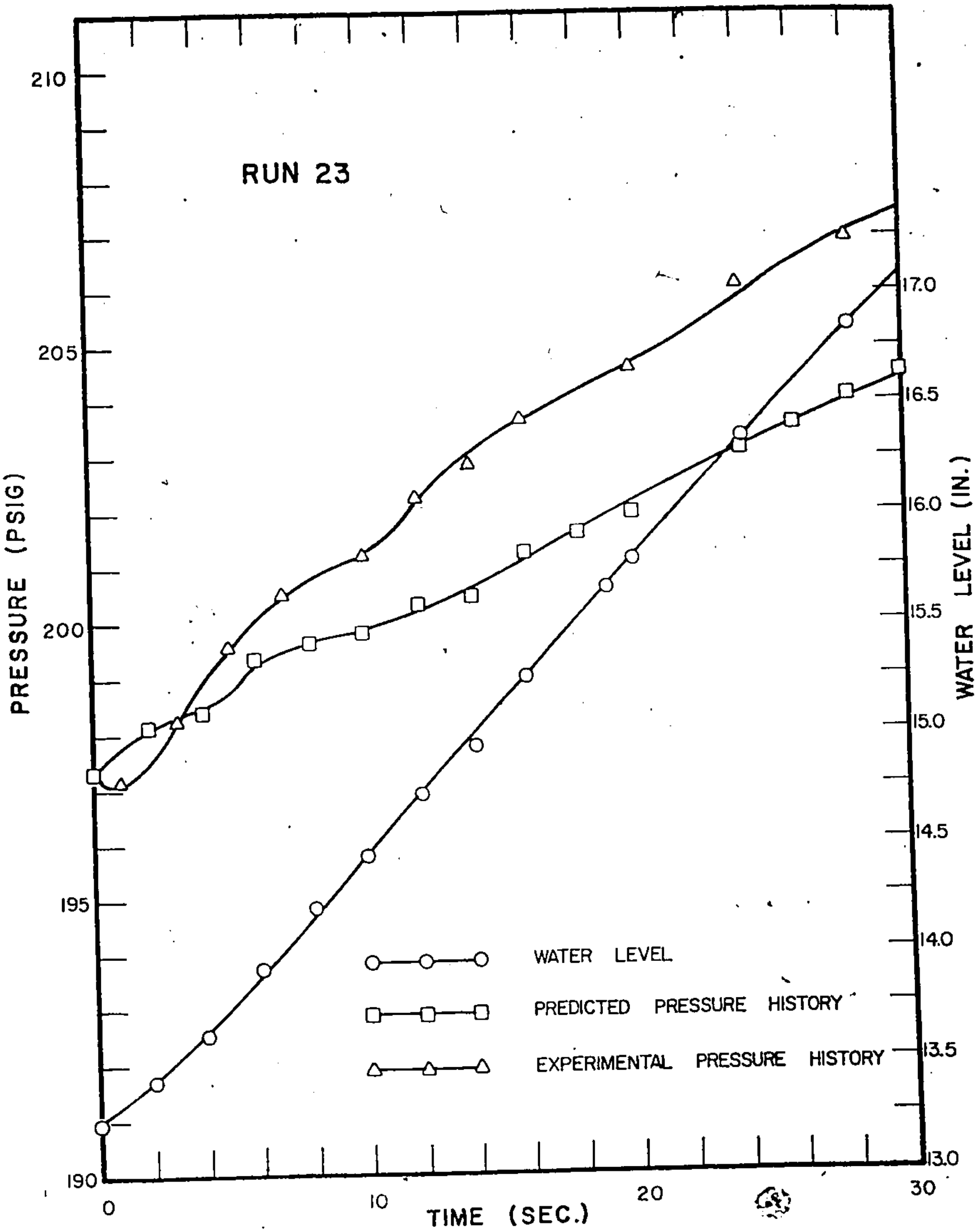


Fig. 4-1-2 Plot of pressure and water level history for pure insurge

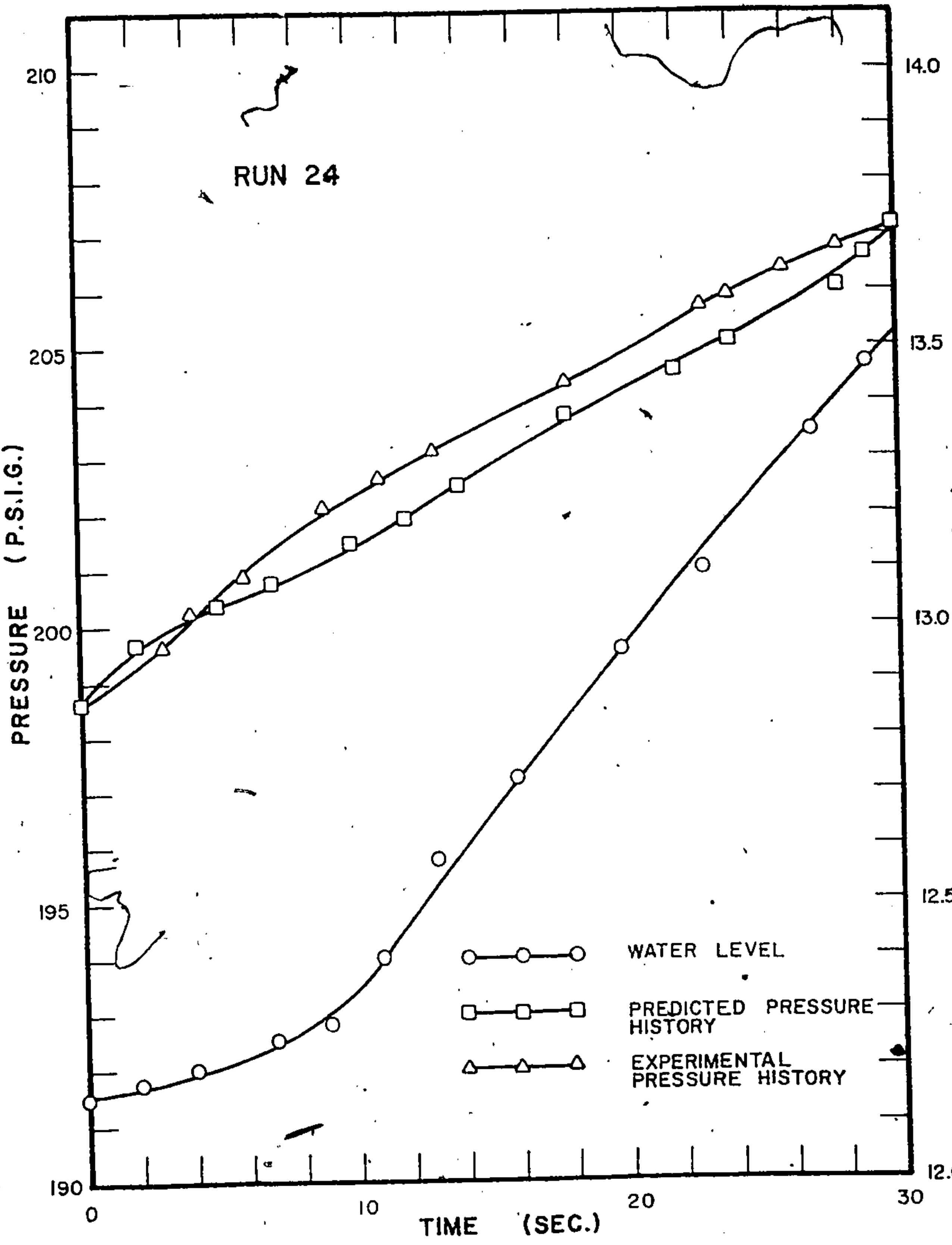


Fig. 4-1-3 Plot of pressure and water level history for pure insurge

## 4-2 Pure Outsurge

Experimental and theoretical pressure transients are plotted as shown in Fig. 4-2-1, 4-2-2 and 4-2-3. These simulation runs are perf[illegible]ed under starting pressure of about 200 p.s.i.g. The variable parameter is the initial change of water level. The variation in the slope of the level at the start of the test run is achieved by adjusting the orifice of the metering valve. The numerical value of the initial slope for each run is presented as followed:-

RUN 17 ALDOT = DERIV (-.201, AL)
PPO = 198.23

RUN 18 ALDOT = DERIV (-.105, AL)
PPO = 200.19

RUN 19 ALDOT = DERIV (-.052, AL)
PPO = 193.77

It was found from a series of test runs with different values of the initial slope that RUN 17, 18 and 19 yield predictions in pressure transient of different magnitudes of accuracies. At the start of the simulation run, sufficient time is allowed for equilibrium to take place. Water level on chart recorder is again checked for constant reading before simulation is initiated.

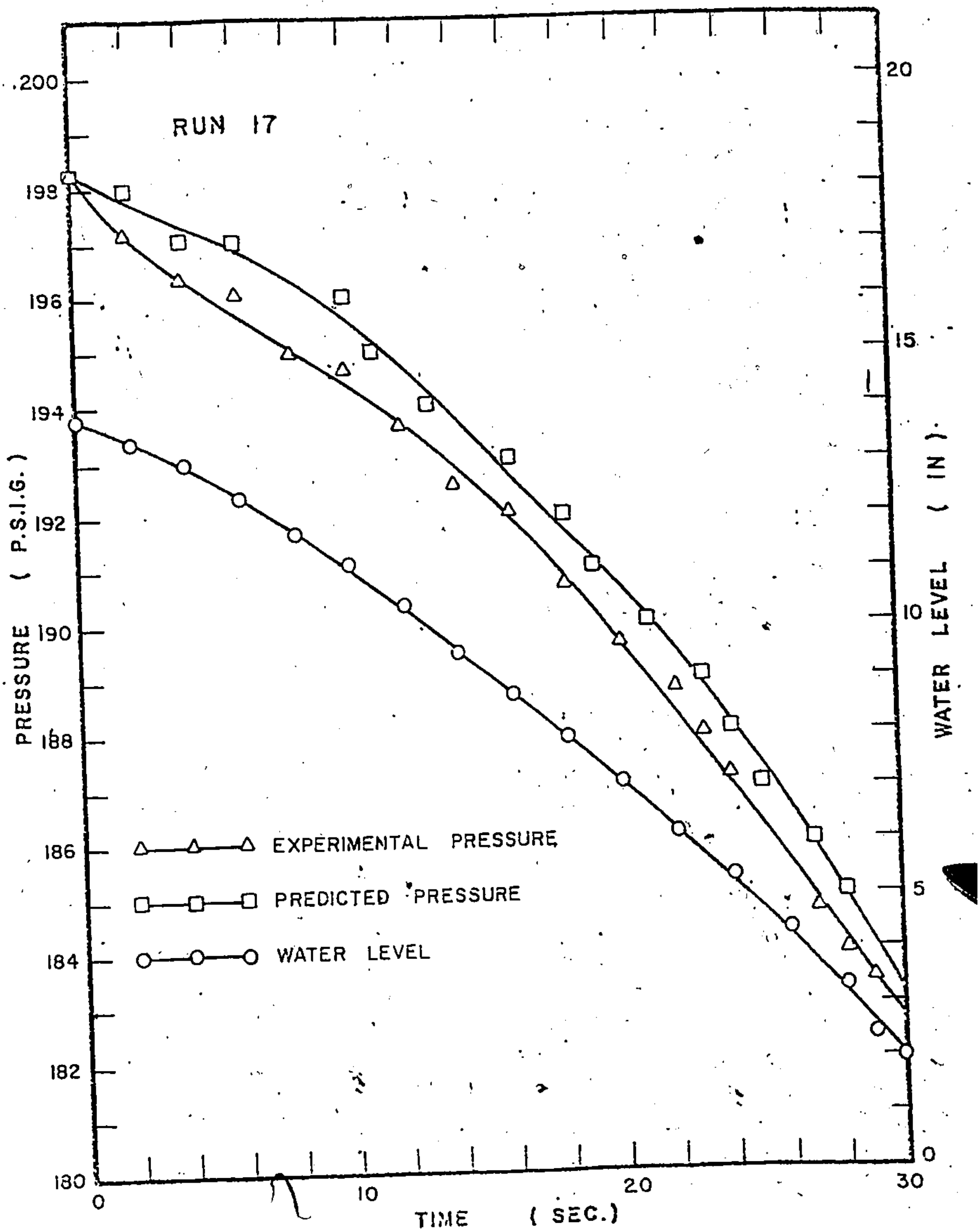
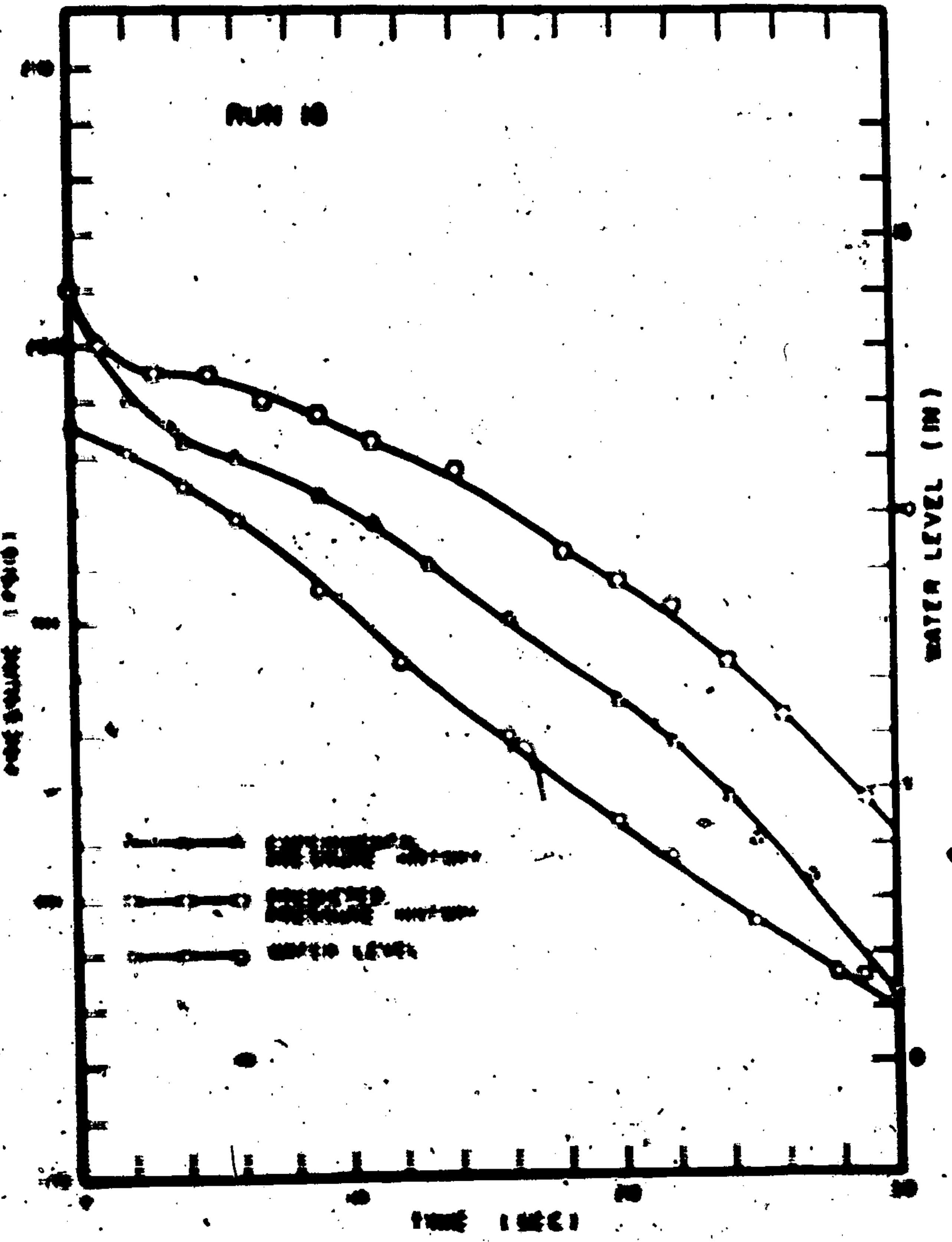


Fig. 4-2-1 Plot of pressure and water level history for pure outsurge


RUN 10
PRESSURE (PSIG)
WATER LEVEL (IN)
WATER LEVEL
TIME (SEC)
0
10
20
30

[illegible]

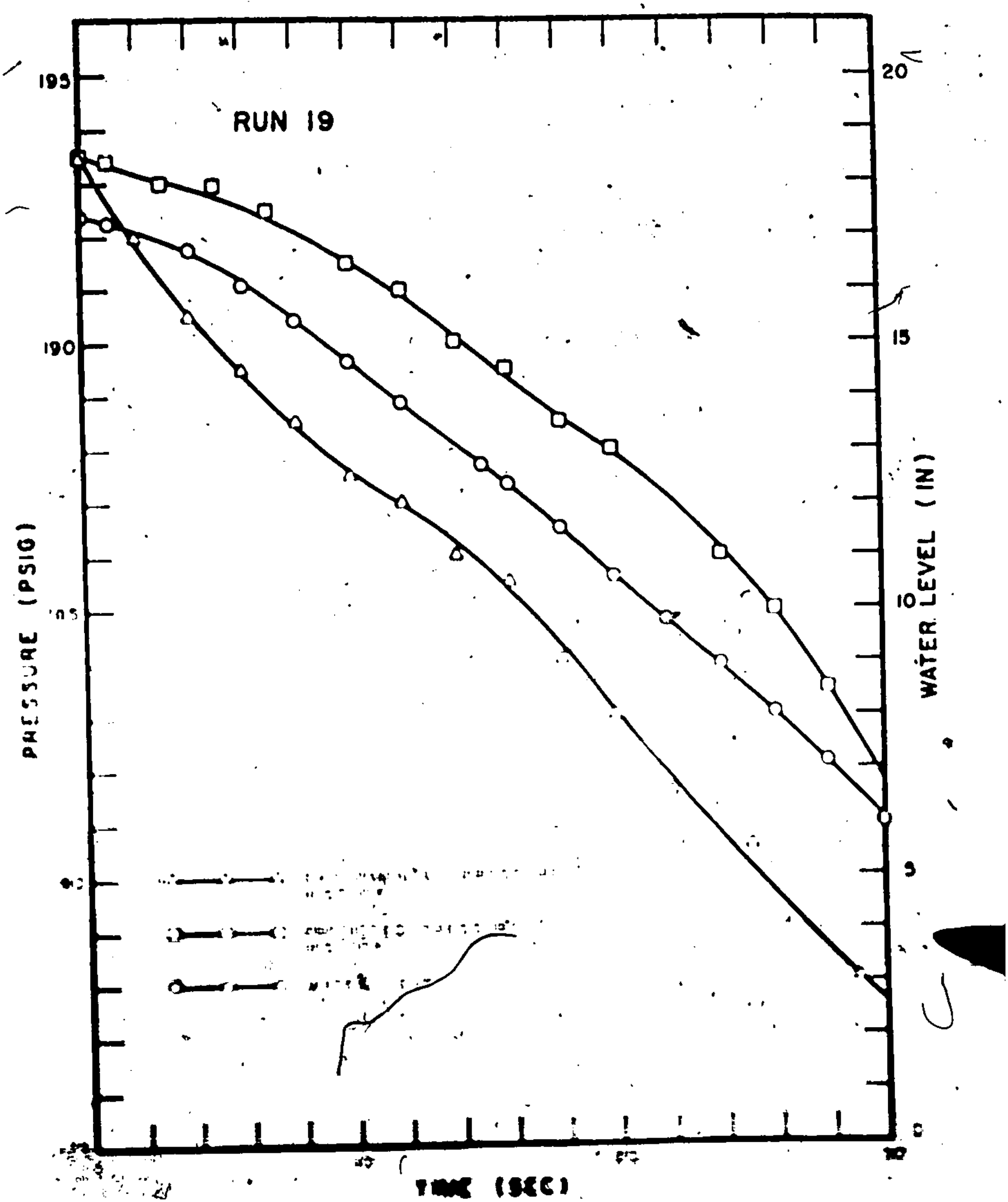


Fig. [illegible] of pressure and water level [illegible] for [illegible]
5.7

## 4-3 Multiple Surge

Results of multiple surge (insurge followed by outsurge) are presented in Fig. 4-3-1, 4-3-2 and 4-3-3. In the insurge portion of the simulation, the duration is for 60 seconds. Since the variable of the change of initial water level for pure insurge using the range of values from 0.030 in/sec to 0.097 in/sec are already selected, the same order of initial slope is utilised in the insurge portion. The numerical value of the initial slope for each run is presented as followed:-

```
RUN 32   ALDOT = DERIV (0.10, ALI)
         PRESG = 195.08
RUN 33   ALDOT = DERIV (0.13, ALI)
         PRESG = 195.19
RUN 34   ALDOT = DERIV (0.04, ALI)
         PRESG = 197.30
```

Outsurge portion starts after 60 seconds and it lasts for about 20 seconds. Water level history at such point in time drops abruptly. This signifies the on-set of outsurge. Simulation for outsurge did not continue longer than 20 seconds duration because the water level in the pressurizer fell too low. Sinusoidal water level history was not achieved. This was mainly due to the way of how nitrogen was introduced [illegible] and released out of the cold tank. The ON-OFF valves in the actual apparatus was manually operated.

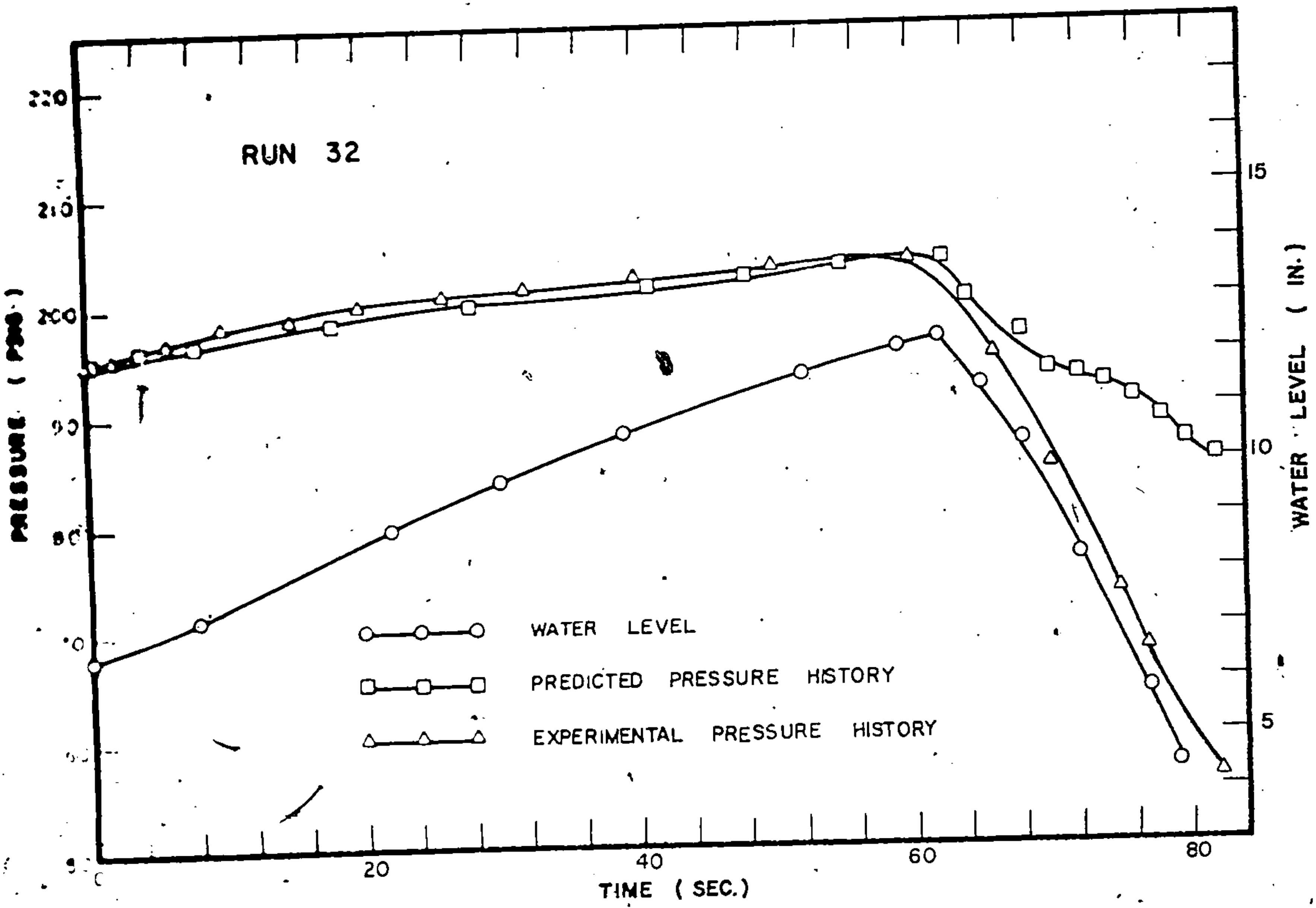


Fig. 4-3-1 Plot of pressure and water level history for multiple surge

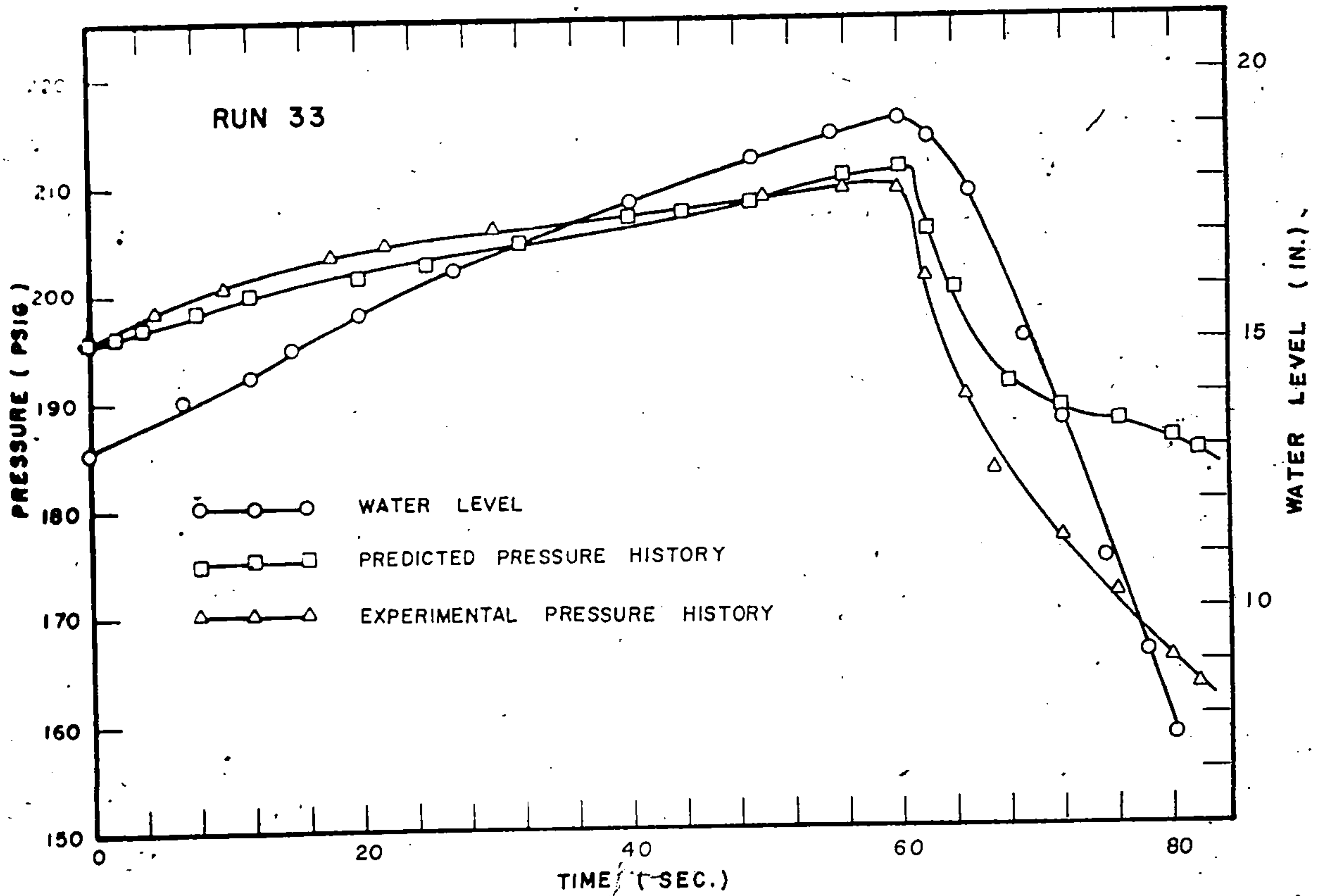


Fig. 4-3-2 Plot of pressure and water level history for multiple surge

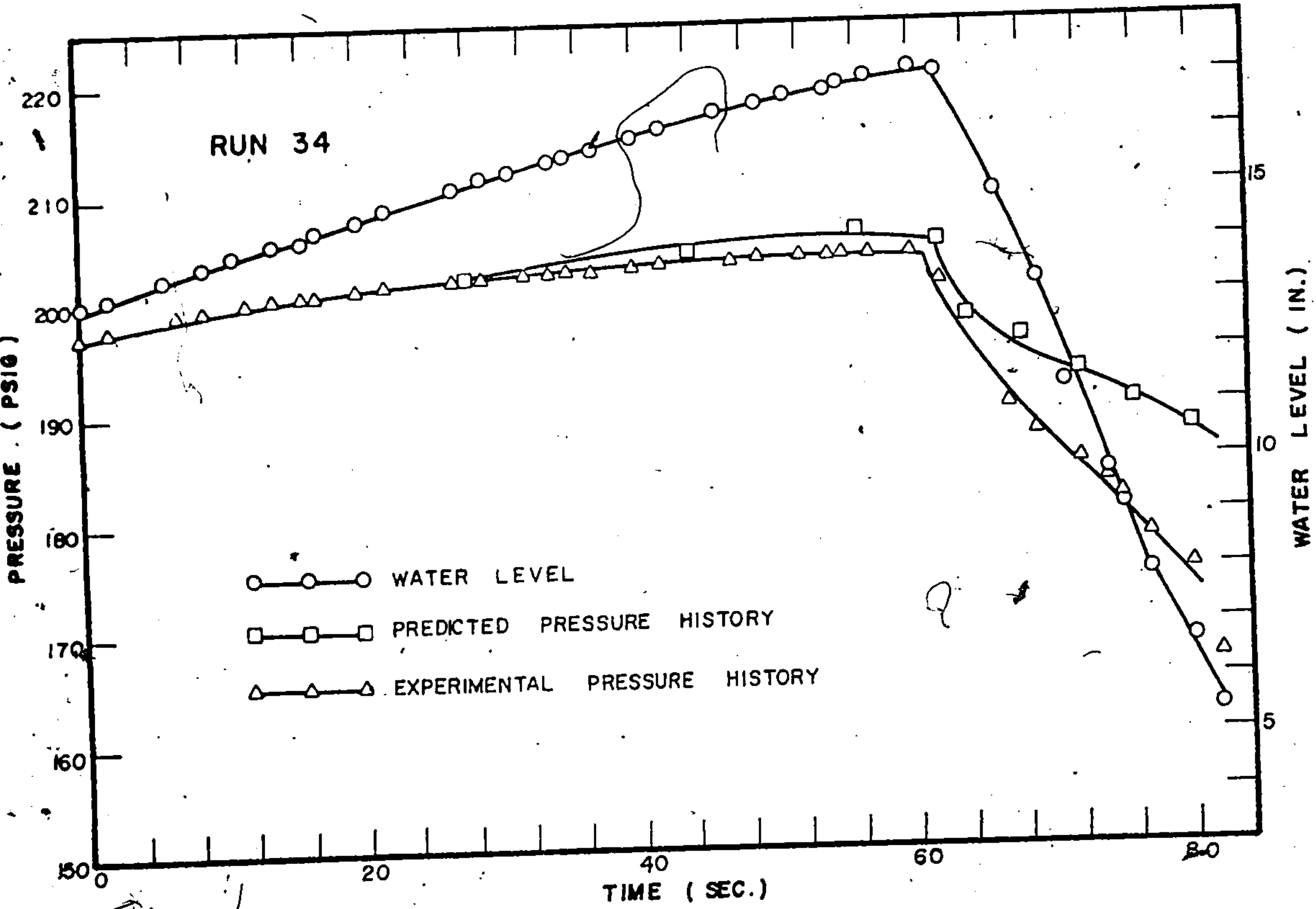


Fig. 4-3-3 Plot of pressure and water level history for multiple surge

## 4-4 Discussion and Conclusion

Results obtained for pure insurge RUN No. 22, 23 and 24 show agreement between the experimental and predicted pressure with different magnitudes of accuracy. A consistent trend, however, shows that experimental pressure is higher than the predicted pressure. The largest amount of error in prediction is about 3 p.s.i. and it occurs on RUN No. 23. In term of the maximum deviation from the experimental result over the pressure increase during the interval the error estimation is about 29%. The water level change for this run is 3.8 inches for a duration of 30 seconds while for RUN No. 22 and RUN No. 24, they are 2.6 inches and 1.4 inches respectively. Therefore it is a marked possibility that greater water level change results in larger error in prediction for the same period of duration. A close inspection of the error estimation (Fig.4-4-2)for these runs points to the fact that there is a certain relationship between the water level change and the magnitude of accuracy in prediction. The value of the initial slope is smallest for RUN No. 24 (.030"/sec) while at the same time it indicates the slowest transient flow rate. The accuracy for this run is almost 10%. RUN No. 22 has an initial slope value of .065"/sec and is the second best while RUN No. 23 which has a value of .097"/sec yields a greater error estimation. In essence, therefore, the slow insurge transient flow rate which is a direct indication of a smaller initial slope of the water level will improve on the prediction result. The water level change for the same duration if it is small, will have a slow insurge transient flow rate. Consequently, the prediction will be better.

In actual experiment performed on insurge for a nuclear reactor loop, the model proposed by Moeck (10) was checked against available data. The observed pressure rise for some particular runs was higher than that was calculated by his model which ignored heat transfer. The agreement between the predicted pressure and observed result was good. However, in another groups of test runs, his model predicted a higher pressure than the actual observed result. This led to the following dilemma: should heat transfer be included to obtain a more accurate simulation of the majority of runs, or should it be ignored in favour of better prediction of occasional severe transient?

From the experiment results obtained for this project, this notion of whether to include heat transfer or not is also noticed. For some of the runs, the predicted pressure is much higher than the experimental one and have a large error percentage while in majority cases they are close to experimental data. The corrective action that comes into light is to use a correction factor in the heat transfer term.

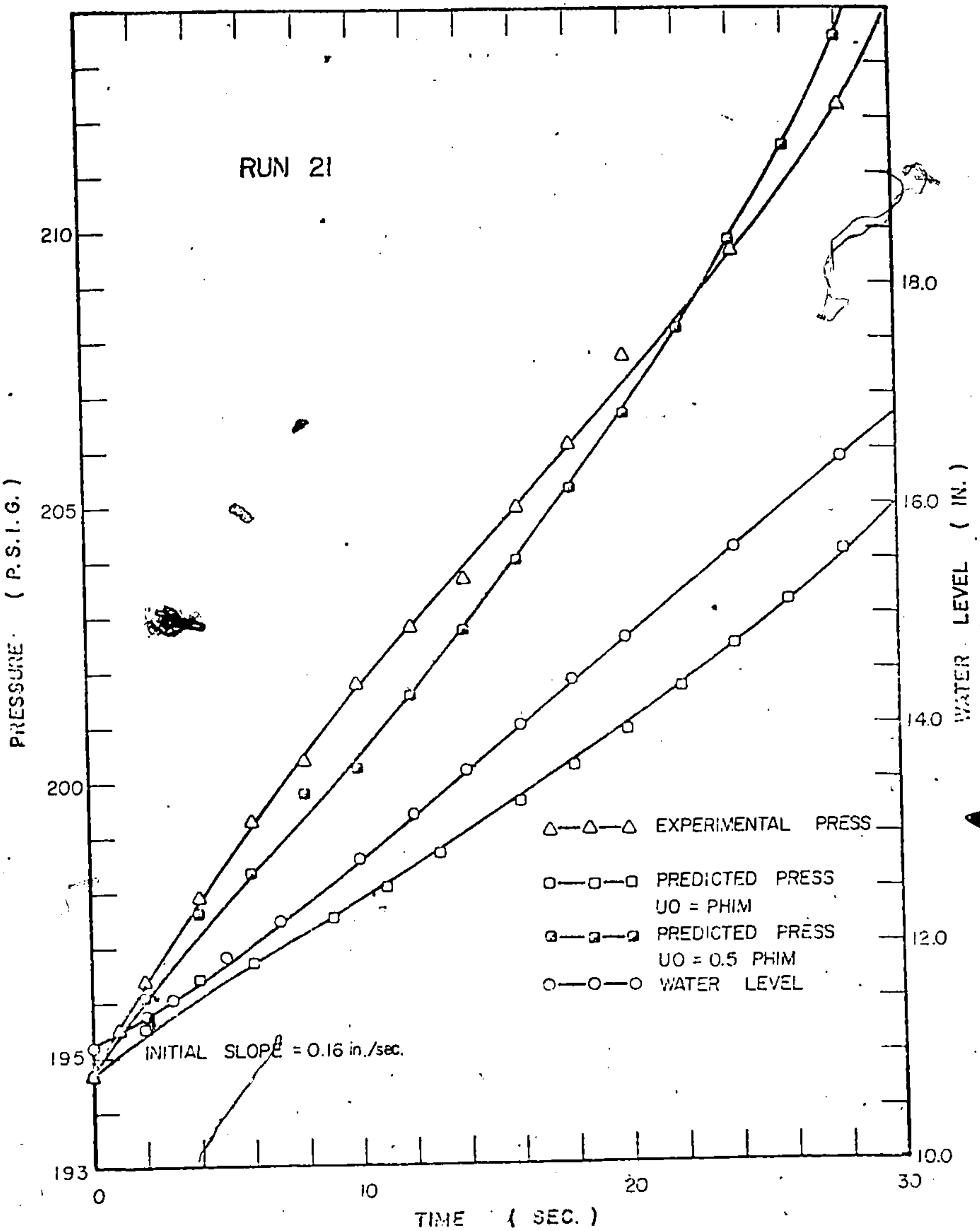


Fig. 4-4-1 Plot of pressure and water level history for pure insurge

[redacted]

This gives a better overall prediction for the pressure. This is presented in Fig. 4-4-1. RUN No. 22 and RUN No.23 are performed at a higher transient flow rate than RUN No.24 and the error estimations are of the larger value than RUN No. 24. With these two runs the above mentioned dilemma can be partially resolved - at severe transient pressure insurge which is dictated by fast transient flow rate, correction factor less than one should be employed. This is to say heat transfer term should not be ignored but on a fractional basis. At slow transient flow rate., correction factor equal to one is used for the heat transfer term. It is the opinion of the writer that a correction factor for heat transfer term should be included for safety reasons. Fast transient flow rate can be detected by the valve of the initial slope of water level and any valve greater than .040 in/sec is considered to be a fast transient flow rate.

For PURE Outsurge results such as RUN No. 17, 18 and 19 have an opposite trend compared to insurge case. The predicted pressure is higher than actual experimental one. In RUN No. 17, the water level drops to a greater amount than other two runs. The prediction error is smallest in this run. At the same time the initial slope of the water level be~~ing~~ the steepest gives a better result. Although the dilemma is not valid in the outsurge case due to the governing equation formulation, transient flow rate plays an important and similar role in order to achieve good prediction. During the actual test runs, this parameter is not monitored. Nevertheless, after several prelimary runs, it is soon found that the influence of fast outsurge rate is indeed a governing factor for good prediction using the proposed model. This can be clearly noticed in the error estimation plot. (Fig. 4-4-3 )

The question of why the situation arises when one needs slow transient flow rate for good prediction in pure insurge and the opposite for pure outsurge? The answer is that for slow insurge (i.e. slow transient flow rate) sufficient time is allowed for heat transfer to take place and equilibrium is achieved during the whole excursion of the water level. For the outsurge case, there is no heat transfer mechanism involved in the model formulation. Although the assumption for the governing equation requires the process to be adiabatic, it turns out that non-equilibrium state occurred in the fast transient flow rate overrides this assumption in order to have good agreement in prediction. In other words a non-equilibrium no heat transfer process models the outsurge case better while a equilibrium with heat transfer process fits into the pure insurge case.

Insurge followed by outsurge is a combined situation of pure insurge and pure outsurge. Typical runs for this case are RUN No. 32, 33 and 34. For the first 60 sec. duration, the insurge portion followed the same trend as described in the above pure insurge case. Close agreement is obtained by virtue of the fact that the initial slope of water level (i.e. transient flow rate) has to be small. RUN No. 34 has the most gentle transient flow rate. Therefore, pressure prediction for the insurge portion of multiple surge is identical to experimental result in the first 28 seconds. It is in that respect slow insurge flow rate allows sufficient time for heat transfer to take place through the pressurizer wall. On the other hand if the water level increases rapidly, the vapor volume decreases. Pressure will in turn rise in a faster pace. For the outsurge portion after 60 seconds, there is a lot of discrepancy between predicted and experimental results. Although faster outsurge rate does help to diminish the error estimation, it does not have the same kind of error magnitude as in the 'Pure' outsurge case. A closer look at the model, one may suspect that the model itself does not have the provision to account for flashing phenomena during sudden release of pressure. The combined effect of great increase in volume and the poor mechanism in transferring heat from liquid into vapor is insufficient to maintain pressure drop. In actual experiment time has not been allowed for equilibrium to take place. Consequently, multiple surge results do not behave as ideally as one would expect.

In spite of this, the information of vapor temperature which serves as a switching creteria between governing equations, may not be good enough for such purpose. A close look at the source programme for multiple surge FUNCTION TEMP is the temperature history for the vapor inside the hot tank. The temperature rises as the insurge takes place and at the same time the water level increases. At the end of 60 seconds duration water level rises to a maximum height and simulation is reverted to outsurge. The temperature follows the trend of water level. It drops to initial temperature in about 12 seconds. The switching criteria which is employed in this project, chooses the outsurge governing equation for the remainder of the simulation run. The switching is done abruptly and in the physical situation time has not been allowed for equilibrium to take place. Referring to Pure Outsurge case, simulation takes place only when equilibrium has been achieved.

In earlier work by Kulkarni, (13) multiple surge simulation by CSMP package temperature is being evaluated as soon as the water level reaches the maximum height. This is done by using $PV = mR(p,T)T$ utilising Newton-Raphson iteration method. In this way every time values of pressure and specific volume are known, temperature $T$ can be established. As outsurge progresses, it reaches a state at which temperature becomes saturation temperature of corresponding pressure. The switch into outsurge governing equation is then implemented. Such a multiple surge trajectory in T-S diagram is similar to Fig. 2-4-2. This alternative way of switching did not find too much success in this investigation with the available experimental result.

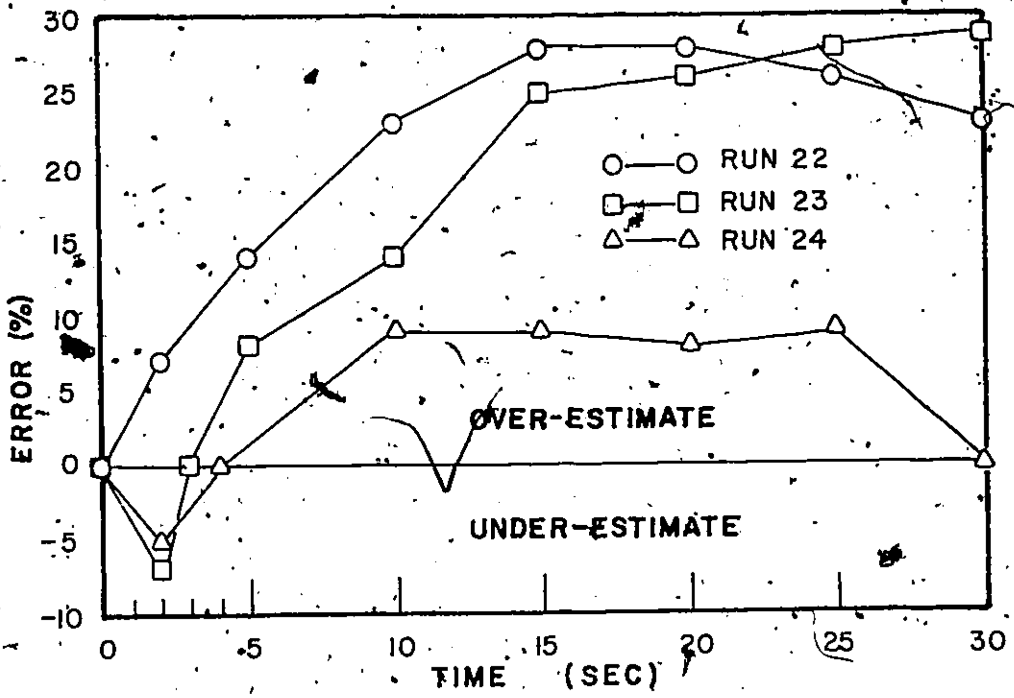


Fig. ~~4-4-2~~.Plot of error estimation for pure insurge

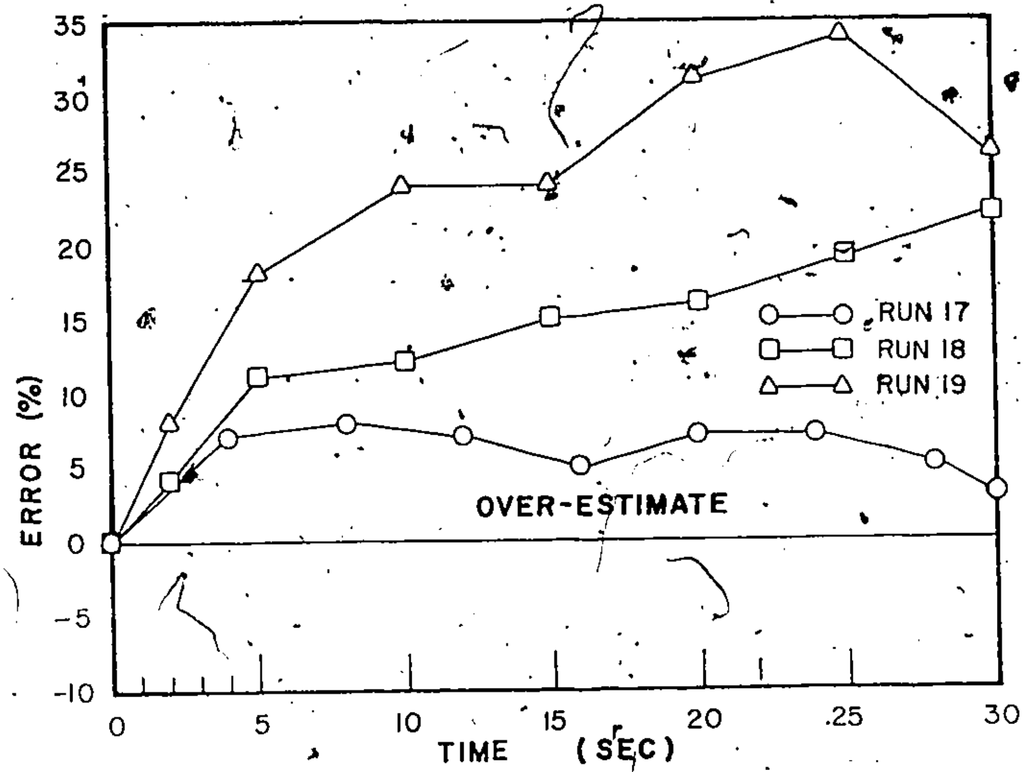


Fig. ~~4-4-3~~ Plot of error estimation for pure outsurge

# Chapter V

## IMPROVEMENT AND RECOMMENDATION FOR FUTURE WORK

Improvements on overall performance of the pressurizer can be accomplished by adding more heaters to countered pressure drop. The power rating for these heaters has to be increased substantially.

Location of heaters are also very important. It should be located at the bottom of the tank. This has the advantage of maintaining the whole volume of water being saturated during steady state, i.e. the energy is being available for counter-acting the pressure fall during the first outsurge starting from equilibrium. However, there are two disadvantages in this arrangement - loss of high-temperature water if insurge is to occur first - during outsurge energy supply by the heating elements takes place in a larger volume of water in comparison with heaters at higher position separated by baffle plate, resulting in a slow temperature rise. Although this feature does not yield benefit with the present model of pressure prediction, it has the flexibility for future work to accommodate different analytical model with heat source.

The size of the pressurizer and the calculation of heat required to maintain constant pressure during outsurge become vital design parameters. Physical dimension of the pressurizer is dictated by maximum insurge volume and outsurge volume. The ratio of total pressurizer volume to volume of coolant is a function of the change of pressurizer from its nominal value. The choice of correct power rating of these heaters is governed by the time allowed to restore to nominal value during pressure fluctuation. Optimum physical dimensioning of pressurizer and satisfactory choice of heater power mean considerable saving when such implementation takes place in an actual reactor loop. Recommendation for future work in this area is worthwhile.

In the new proposal of design arrangement of heaters, two groups of elements are used. The original bank of heaters is employed to bring the pressurizer to initial testing condition. It also serves the purpose of maintaining equilibrium state. The second group of heaters is situated at higher elevation inside the pressurizer and is used to keep the pressure from falling too low. Baffle plates and containment are also incorporated to improve the overall performance of the pressurizer. They are mainly to achieve better mixing during insurge and for faster recovery of pressure during outsurge with baffle plates and second bank of heaters.

Transient Flow Rate should be included and monitored in the future improvement phase of this project. This requires additional purchase of a differential transducer and an amplifier plug-in unit. The arrangement is very much similar to the level measurement in the pressurizer, except this is located on the cold tank. Transient flow rate is an important parameter which would affect the accuracy of the prediction of pressure. For simple and approximate calculation of transient flow rate the following difference method can be used.

$$\phi_v = -Acw\frac{Hcw(t)-Hcw(t-\ t)}{\Delta t} \qquad \text{------- Eqn. 5.1.}$$

where

Hcw(t) = the height of water in cold tank at time t

Hcw(t-Δt) = the height of water in cold tank at time t earlier

Acw = cross sectional area of cold tank

Hcw(t) and Hcw(t-Δt) represent the level history of the water in cold tank. This information is obtained by the signal output P of the differential pressure transducer. The technique is similar to the measurement of the level history in the pressurizer.

Instrumentation for measurement of pressure, temperature, water level and transient flow rate requires the new HPIB 3050 system. This provides not only all the data logging capabilities but it will also control function to induce different patterns of insurge and outsurge. In this way, fully automatic operating system is realised. This opens to numerous ways of simulation of test runs under different initial conditions and such automatic control system suggested in Fig. 5-2 presents a financial investment of thousands of dollars.

With this new proposal of experimental set-up, multiple surge of other type such as outsurge followed by insurge can also be investigated. Additional installation of immersion heaters and baffle partitions arrangement will help to prevent drastic drop in pressure during outsurge stage. At the beginning of insurge, buffer tank serves a useful purpose of minimising mixing effect of cold water in the pressurizer. It is also velieved that water level history excursion will behave in a much gentle fashion.

Prelimary test runs on outsurge followed by insurge simulation were performed. Prediction of pressure transient was not satisfactory. Existing governing equations did not yield close agreement with experimental results. In light of this new proposal of process control and apparatus modification, the writer believes that the laboratory size surge tank has the potential to accommodate future development of analytical models and would be able to verify these models under different operating conditions.

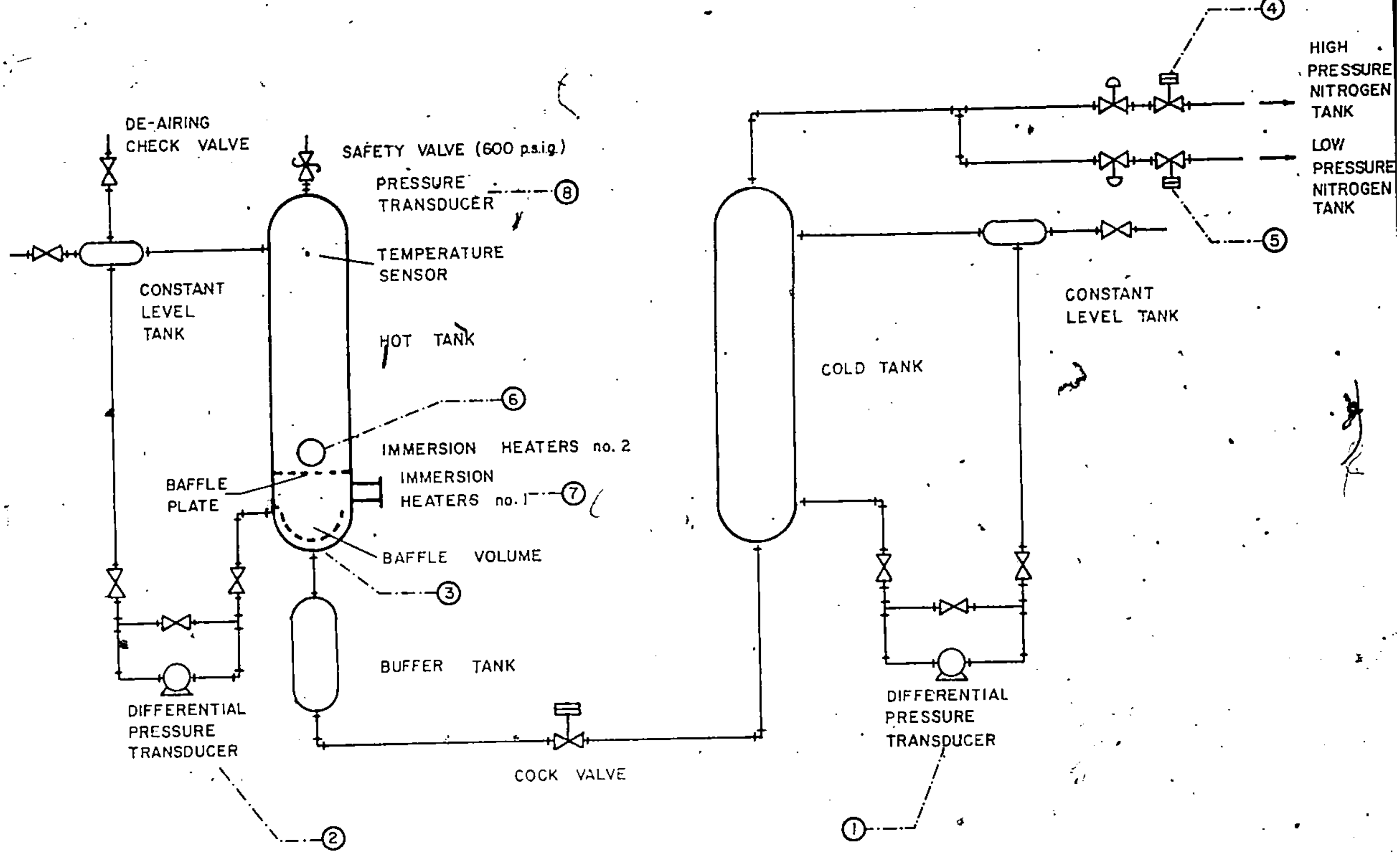


Fig. 5-1 SCHEMATIC DIAGRAM OF MODIFIED SURGE TANK EXPERIMENT

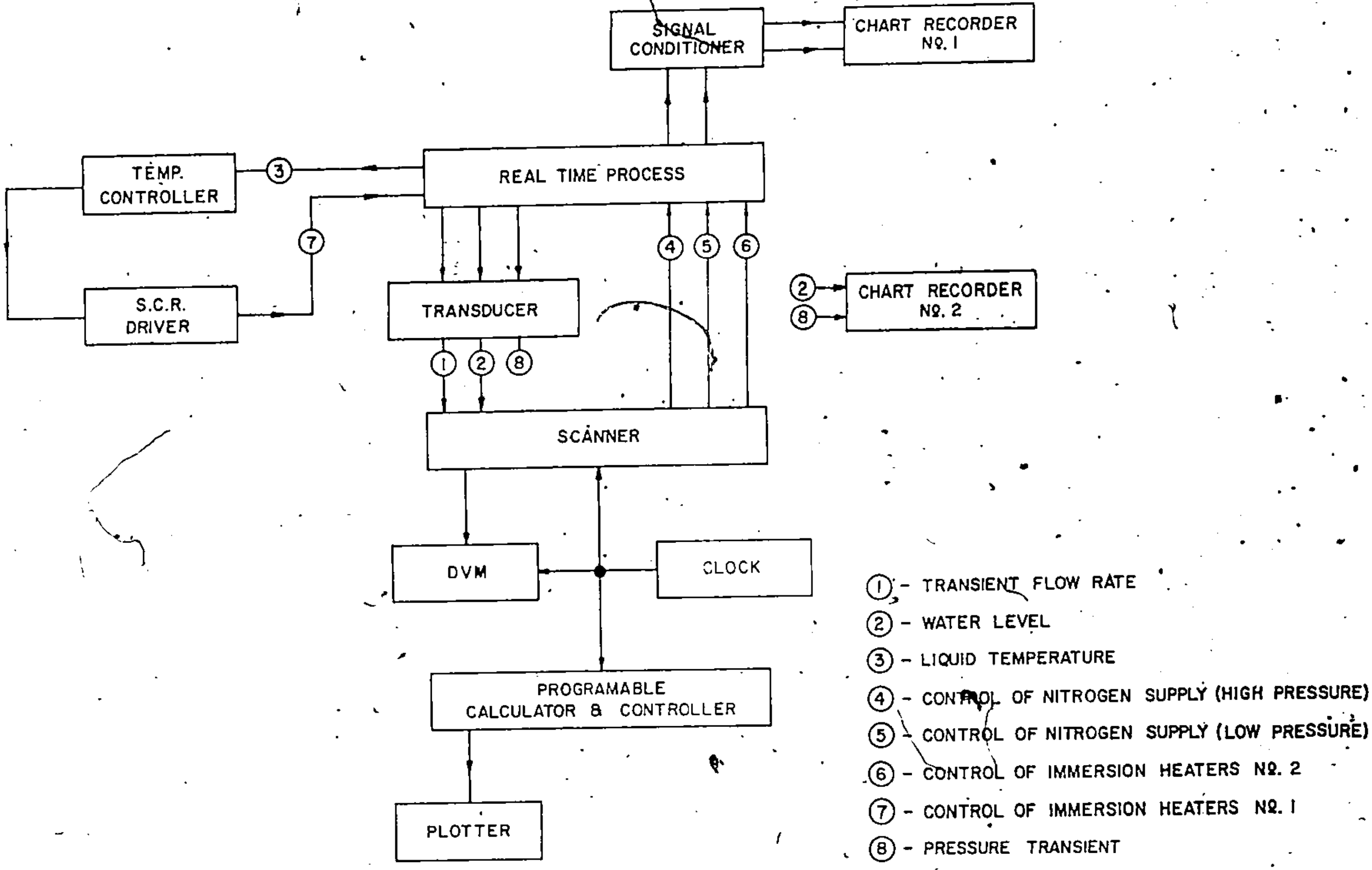


Fig. 5-2 NEW PROPOSAL OF PROCESS CONTROL AND RECORDING SET-UP

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12. IBM "System /360 Continuous System Modeling Program User's Manual", Program Number 360A-CX-16X.

13. Kulkarni, K., "Application of a CSMP Technique for Pressure Prediction During Insurge, Outsurge and Multiple Surge", M.A.Sc. Thesis, Department of Mechanical Engineering, University of Ottawa, 1974.

# APPENDIX

```
FORTRAN IV G LEVEL  21                    MAIN                  DATE = 76159          14/13/04

 0001                  DIMENSION ITT(100),VO1(100),IT(100),VO2(100),H(100),PRESS(100)
                C      GA1 : GAIN OF AMPLIFIER #1
                C      GA2 : GAIN OF AMPLIFIER #2
                C      H2 : THE FIXED DISTANCE BETWEEN THE TOP AND BOTTOM ON SIDE OF THE
                C      PRESSURIZER
                C      CON1 : DENSITY OF WATER @ 350F - DENSITY OF STEAM @ 350F
                C      CON2 : THE DENSITY OF WATER @ 150F - DENSITY OF STEAM @ 350F
                C
                C
 0002                  N=26
 0003                  V1IN=415.9
 0004                  V2IN=718.6
 0005                  GA1=138.058
 0006                  GA2=133.976
 0007                  H2=24.0335
 0008                  CON1=55.45-0.0308
 0009                  CON2=61.3-0.0308
                C
                C
                C      CONVERTING MV INTO PRESSURE OF INITIAL VALUE BY MULTIPLYING A
                C      CONVERSION FACTOR ( UNIT = PSIG)
                C
                C
 0010                  PRESC=V2IN*0.27044
 0011                  DIFPO=13.32271*14.2234/1000.*(V1IN-0.0)/GA1
                C
                C
                C      CONVERTING MV INTO WATER LEVEL OF INITIAL VALUE BY MULTIPLYING A
                C      CONVERSION FACTOR (UNIT = IN)
                C
                C
 0012                  H0=((-DIFPO*144.)+H2/12.*CON2)/CON1*12.
 0013                  WRITE (6,101)
 0014             101  FORMAT (///,2X,101('-'))
 0015                  WRITE (6,100)
 0016             100  FORMAT (2X,'|',1X,2('TIME',3X,'VOLT 1',3X,'HEIGHT',1X,'|',1X,'TIME
                      &',3X,'VOLT 2',3X,'PRESS',2X,'|',1X),/,2X,'|',1X,2(' SEC',3X,'MILI
                      &V',3X,'INCHES',1X,'|',1X,' SEC',3X,'MILI V',4X,'PSIG',2X,'|',1X),/
                      &1(2X,'|',24X,'|',24X,'|',24X,'|',24X,'|'))
 0017                  K=0
 0018                  DO 2 II=1,N
 0019                  READ (5,102) ITT(II),VO1(II),IT(II),VO2(II)
 0020             102  FORMAT (I3,3X,F10.4,    I3,3X,F10.4)
                C
                C
                C      CONVERTING MV INTO PRESSURE BY MULTIPLYING A CONVERSION FACTOR
                C      ( UNIT = PSIG )
                C
```

App.1 Source programme for data conversion

```
0021        C          PRESS(II)=0.27044*VO2(II)
0022                   DIFP=13.32271*14.2234/1000.0*VO1(II)/GA1
0023                   H(II)=((-DIFP*144.0)+H2/12.0*CON2)/CON1*12.0
0024                   IF (II.EQ.N .AND. K.EQ.1) GO TO 160
0025                   IF( II.EQ.N) GO TO     130
0026                   IF (K.LT.1) GO TO 110
0027                   K=0
0028                   WRITE (6,103)
0029             103   FORMAT (2X,'|',4(24X,'|'))

FORTRAN IV G LEVEL  21                MAIN              DATE = 76159          14/13/04

 0030                  WRITE (6,106) ITT(II-1),VO1(II-1),H(II-1),IT(II-1),VO2(II-1)
                      &,PRESS(II-1),ITT(II),VO1(II),H(II),IT(II),VO2(II),PRESS(II)
 0031            106   FORMAT (2X,'|',4(2X,I3,3X,F6.2,3X,F6.2,1X,'|'),/,2X,'|',24X,'|',24
                      &X,'|',24X,'|',24X,'|')
 0032                  GO TO 2
 0033            110   K=K+1
 0034            2     CONTINUE
 0035            130   WRITE (6,103)
 0036                  WRITE (6,140) ITT(II),VO1(II),H(II),IT(II),VO2(II),PRESS(II)
 0037            140   FORMAT  (2X,'|',2(2X,I3,3X,F6.2,3X,F6.2,1X,'| ),2(24X,'|'))
 0038                  GO TO 170
 0039            160   WRITE (6,103)
 0040                  WRITE (6,106) ITT(II-1),VO1(II-1),H(II-1),IT(II-1),VO2(II-1)
                      &,PRESS(II-1),ITT(II),VO1(II),H(II),IT(II),VO2(II),PRESS(II)
 0041            170   WRITE (6,150)
 0042            150   FORMAT (2X,104('-'))
 0043                  RETURN
 0044                  END
```

Source programme for data conversion (continue) -ii-

```
 TIME   VOLT 1    HEIGHT   | TIME   VOLT 2   PRESS   | TIME   VOLT 1    HEIGHT  | TIME   VOLT 2   PRESS
 SEC    MILI V    INCHES   | SEC    MILI V   PSIG    | SEC    MILI V    INCHES  | SEC    MILI V   PSIG

   0    415.90     8.77    |   0    718.60   194.34  |   1    415.60     8.78   |   1    718.70   194.37
   2    413.10     8.89    |   2    722.20   195.31  |   3    409.00     9.07   |   3    725.50   196.20
   4    404.70     9.25    |   4    728.30   196.96  |   5    400.20     9.44   |   5    731.20   197.75
   6    395.00     9.67    |   6    733.80   198.45  |   7    390.00     9.88   |   7    736.10   199.07
   8    384.70    10.11    |   8    738.40   199.69  |   9    379.80    10.32   |   9    740.70   200.31
  10    374.10    10.56    |  10    742.80   200.88  |  11    368.70    10.79   |  11    745.10   201.50
  12    363.70    11.01    |  12    747.10   202.05  |  13    358.30    11.24   |  13    749.20   202.61
  14    351.50    11.53    |  14    751.70   203.29  |  15    346.30    11.75   |  15    753.60   203.80
  16    340.80    11.99    |  17    755.50   204.32  |  17    335.40    12.22   |  18    757.70   204.91
  18    329.80    12.46    |  19    759.70   205.45  |  19    324.00    12.70   |  20    761.80   206.02
  20    318.70    12.93    |  21    763.80   206.56  |  22    307.80    13.40   |  23    768.00   207.70
  23    301.90    13.65    |  24    770.20   208.29  |  26    290.90    14.12   |  26    774.50   209.46
  28    279.70    14.60    |  28    778.90   210.65  |  30    289.10    14.20   |  30    783.30   211.84
```

App.2 Sample of data conversion print-out

```
        ****CONTINUOUS SYSTEM MODELING PROGRAM****

    ***PROBLEM INPUT STATEMENTS***

****************************************************************
*                                                              *
*           RUN=22, 'PURE' INSURGE                             *
*           INITIAL PRESSURE  APPROX.=200 P.S.I.G.             *
*                                                              *
****************************************************************
RENAME    TIME=T
INITIAL
          FACTOR=1.
PARAM     K=1.26
          PI=4.0*ATAN(1.00)
          PRESG=203.87
          PRESO=PRESG+14.5
          PZERO=PRESG*0.068948
****************************************************************
*                                                              *
*           ALL PHYSICAL PARAMETERS OF THE PRESSURIZER         *
*           ARE SPECIFIED AS FOLLOWED :-                       *
*                                                              *
*           UNITS OF THESE PARAMETERS ARE  A=CU.M., VD=CU.M.,  *
*                                                              *
*           DIAM=M,  B=CU.M/CM,  THW=M,  ALPHA=SQ.M/SEC.       *
*                                                              *
*           HEIGHT=CM                                          *
*                                                              *
****************************************************************
          DIAM=7.236*0.0254
          HEIGHT=27.928*2.54
          AHCMS=PI*DIAM*DIAM/2.
          A=1.6255E-03
          THW=0.4*0.0254
          VD=2.0167E-02
          B=PI*DIAM*DIAM/400.
****************************************************************
*                                                              *
*           UNITS OF VARIABLE NAMES :  SPHEAT=BTU/LB-F,        *
*                                                              *
*           AK=BTU/HR-FT-F                                     *
*                                                              *
****************************************************************
PARAM     SPHEAT=0.111,AK=10.0,DODT0=0.
          DX=THW/10.
          S=ALPHA/(DX**2.)
```

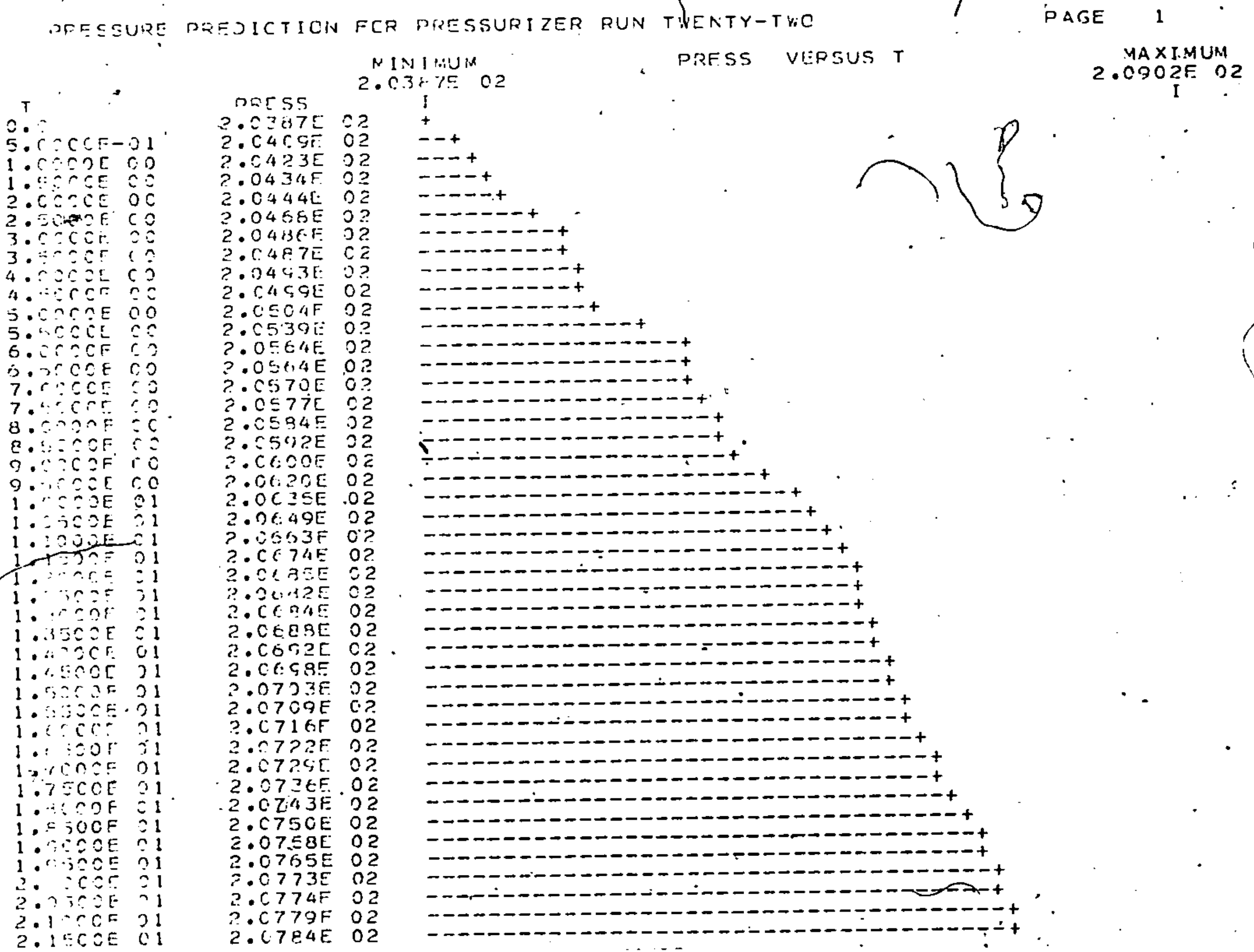
App. 3    Source programme for pure insurge

```
************************************************************
*
*              DUE TO MODEL EQUATION REQUIREMENT UNITS  RHO=LB/CU.M.
*
*              SPHE=JOULES/LB-F
*
************************************************************
          SPHE=SPHEAT*1054.8
          RHO=490./((12.*.0254)**3.)
          ALPHA=(10./(490.*0.111))*.0254*.0254*144./3600.
************************************************************
*
*              PRESSURE TRANSIENT MODELLING SECTION USING GOVERNING
*              EQUATIONS
*              P  IS IN BAR
*              PRESS IS GAGE PRESSURE (P.S.I.G.)
*
************************************************************
DYNAMIC
          PA=P+1.
          PRESA=PRESS+14.5
          AWALL=PI*DIAM*(HEIGHT-L)/100.
          AREA=AHEMS+AWALL
          P=INTGRL(PZERO,PDOT)
          PCON=P*K*B*LDOT
          AM=PCON-M
          PDOT=AM/(VD-A-B*L)
          M=K*DRDH*DCDT*P*1.E-06
          PRESS=P/.068948
************************************************************
*
*               INPUT VARIABLE TO THE MODEL
*               LE IS THE WATER LEVEL HISTORY FOR THIS RUN
*
************************************************************
FUNCTION LE=0.,10.31,2.,10.44,3.,10.55,5.,10.69,...
          6.,10.84,9.,11.12,11.,11.37,12.,11.49,20.,12.15,...
          23.,12.36,25.,12.57,28.,12.77,36.,13.28
************************************************************
*
*               UTILISATION OF FUNCTION GENERATOR AND
*               DERIVATIVE PACKAGE OF LE HISTORY
*
************************************************************
          ALI=AFGEN(LE,T)
          L=ALI*2.54
          ALDOT=DERIV(0.065,ALI)
          LDOT=ALDOT*2.54
```

**Source programme for pure insurge (continue)**

```
***********************************************************************
*                                                                     *
*           THERMODYNAMIC PROPERTIES AS FUNCTION OF PRESSURE          *
*           UNITS OF THESE PROPERTIES ARE AS FOLLOWED :-              *
*                                                                     *
*           DRDH=C.C./JOULES, TSAT=R                                  *
*                                                                     *
***********************************************************************
      DRDH=3.233142E-01-1.136499E-02*PA
      TSAT=0.51693E03+0.19759E01*PRESA+0.48760E-02*PRESA**2...
      -0.50558E-04*PRESA**3+0.85802E-07*PRESA**4
      PHIO=0.51693E03+0.19759E01*PRESO+0.48760E-02*PRESO**2...
      -0.50558E-04*PRESO**3+0.85802E-07*PRESO**4
***********************************************************************
*                                                                     *
*           CALCULATION OF HEAT TRANSFER TO THE PRESSURIZER WALL      *
*                                                                     *
***********************************************************************
      PHIM=TSAT-PHIO
      U0=FACTOR*PHIM
      UD1=S*(U0-2.*U1+U2)
      UD2=S*(U1-2.*U2+U3)
      UD3=S*(U2-2.*U3+U4)
      UD4=S*(U3-2.*U4+U5)
      UD5=S*(U4-2.*U5+U6)
      UD6=S*(U5-2.*U6+U7)
      UD7=S*(U6-2.*U7+U8)
      UD8=S*(U7-2.*U8+U9)
      UD9=S*(U8-2.*U9+U10)
      UD10=S*(U9-U10)*2.
      U1=INTGRL(0.0,UD1)
      U2=INTGRL(0.0,UD2)
      U3=INTGRL(0.0,UD3)
      U4=INTGRL(0.0,UD4)
      U5=INTGRL(0.,UD5)
      U6=INTGRL(0.,UD6)
      U7=INTGRL(0.,UD7)
      U8=INTGRL(0.,UD8)
      U9=INTGRL(0.,UD9)
      U10=INTGRL(0.,UD10)
      SIGMA=DX*(U0+4.*(U1+U3+U5+U7+U9)+2.*(U2+U4+U6+U8)+U10)/3.
      Q=AREA*RHO*SPHE*SIGMA
      DQDT=DERIV(DQDT0,Q)
***********************************************************************
*                                                                     *
*           SPECIFICATION OF DURATION OF SIMULATION RUN AND           *
*           OUTPUT PLOT OF PRESSURE TRANSIENT VS. TIME                *
*                                                                     *
***********************************************************************
PRTPLT.   PRESS
TIMER     FINTIM=30.,CUTDEL=0.5,PRDEL=0.5
LABEL     PRESSURE PREDICTION FOR PRESSURIZER RUN TWENTY-TWO
          END
          STOP
```

Source programme for pure insurge (continue)



```
PRESSURE PREDICTION FOR PRESSURIZER RUN TWENTY-TWO                          PAGE    1

                                  MINIMUM              PRESS   VERSUS T              MAXIMUM
                                  2.0387E 02                                         2.0902E 02
     T                    PRESS   I                                                     I
  0.0                  2.0387E 02
  5.0000E-01           2.0409E 02
  1.0000E 00           2.0423E 02
  1.5000E 00           2.0434E 02
  2.0000E 00           2.0444E 02
  2.5000E 00           2.0466E 02
  3.0000E 00           2.0486E 02
  3.5000E 00           2.0487E 02
  4.0000E 00           2.0493E 02
  4.5000E 00           2.0499E 02
  5.0000E 00           2.0504E 02
  5.5000E 00           2.0539E 02
  6.0000E 00           2.0564E 02
  6.5000E 00           2.0564E 02
  7.0000E 00           2.0570E 02
  7.5000E 00           2.0577E 02
  8.0000E 00           2.0584E 02
  8.5000E 00           2.0592E 02
  9.0000E 00           2.0600E 02
  9.5000E 00           2.0620E 02
  1.0000E 01           2.0635E 02
  1.0500E 01           2.0649E 02
  1.1000E 01           2.0663E 02
  1.1500E 01           2.0674E 02
  1.2000E 01           2.0685E 02
  1.2500E 01           2.0682E 02
  1.3000E 01           2.0684E 02
  1.3500E 01           2.0688E 02
  1.4000E 01           2.0692E 02
  1.4500E 01           2.0698E 02
  1.5000E 01           2.0703E 02
  1.5500E 01           2.0709E 02
  1.6000E 01           2.0716E 02
  1.6500E 01           2.0722E 02
  1.7000E 01           2.0729E 02
  1.7500E 01           2.0736E 02
  1.8000E 01           2.0743E 02
  1.8500E 01           2.0750E 02
  1.9000E 01           2.0758E 02
  1.9500E 01           2.0765E 02
  2.0000E 01           2.0773E 02
  2.0500E 01           2.0774E 02
  2.1000E 01           2.0779E 02
  2.1500E 01           2.0784E 02
```

App.4 Pure insurge pressure transient print-out

```
   FRESSURF PRECICTICN FCR PRESSURIZER RUN TWENTY-TWO                PAGE   2
                         MINIMUM           PRESS  VERSUS T                MAXIMUM
                       2.0387E 02                                       2.0902E 02
                            I                                               I
 T             PRESS        -------------------------------------+
2.2000E 01    2.0789E 02    -------------------------------------+
2.2500E 01    2.0795E 02    --------------------------------------+
2.3000E 01    2.0801E 02    ----------------------------------------+
2.3500E 01    2.0823E 02    -----------------------------------------+
2.4000E 01    2.0839E 02    -------------------------------------------+
2.4500E 01    2.0853E 02    --------------------------------------------+
2.5000E 01    2.0857E 02    --------------------------------------------+
2.5500E 01    2.0862E 02    --------------------------------------------+
2.6000E 01    2.0864E 02    --------------------------------------------+
2.6500E 01    2.0867E 02    ---------------------------------------------+
2.7000E 01    2.0871E 02    ---------------------------------------------+
2.7500E 01    2.0876E 02    ----------------------------------------------+
2.8000E 01    2.0882E 02    ----------------------------------------------+
2.8500E 01    2.0886E 02    ----------------------------------------------+
2.9000E 01    2.0891E 02    -----------------------------------------------+
2.9500E 01    2.0896E 02    -----------------------------------------------+
3.0000E 01    2.0902E 02    ------------------------------------------------
```

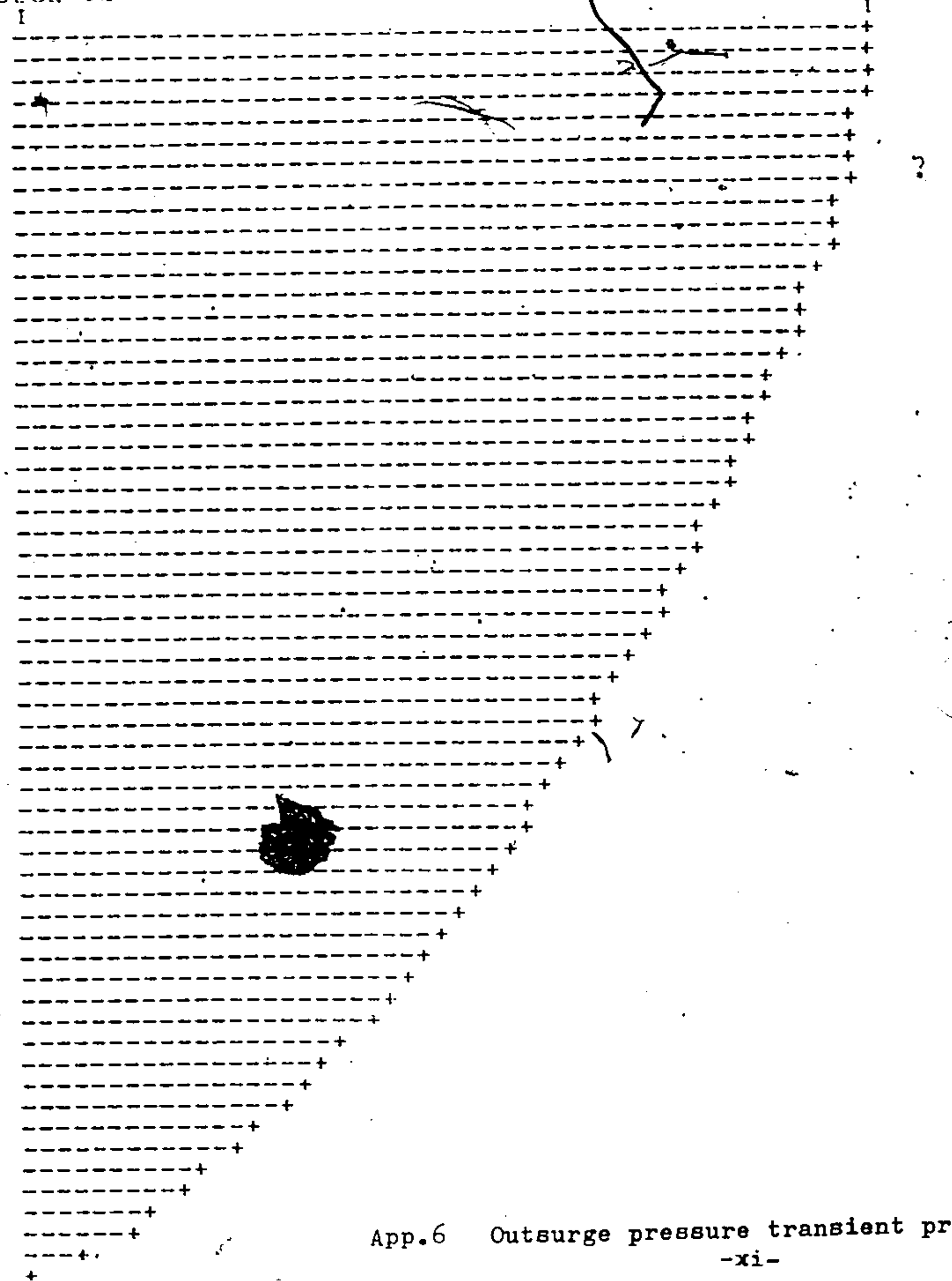
Pure insurge pressure transient print-out (continue) -viii-

```
         ****CONTINUOUS SYSTEM MODELING PROGRAM****

    ***PROBLEM INPUT STATEMENTS***

********************************************************************
*                                                                  *
*              RUN= 17,'PURE' OUTSURGE                             *
*              INITIAL PRESSURE APPROX.=200P.S.I.G.                *
*                                                                  *
********************************************************************
         RENAME TIME=T
********************************************************************
*                                                                  *
*              ALL PHYSICAL PARAMETERS OF THE PRESSURIZER ARE SPECIFIED *
*              AS FOLLOWED:-                                       *
*                                                                  *
*              UNITS OF THESE PARAMETERS ARE  A= CU.M, J= BAR-CU.FT/BTU, *
*                                                                  *
*              VD= CU.M, DIAM= M, B= CU.M/CM                       *
*                                                                  *
********************************************************************
INITIAL
PARAM     A=1.6255E-03,J=0.37269
          PZERO=PPO/14.5
          PI=4.0*ATAN(1.00)
          VD=2.0167E-02
          B=PI*DIAM*DIAM/400.
          DIAM=7.236*0.0254
********************************************************************
*                                                                  *
*              INPUT VARIABLES TO THE MODEL                        *
*              LEVEL  IS THE WATER LEVEL HISTORY FOR THIS RUN      *
*              PPO  IS THE STARTING PRESSURE OF THE SYSTEM IN P.S.I.G. *
*                                                                  *
********************************************************************
FUNCTION LEVEL=0.,13.731,2.,13.329,3.,13.128,4.,12.927,...
          5.,12.726,6.,12.324,7.,12.042,8.,11.640,9.,11.319,...
          10.,10.997,12.,10.314,14.,9.469,16.,8.665,18.,7.851,...
          20.,7.057,22.,6.173,24.,5.289,26.,4.284,28.,3.279,...
          29.,2.377
          PPO=190.768
DYNAMIC
********************************************************************
*                                                                  *
*              UTILISATION OF FUNCTION GENERATOR AND               *
*              DERIVATIVE PACKAGE OF LEVEL HISTORY                 *
*                                                                  *
*              LDOT= CM/SEC, L= CM                                 *
*                                                                  *
********************************************************************
          AL=NLFGEN(LEVEL,T)
          ALDOT=DERIV(-0.201,AL)
          LDOT=ALDOT*2.54
          L=AL*2.54
          PA=P+1.0
```

```
************************************************************
*                                                          *
*         THERMODYNAMIC PROPERTIES AS FUNCTION OF PRESSURE *
*         UNITS OF THESE PROPERTIES ARE AS FOLLOWED :-     *
*                                                          *
*         DVG= CU.FT/LBM-BAR, DHFF=BTU/LBM-BAR, DHG= BTU/LBM-BAR,
*                                                          *
*         HFG= BTU/LBM, VF= CU.FT/LBM, VG= CU.FT/LBM .     *
*                                                          *
************************************************************
      DVG=-0.1704
      DHF=0.2357463E3-0.3010791E2*PA+0.7060572*PA**2+...
      0.1970007E-1*PA**3
      DHG=0.2215561E2-0.3228696E1*PA+0.1237115*PA**2
      HFG=0.920282E03-0.555449E01*PA
      VF=0.172335E-01+0.836843E-04*PA
      VG=0.464061E01-0.170588*PA
************************************************************
*                                                          *
*         PRESSURE TRANSIENT MODELLING SECTION USING GOVERNING
*         EQUATIONS                                        *
*         P  IS IN BAR                                     *
*         PRESS  IS GAGE PRESSURE                          *
*                                                          *
************************************************************
      DLDP=(A*F1+VD*F2)/B+F1*L
      DPDL=1./DLDP
      PDOUT=DPDL*LDOT
      SOUT=(VG/VF*DHF-DHG)/HFG
      F1=SOUT+DVG/VG
      MOUT=(DHG-VG/J)/HFG
      F2=MOUT-DVG/VG
      P=INTGRL(PZERO,PDOUT)
      PRESS=P*14.5
************************************************************
*                                                          *
*         SPECIFICATION OF DURATION OF SIMULATION RUN AND  *
*         OUTPUT PLOT OF PRESSURE TRANSIENT VS. TIME       *
*                                                          *
************************************************************
PRTPLT    PRESS
TIMER     FINTIM=29.0,DELT=0.001,CUTDEL=0.5
LABEL     PURE  OUTSURGE  RUN= 17
          END
          STOP
```

Source programme for pure outsurge (continue)-x-

```
PURF   OUTSURGE   RUN= 17                                                                          PAGE    1
                                         MINIMUM                  PRESS   VERSUS  T                     MAXIMUM
                                        1.7528E 02                                                     1.9077E 02
  T                          PRESS
0.0                        1.9077E 02
5.0000E-01                 1.9068E 02
1.0000E 00                 1.9059E 02
1.5000E 00                 1.9051E 02
2.0000E 00                 1.9042E 02
2.5000E 00                 1.9033E 02
3.0000E 00                 1.9024E 02
3.5000E 00                 1.9015E 02
4.0000E 00                 1.9006E 02
4.5000E 00                 1.8997E 02
5.0000E 00                 1.8988E 02
5.5000E 00                 1.8971E 02
6.0000E 00                 1.8950E 02
6.5000E 00                 1.8936E 02
7.0000E 00                 1.8924E 02
7.5000E 00                 1.8905E 02
8.0000E 00                 1.8884E 02
8.5000E 00                 1.8867E 02
9.0000E 00                 1.8852E 02
9.5000E 00                 1.8836E 02
1.0000E 01                 1.8819E 02
1.0500E 01                 1.8802E 02
1.1000E 01                 1.8784E 02
1.1500E 01                 1.8766E 02
1.2000E 01                 1.8747E 02
1.2500E 01                 1.8725E 02
1.3000E 01                 1.8702E 02
1.3500E 01                 1.8678E 02
1.4000E 01                 1.8652E 02
1.4500E 01                 1.8629E 02
1.5000E 01                 1.8605E 02
1.5500E 01                 1.8581E 02
1.6000E 01                 1.8557E 02
1.6500E 01                 1.8532E 02
1.7000E 01                 1.8507E 02
1.7500E 01                 1.8481E 02
1.9000E 01                 1.8455E 02
1.3500E 01                 1.8429E 02
1.9000E 01                 1.8402E 02
1.9500E 01                 1.8374E 02
2.0000E 01                 1.8346E 02
2.0500E 01                 1.8316E 02
2.1000E 01                 1.8285E 02
2.1500E 01                 1.8252E 02
2.2000E 01                 1.8218E 02
2.2500E 01                 1.8185E 02
2.3000E 01                 1.8151E 02
2.3500E 01                 1.8116E 02
2.4000E 01                 1.8080E 02
2.4500E 01                 1.8040E 02
2.5000E 01                 1.7999E 02
2.5500E 01                 1.7955E 02
2.6000E 01                 1.7908E 02
2.6500E 01                 1.7863E 02
2.7000E 01                 1.7817E 02
2.7500E 01                 1.7769E 02
2.8000E 01                 1.7720E 02
2.8500E 01                 1.7632E 02
```



App.6 Outsurge pressure transient print-out

```
************************************************************
*                                                          *
*         RUN=32, MULTIPLE SURGE                           *
*         INITIAL PRESSURE APPROX.=200 P.S.I.G.            *
*         INITIAL TEMPERATURE APPROX.=388 F                *
*                                                          *
************************************************************
RENAME    TIME=T
INITIAL
          TEMPIN=388.66
          KEYIN=1.
          KEYOUT=0.
          K=1.26
          J=0.37259
          PI=4.0*ATAN(1.00)
          PZERO=PRESG*0.068948
INCON     PRESS=195.079
          PRESG=195.079
          PRES0=PRESG+14.5
          A=1.6255E-03
          VD=2.0167E-02
************************************************************
*                                                          *
*         ALL PHYSICAL PARAMETERS OF THE PRESSURIZER       *
*         ARE SPECIFIED AS FOLLOWED :-                     *
*                                                          *
*         UNITS OF THESE PARAMETERS ARE  A=CU.M, VD=CU.M,  *
*                                                          *
*         DIAM=M, B=CU.M/CM, THW=M, ALPHA=SQ.M/SEC,HEIGHT=CM
*                                                          *
************************************************************
          DIAM=7.236*0.0254
          HEIGHT=27.928*2.54
          AHEMS=PI*DIAM*DIAM/2.
          THW=0.4*0.0254
          B=PI*DIAM*DIAM/400.
************************************************************
*                                                          *
*         UNITS OF VARIABLE NAMES : SPHEAT=BTU/LBM-F,      *
*                                                          *
*         AK=BTU/HR-FT-F                                   *
*                                                          *
************************************************************
PARAM     SPHEAT=0.111,AK=10.0,DQDT0=0.
          DX=THW/10.
          S=ALPHA/(DX**2.)
```

App. 7 Source programme for multiple surge

```
*****************************************************
*                                                   *
*          DUE TO GOVERNING EQUA TION REQUIREMENT UNITS :-  *
*                                                   *
*          RHO=LBM/CU.M, SPHE=JOULES/LBM-F          *
*                                                   *
*****************************************************
      SPHE=SPHEAT*1054.8
      RHO=490./((12.*0.0254)**3.)
      ALPHA=(10./(490.*0.111))*0.0254*0.0254*144./3600.
*****************************************************
*                                                   *
*          INPUT VARIABLES TO THE MODEL             *
*          LE IS THE WATER LEVEL HISTORY FOR THIS RUN  *
*          TEMP IS THE TEMPERATURE HISTORY OF THE VAPOUR  *
*                                                   *
*****************************************************
FUNCTION LE=0.,6.561,2.,6.597,3.,6.718,5.,6.987,...
      8.,7.273,12.,7.783,15.,8.041,19.,8.587,22.,8.845,...
      30.,9.721,35.,10.143,39.,10.573,45.,11.064,52.,11.598,...
      55.,11.775,57.,11.952,59.,12.125,62.,12.286,68.,10.340,...
      72.,8.222,75.,6.999,77.,5.729,79.,4.403,82.,3.197,...
      92.,2.328
FUNCTION TEMP=0.,388.66,60.,391.66,72.,389.33,74.,387.66,82.,380.00,...
      86.,376.00
DYNAMIC
*****************************************************
*                                                   *
*          UTILISATION OF FUNCTION GENERATOR AND    *
*          DERIVATIVE PACKAGE OF LE HISTORY         *
*                                                   *
*****************************************************
      ALI=AFGEN(LE,T)
      L=ALI*2.54
      ALDOT=DERIV(0.018,ALI)
      LDOT=ALDOT*2.54
      AWALL=PI*DIAM*(HEIGHT-L)/100.
      AREA=AREMS+AWALL
      PRESA=PRESS+14.5
      TSAT=0.51693E03+0.19759E01*PRESA+0.48760E-02*...
      PRESA**2-0.50558E-04*PRESA**3+0.85802E-07*PRESA**4
      PHIO=0.51693E03+0.19759E01*PRESO+0.48760E-02*...
      PRESO**2-0.50558E-04*PRESO**3+0.85802E-07*PRESO**4
      PHTM=TSAT-PHIO
```

Source programme for multiple surge (continue)

```
***********************************************************
*                                                         *
*          THERMODYNAMIC PROPERTIES AS FUNCTION OF PRESSURE*
*          UNITS OF THESE PROPERTIES ARE AS FOLLOWED :-   *
*                                                         *
*          DVG=CU.FT/LBM-BAR, DHF=BTU/LBM-BAR, DHG=BTU/LBM-BAR
*                                                         *
*          HFG=BTU/LBM, VF=CU.FT/LBM, VG=CU.FT/LBM,       *
*                                                         *
*          DRDH=C.C./JOULES                               *
*                                                         *
***********************************************************
      PA=P+1.0
      DVG=-0.17059
      DHF=6.74
      DHG=1.09
      HFG=0.920282E03-0.555449E01*PA
      VF=0.172335E-01+0.836843E-04*PA
      VG=0.464061E01-0.170588*PA
      DRDH=3.233142E-01-1.136499E-02*PA
***********************************************************
*                                                         *
*          CALCULATION OF HEAT TRANSFER TO THE PRESSURIZER WALL
*                                                         *
***********************************************************
      U0=PHIM
      UD1=S*(U0-2.*U1+U2)
      UD2=S*(U1-2.*U2+U3)
      UD3=S*(U2-2.*U3+U4)
      UD4=S*(U3-2.*U4+U5)
      UD5=S*(U4-2.*U5+U6)
      UD6=S*(U5-2.*U6+U7)
      UD7=S*(U6-2.*U7+U8)
      UD8=S*(U7-2.*U8+U9)
      UD9=S*(U8-2.*U9+U10)
      UD10=S*(U9-U10)*2.
      U1=INTGRL(0.0,UD1)
      U2=INTGRL(0.0,UD2)
      U3=INTGRL(0.0,UD3)
      U4=INTGRL(0.0,UD4)
      U5=INTGRL(0.0,UD5)
      U6=INTGRL(0.0,UD6)
      U7=INTGRL(0.0,UD7)
      U8=INTGRL(0.0,UD8)
      U9=INTGRL(0.0,UD9)
      U10=INTGRL(0.0,UD10)
      SIGMA=DX*(U0+4.*(U1+U3+U5+U7+U9)+2.*(U2+U4+U6+U8)+U10)/3.
      Q=AREA*RHO*SPHE*SIGMA
      DQDT=DERIV(DQDT0,Q)
```

Source programme for multiple surge (continue)

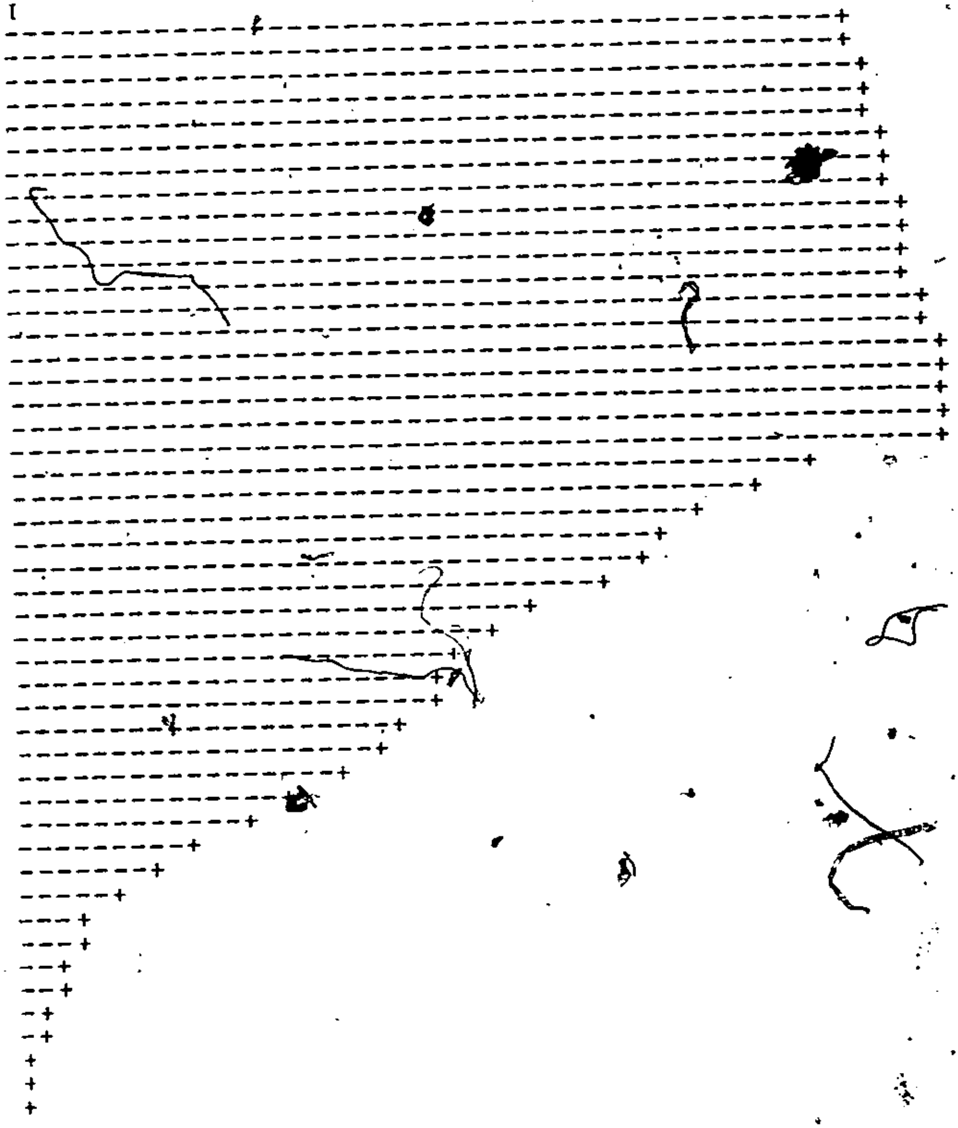
```
*************************************************************
*                                                           *
*          PRESSURF TRANSIEN T MODELLING SECTION USING      *
*          GOVERNING EQUATIONS                              *
*                                                           *
*************************************************************
       M=K*DRDH*DQDT*P*1.E-06
       VOLWAT=VD-A-B*L
       PDIN=(P*K*B*LDOT-M)/VOLWAT
       PDOT=KEYIN*PDIN+PDOUT*KEYOUT
       P=INTGRL(PZERO,PDOT)
       DLDP=(A*F1+VD*F2)/B+F1*L
       DPDL=1./DLDP
       PDOUT=DPDL*LDOT
       SOUT=(VG/VF*DHF-DHG)/HFG
       F1=SOUT+DVG/VG
       MOUT=(DHG-VG/J)/HFG
       F2=MOUT-DVG/VG
       STEMP=AFGEN(TEMP,T)
*************************************************************
*                                                           *
*          NOSORT SECTION IS USED TO SWITCH GOVERNING EQUATIONS *
*          FROM INSURGE TO OUTSURGE                         *
*                                                           *
*          CONDITIONS OF FLAGS KEYIN AND KEYOUT:-           *
*          KEYIN=1, INSURGE GOVERNING EQUATION IS USED      *
*          KEYOUT=1, OUTSURGE GOVERNING EQUATION IS USED    *
*          AT NO TIME THAT KEYIN AND KEYOUT CAN HAVE THE SAME *
*          VALUE                                            *
*                                                           *
*************************************************************
NOSORT
       KEYIN=1
       IF ((T.GT.0.).AND.(ALDOT.LE.0.0005)) M=0
       IF ((M.EQ.0).AND.(STEMP.LE.TEMPIN)) KEYIN=0
       KEYOUT=1-KFYIN
SORT
       PRESS=P/0.068948
*************************************************************
*                                                           *
*          SPECIFICATION OF DURATION OF SIMULATION RUN      *
*          AND OUTPUT PLOT OF PRESSURE TRANSIENT VS, TIME   *
*                                                           *
*************************************************************
PRTPLT PRESS
TIMER  FINTIM=90.,DELT=.001,PRDEL=1.,OUTDEL=1.
LABEL    PRESSURE PREDICTION OF MULTIPLE SURGE RUN#32 INSURGE
       PRINT  M,PRESS,KEYIN,KEYOUT
       END
       STOP
ENDJOB
```

Source programme for multiple surge (continue)

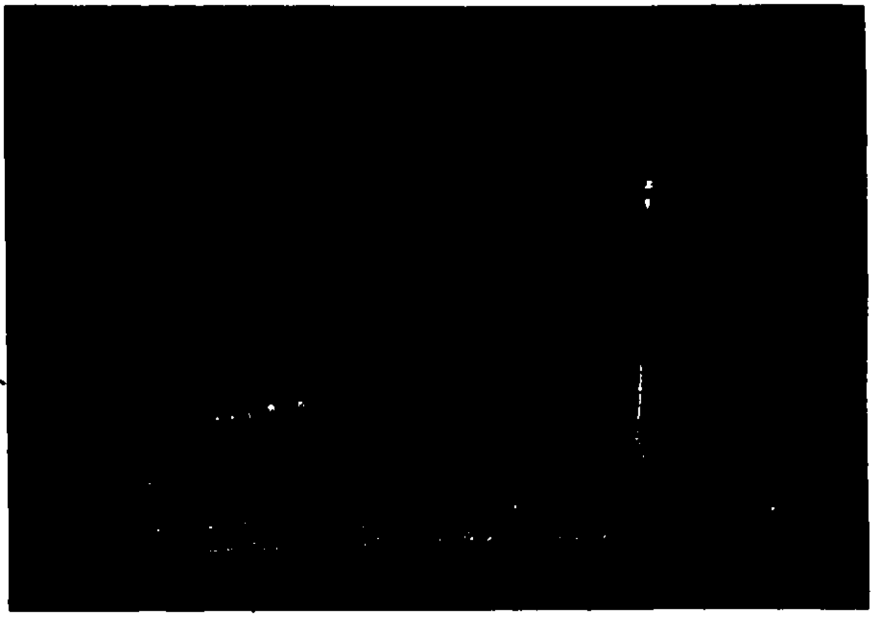
```
PRESSURE PREDICTION OF MULTIPLE SURGE RUN=32 INSURGE                    PAGE    1
                                   MINIMUM              PRESS   VERSUS T                    MAXIMUM
                                  1.8394E 02                                               2.0386E 02
T                      PRESS          I                                                         I
0.0                 1.9508E 02
1.0000E 00          1.9515E 02
2.0000E 00          1.9520E 02
3.0000E 00          1.9567E 02
4.0000E 00          1.9600E 02
5.0000E 00          1.9625E 02
6.0000E 00          1.9629E 02
7.0000E 00          1.9639E 02
8.0000E 00          1.9650E 02
9.0000E 00          1.9676E 02
1.0000E 01          1.9695E 02
1.1000E 01          1.9713E 02
1.2000E 01          1.9730E 02
1.3000E 01          1.9728E 02
1.4000E 01          1.9733E 02
1.5000E 01          1.9741E 02
1.6000E 01          1.9774E 02
1.7000E 01          1.9798E 02
1.8000E 01          1.9820E 02
1.9000E 01          1.9841E 02
2.0000E 01          1.9834E 02
2.1000E 01          1.9839E 02
2.2000E 01          1.9847E 02
2.3000E 01          1.9868E 02
2.4000E 01          1.9886E 02
2.5000E 01          1.9902E 02
2.6000E 01          1.9919E 02
2.7000E 01          1.9935E 02
2.8000E 01          1.9952E 02
2.9000E 01          1.9969E 02
3.0000E 01          1.9985E 02
3.1000E 01          1.9997E 02
3.2000E 01          1.9996E 02
3.3000E 01          2.0006E 02
3.4000E 01          2.0018E 02
3.5000E 01          2.0030E 02
3.6000E 01          2.0057E 02
3.7000E 01          2.0078E 02
3.8000E 01          2.0098E 02
3.9000E 01          2.0117E 02
4.0000E 01          2.0120E 02
4.1000E 01          2.0129E 02
4.2000E 01          2.0141E 02
4.3000E 01          2.0153E 02
```

App.8 Multiple surge pressure transient print-out -xvi-

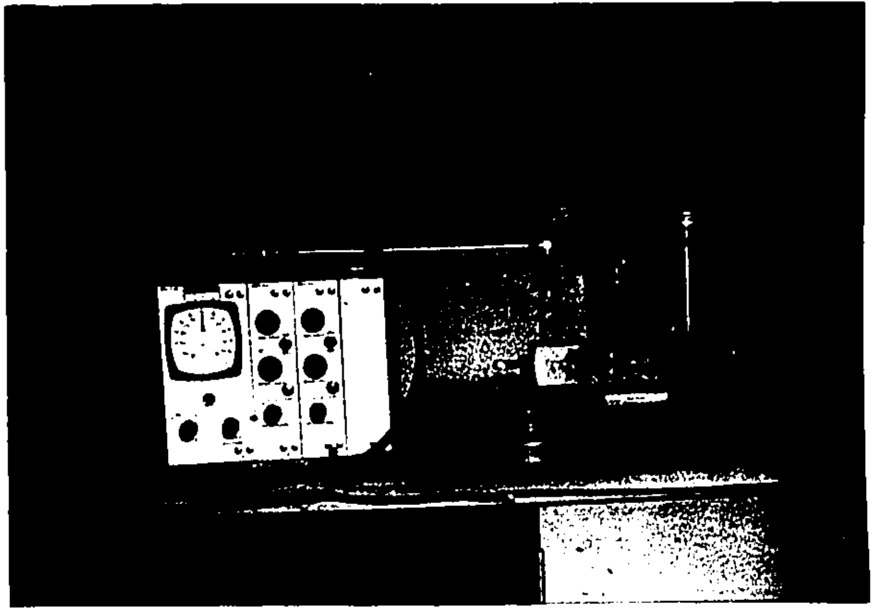
```
PRESSURE PREDICTION OF MULTIPLE SURGE RUN=32 INSURGE                  PAGE    2

                                   MINIMUM            PRESS   VERSUS T                 MAXIMUM
                                   1.8394E 02                                          2.0386E 02
     T                  PRESS       I                                                   I
 4.4000E 01          2.0166E 02
 4.5000E 01          2.0180E 02
 4.6000E 01          2.0190E 02
 4.7000E 01          2.0202E 02
 4.8000E 01          2.0215E 02
 4.9000E 01          2.0229E 02
 5.0000E 01          2.0242E 02
 5.1000E 01          2.0256E 02
 5.2000E 01          2.0271E 02
 5.3000E 01          2.0272E 02
 5.4000E 01          2.0279E 02
 5.5000E 01          2.0288E 02
 5.6000E 01          2.0321E 02
 5.7000E 01          2.0344E 02
 5.8000E 01          2.0363E 02
 5.9000E 01          2.0383E 02
 6.0000E 01          2.0376E 02
 6.1000E 01          2.0380E 02
 6.2000E 01          2.0386E 02
 6.3000E 01          2.0101E 02
 6.4000E 01          1.9960E 02
 6.5000E 01          1.9861E 02
 6.6000E 01          1.9784E 02
 6.7000E 01          1.9721E 02
 6.8000E 01          1.9667E 02
 6.9000E 01          1.9507E 02
 7.0000E 01          1.9413E 02
 7.1000E 01          1.9341E 02
 7.2000E 01          1.9292E 02
 7.3000E 01          1.9278E 02
 7.4000E 01          1.9224E 02
 7.5000E 01          1.9169E 02
 7.6000E 01          1.9078E 02
 7.7000E 01          1.8983E 02
 7.8000E 01          1.8877E 02
 7.9000E 01          1.8764E 02
 8.0000E 01          1.8693E 02
 8.1000E 01          1.8617E 02
 8.2000E 01          1.8538E 02
 8.3000E 01          1.8523E 02
 8.4000E 01          1.8505E 02
 8.5000E 01          1.8487E 02
 8.6000E 01          1.8469E 02
 8.7000E 01          1.8451E 02
 8.8000E 01          1.8432E 02
 8.9000E 01          1.8413E 02
 9.0000E 01          1.8394E 02
```



Multiple surge pressure transient print-out (continue) -xvii-



App.9 The Temperature Sensor and Safety Valve Assembly



App.10 Pressure Transducer Calibration Apparatus