THE ANALYSIS AND COMPUTATION OF STEAM SURGE TANK DYNAMICS FOR LIGHT AND HEAVY WATER SYSTEMS

by

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ABSTRACT

The need for a solution to the problem of predicting steam surge tank pressure transients, for prescribed time variations in liquid level, has become particularly acute with the advent of the Nuclear Power Reactor. These pressure transients may cause unacceptable piping system stresses. In addition, changes in coolant density associated with pressure transients can cause serious alterations in reactivity and thus interfere with reactor control.

The theoretical models and computational techniques described in this thesis, are utilized for predicting pressure transients during prescribed rates of increase or decrease of tank level. The analytical approach is a rigorous one and is somewhat unique in that no empirical system constants are required. Included is a documented digital computer program which is based on the theoretical models and can be used to predict pressure transients for any steam surge tank containing light or heavy water. Experimental data obtained from numerous tests on an actual heavy water reactor surge tank, for both insurge and outsurge, is included. It is found that the isentropic models for compression and expansion of the vapor are highly inappropriate, and very good agreement between experiment and predictions is obtained with the above program. While the analysis and development of computational methods is conducted primarily to solve

liquid insurge and outsurge problems associated with nuclear power plant surge tanks, it is obvious that the results apply to any vessel where compression or expansion of a vapor is brought about by changes in level of the liquid phase.

CONTENTS

NOMENCLATURE

A	Vapor surface area
a_n	$= \dfrac{(2n+1)^2 \pi^2 \kappa_w}{4\ell^2}$
a_n^*	$= a_n \cdot \Delta t$
C_{p_f}	Liquid specific heat
C_{p_w}	Specific heat of wall material
e	Specific internal energy of vapor
e_f	Specific internal energy of liquid condensed out of the system
G	Constant defined in text
H	Constant defined in text
h	Vapor specific enthalpy
h_{fg}	Specific enthalpy of evaporation
K	Sensible heat transfer coefficient
ℓ	Wall thickness
m	Mass of vapor
P	Pressure of the system
Q	Net heat input to the system
$Q_{p\ell}$	Heat content of the liquid in the vessel per unit area at the end of the pth interval of time
Q_{pw}	Heat content of the wall per unit area at the end of the pth interval of time
$R(P,T)$	Modified universal gas constant
T	Vapor ambient temperature

T_s	Vapor saturation temperature
t	Time
V	Volume of vapor
v_n	= Vapor saturation temperature at the end of 'n' intervals of time - temperature at start of compression
α	$= \frac{2\kappa_w \rho_w \quad C_{p_w}}{\ell}$
Δt	Time increment
κ_f	Liquid thermal diffusivity
κ_w	Wall thermal diffusivity
ρ_f	Liquid density
ρ_w	Density of wall material

COMPUTER INPUT SYMBOLS

Insurge Program

ALEVEL (I)	Liquid level at the beginning of I'th interval	inches
ALIM 1	Temperature convergence limit	
ALIM 2	Pressure convergence limit	
ALM	Liquid level (tank half full)	inches
ALW	Cylindrical wall upper level	inches
CK	Sensible heat transfer coefficient	$BTU/hr/ft^2/^oF$
CONW	Thermal conductivity of wall material	$BTU/hr/ft/^oF$
CONWT	Thermal conductivity of liquid	$BTU/hr/ft/^oF$
CPW	Specific heat of wall material	$BTU/lb/^oF$
CPWT	Specific heat of liquid	$BTU/lb/^oF$
DET	Temperature increment	^oF
DIA	Surge tank diameter	inches
DP	Pressure increment	psi
DT	Time increment	seconds
NU	Total number of time intervals + 1	
P(1)	Initial pressure	psia
ROWW	Density of wall material	lbs/ft^3
ROWWT	Density of liquid	lbs/ft^3
THW	Wall thickness	inches

TYPE	Type greater than 1.0 indicates heavy water	
VOLUME	Total tank volume	ft^3

Outsurge Program

ALO	Initial level	inches
ALIM	Pressure convergence limit	
ALLIM	Lower level limit	
ALM	Liquid level (tank half full)	inches
DIA	Surge tank diameter	inches
DL	Level increment	inches
DP	Pressure increment	psi
PO	Initial pressure	psia
TYPE	Type greater than 1.0 indicates heavy water	
VOLUME	Total tank volume	ft^3

CHAPTER 1

INTRODUCTION

Any closed liquid system subject to temperature and volume changes must be protected from excessive pressure build-up by a chamber capable of cushioning the volume transients of the system. These chambers are generally gas- or vapor-filled, and are often called surge tanks. The lower portion of the tank is filled with liquid while the upper portion contains vapor. The outer surface of the tank is insulated to minimize heat losses to the surroundings. In a typical reactor design a steam surge tank, sometimes referred to as a pressurizer, is connected to the primary coolant circuit[*] as shown in Figure 1.

By means of heaters submerged in the liquid portion of the tank, the vapor pressure and hence the system pressure may be adjusted to the desired levels for steady state operation. When the plant load is reduced the average coolant temperature may be raised. With the increase in average coolant temperature the liquid volume increases, thereby compressing the vapor in the pressurizer. The resulting pressure rise in the entire liquid system can thus be limited to a small magnitude with a proper surge tank design. In water-cooled nuclear reactor design, the surge tank-pressurizer is a particularly important component of

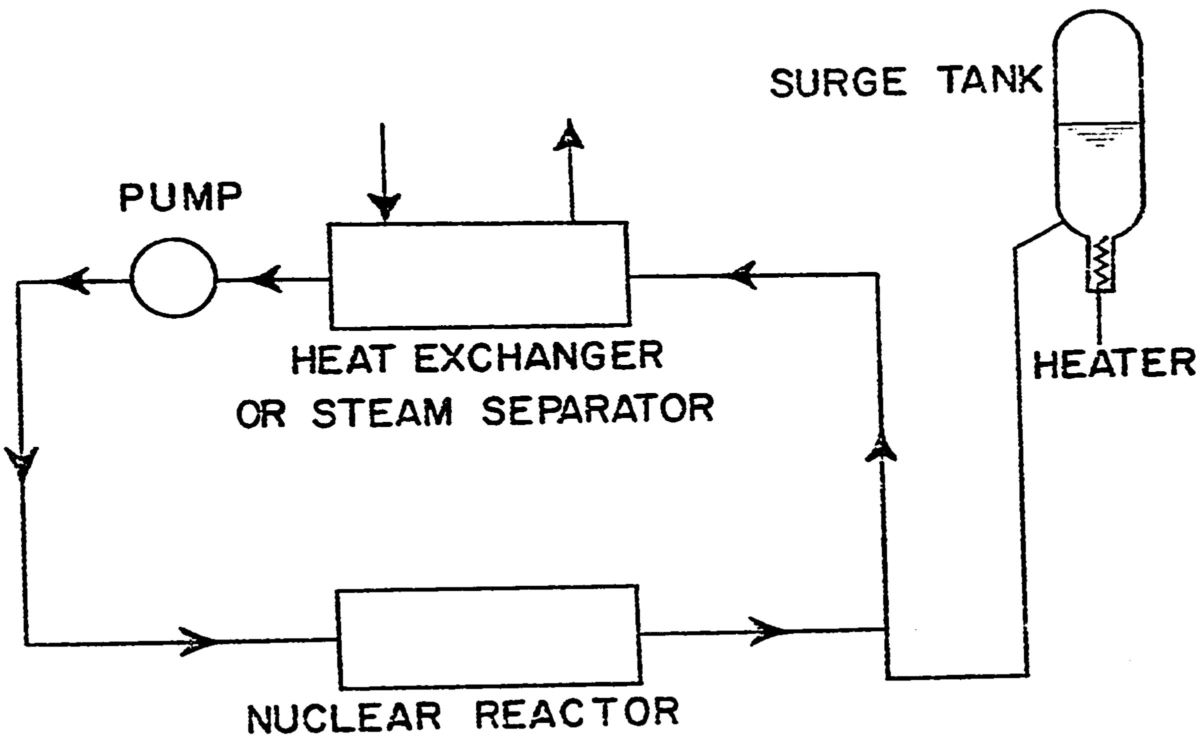

FIG. I TYPICAL NUCLEAR REACTOR PRIMARY COOLANT CIRCUIT.

appreciable size. The optimization of this piece of equipment can therefore effect substantial savings in weight, size and cost.

The surge tank thus serves a dual function. It provides a means of controlling the system pressure, as well as taking care of liquid thermal expansion by admitting the liquid.

It becomes necessary to develop a theoretical approach for predicting pressure rise during insurge in order to make provision for associated increases in system piping stresses and changes in reactivity. Reactivity will be effected by changes in coolant density. Furthermore, one must have the capability of predicting pressure transients during outsurge so as to make sure that flashing does not occur in the liquid cooled systems and reactivity effects can be predicted for any system.

A number of theoretical models have been proposed for predicting pressure rise during insurge. All the researchers agree at one point that the isentropic model is inappropriate and the pressures predicted on the basis of this model are excessively high compared to those measured during experiment. This discrepancy is related to the fact that during insurge heat will flow from the hot compressed vapor into the walls of the tank and also down into the liquid.

Drucker and Tong [1,3] conducted a series of experiments on a low pressure laboratory model surge tank and tried to obtain a mathematical correlation between level and pressure. They used a step-by-step time increment approach and conducted the energy balance at the end of each time interval. The work done on the vapor, as well as the heat flow from it, was also considered. The heat flow from the vapor was calculated from an empirical heat-sink constant for the vessel walls and liquid, which was obtained experimentally.

Drucker and Gorman [2] described an analytical procedure for predicting pressure behavior, which was somewhat similar to the procedure described by Drucker and Tong [1,3] except that no empirical constants were required. Good agreement between experiment and predicted values was obtained. The above work was performed in the low pressure range and was far outside the range encountered in most practical applications. The constants evaluated were only appropriate to calculate thermodynamic properties in the low pressure region.

In a later publication Drucker [4] has described an ideal pressurizer and discussed different ways of improving its performance and decreasing the vessel size.

Honert [5] described the results of experiments carried out on a 1 m^3 water steam pressurizer at 125 atm. He studied the effects of outsurge, insurge, electrical heating and spray injection.

Melker and Latzko [8] studied the response of a pressurizer to multiple surges. A theoretical model of the process of energy exchange within the pressurizer was established.

Nahavandi and Makkenchery [9] developed a theoretical model based on the concepts of bubble rise and condensate drop velocity. The continuity and energy equations were applied and good agreement between experimental and predicted values was obtained.

An outsurge may be caused by the increased load demand from a power plant. An increased load causes an increased heat removal from the primary coolant circuit which causes a decrease in volume of the coolant. To make up for the volume loss, liquid is extracted from the pressurizer and a pressure drop generally results. This type of surge is called an outsurge. Very little work has been done on pressure transients during outsurge.

Honert [5] has described a very complex model involving sub-cooling of the vapor. Such complications do not appear to be warranted for the analysis of systems such as that described in this thesis. (For example, the Nuclear Power Demonstration reactor system of Atomic Energy of Canada Ltd.). A relatively simple theoretical model has been utilized by Gorman [6] to predict pressure behaviour during outsurge from an actual reactor surge tank at operating pressures and given surge rates. The inadequacy of the closed isentropic expansion model has also been demonstrated.

CHAPTER 2

FORMULATION OF THE PROBLEMS

The Insurge Problem

The vapor in the surge tank is considered as an open thermodynamic system and a set of equations has been developed which relates the changes in vapor properties to the work done on it through compression and the heat given up to the heat sinks, i.e, the vessel walls and liquid. When an insurge to the pressurizer occurs, the vapor pressure and temperature begin to rise. As a result, the saturation temperature increases and vapor condenses on the cooler boundary surfaces and heat is transferred through the boundaries to the vessel walls and liquid. Any condensate formed during insurge ceases to be part of this system. In addition, heat is transferred from the superheated vapor to the boundaries as a result of sensible heat transfer due to the superheat. It is assumed that the tank has perfect exterior thermal insulation, that the whole tank and its contents are initially at uniform temperature, and that the temperature of the incoming liquid does not affect the process, i.e., no significant mixing occurs. In the analysis of the system no restrictive assumptions, such as saturation process or isentropic process, are made.

In keeping with the first law of thermodynamics, one may write for the vapor system [1]

$$\frac{d}{dt}(m\ e) = \frac{dQ}{dt} - P\frac{dV}{dt} + e_f\frac{dm}{dt}$$

or

$$\frac{d}{dt}(m\ h) = \frac{dQ}{dt} + V\frac{dP}{dt} + e_f\frac{dm}{dt} \qquad (2.1)$$

Derivation of equation (2.1) is based on the assumption that the work of compression is reversible, i.e., dW = PdV. This assumption is considered to be valid because of the fact that the compression is relatively slow.

The heat transfer to the vessel walls and liquid can be written as

$$-\frac{dQ}{dt} = KA(T-T_s) - h_{fg}\frac{dm}{dt} \qquad (2.2)$$

The equation of state is written as

$$PV = m\ R(P,T)T \qquad (2.3)$$

Vapor does not behave as a perfect gas in the region of interest and the assumption that R(P,T) is constant can lead to serious error in the predictions.

The objective of the analysis is to predict the pressure behavior of the vapor for a given time rate of liquid insurge. A solution is obtained by using an iteration method. The initial conditions of vapor at the start of insurge to the pressurizer are considered to be known. The dimensions of the vessel and the material from which it is fabricated are known. The vessel walls and the liquid in the vessel are considered to be homogeneous in temperature throughout.

The time of insurge is broken up into a finite number of equal time intervals, each of magnitude Δt. The vapor pressure is assumed to vary linearly with time. The vapor pressure and hence the saturation temperature is estimated at the end of each successive time interval. The work done on the vapor during the interval, due to compression, is calculated. By using the estimated temperature, the heat flow to the heat sinks is computed. The validity of the estimated pressure is checked by carrying out the energy balance. The estimate is corrected each time to have the energy balance within specified limits and then the computation is carried out for the next interval.

Heat Flow to Vessel Walls and Liquid in Vessel

The inner surface of the vessel walls in contact with the vapor is assumed to follow the vapor saturation temperature history at all times during the interval. The heat content of the wall per unit wall area at the end of 'p' intervals of time is computed by integrating the temperature distribution across the wall at time $t = p \times \Delta t$. An expression has been developed by Gorman [10] and is as follows:

$$Q_{pw} = \sum_{n=1}^{p} v_n \, G_{(p-n)} \tag{2.4}$$

where

$$G_c = \frac{\alpha}{\Delta t} \sum_{n=0}^{\infty} e^{-c\,a_n^*} \left\{ \frac{e^{a_n^*} + e^{-a_n^*} - 2}{a_n^2} \right\} \quad ; \text{ for } C \neq 0$$

$$G_c = \frac{\alpha}{\Delta t} \sum_{n=0}^{\infty} \frac{1}{a_n} \left\{ \Delta t - \frac{(1 - e^{-a_n^*})}{a_n} \right\} \quad ; \text{ for } C = 0 \tag{2.5}$$

Similarly an expression for the heat content of the liquid in the vessel per unit area at the end of the pth interval of time has been developed [10] and is as follows:

$$Q_{p\ell} = \sum_{n=1}^{p} v_n \, H_{(p-n)} \tag{2.6}$$

where

$$H_c = \frac{4 \rho_f C_{p_f} \sqrt{\kappa_f \Delta t}}{3\sqrt{\pi}} \left\{ (C-1)^{3/2} + (C+1)^{3/2} - 2(C)^{3/2} \right\}; \quad \text{for } C \neq 0 \tag{2.7}$$

$$H_c = \frac{4 \rho_f C_{p_f} \sqrt{\kappa_f \Delta t}}{3\sqrt{\pi}} \quad ; \text{ for } C = 0$$

At the start of the insurge the heat content of the walls and liquid in the vessel, is considered to be zero. The heat transfer during the interval is calculated by subtracting the heat contents at the beginning and end of the time interval. It is interesting to note that the constants G_n and H_n are to be evaluated only once for any particular vessel geometry and can be stored and are used when required.

Solution of Equations

Consider a small time interval $\Delta t = t'' - t'$. Assuming the mean values of the variables for the interval to be equal to the arithmetic average of the values at the beginning and end of the interval, the equations (2.1) and (2.2) are integrated to give, respectively

$$(m''h'' - m'h') - (Q''-Q') - \overline{V}\,(P''-P') - \overline{e_f}\,(m''-m') = 0 \qquad (2.8)$$

and

$$-(Q''-Q') - K\,\overline{A(T-T_s)}\,\Delta t + \overline{h_{fg}}\,(m''-m') = 0 \qquad (2.9)$$

Where single and double superscripts refer to values of the properties at the beginning and end of the time interval respectively, and barred quantities represent mean values of the properties over the time interval. For the equations (2.8) and (2.9) to be valid the pressure and mass must be monotonic functions of time.

Solution Procedure

A step by step procedure, used to obtain the solutions, is described below. Computer sub-programs required to calculate various thermodynamic properties and other constants at various steps of the computation are discussed in Chapter 3.

1. Assume a value of pressure at the end of the first time interval. The initial conditions of the system are known.

2. To avoid overshooting of the actual pressure, the assumed value of pressure should be sufficiently below the pressure calculated on the basis of isentropic compression and slightly above the initial pressure.

3. Values for saturation temperature, enthalpy of saturated liquid, and enthalpy of evaporation associated with the assumed pressure are computed.

4. Once the saturation temperature associated with the assumed pressure is known, the heat transfer per unit area to the vessel walls and liquid can be calculated by using equations (2.4) and (2.6), respectively.

In the computation of heat transfer to walls the mean exposed wall area throughout any interval is used.

5. Now the ambient temperature of the vapor is computed. This temperature will be higher than the vapor saturation temperature if superheating has occurred. To start the computation the ambient temperature is assumed to be equal to the saturation temperature, and then the gas constant R(P,T) is computed associated with the assumed pressure and ambient temperature. By using equation (2.9) the ambient temperature is computed.

The difference between the computed and assumed temperature is designated as the error. The computed value of temperature is used to calculate the gas constant R(P,T). By using the recent value of gas constant and equation (2.9), a new temperature is computed. The difference in successively computed temperatures is set equal to a new value of error. This procedure is repeated till the error changes sign. The mathematically exact temperature lies between the two most recent values of computed temperature. By selecting new values of temperature, weighted according to the amount of error associated with adjacent computed values, it is easy to compute the exact temperature until the error is within prescribed limits. It is important to note that while this method will work for any system and pressure range, the Euler convergence method utilized by Drucker and Gorman [2] does not converge for the high pressure systems described here.

6. Now all the necessary information is available to evaluate the left hand side of equation (2.8). This quantity is designated as the error. Now the assumed pressure is given a small positive increment and the entire computation beginning at step one is repeated. This procedure is repeated until a change in the sign of the error is obtained. The exact pressure is then converged upon in a manner identical to that described in step five.

The initial conditions for the next time increment and the final conditions for the last time increment will be the same and therefore the initial conditions for each subsequent time increment will be known. The pressure behavior for the entire insurge transient can therefore be computed.

The Outsurge Problem

The theoretical model used to predict pressure behavior during outsurge is a relatively simple one. The outsurge is considered to begin with the liquid and vapor in the tank in a known state of thermodynamic equilibrium. It has been shown that the assumption of isentropic expansion of the entire contents of the vessel is inappropriate [6]. This is because liquid rushing from the bottom of the tank to the reactor circuit has no opportunity to take up thermodynamic equilibrium with the liquid-vapor system in the tank.

The mechanism of heat transfer is considerably different as compared to the insurge problem. Heat will enter the vapor phase through sensible heat transfer only and heat transfer through condensation is not available. Because of the relatively poor mechanism of heat transfer and the amount of time involved, its effect is neglected completely and the outsurge process is assumed to be adiabatic.

The outsurge is considered to be broken up into small increments, each increment corresponding to a drop in tank level. The system consisting of the initial tank content is considered to undergo a closed isentropic expansion associated with the first incremental drop in level. A solution for the pressure at the end of this expansion is obtained. Now the new system consisting of the liquid and vapor in the tank is considered, at the beginning of second increment. Again, this system is considered to undergo a closed isentropic expansion, and a solution for the pressure at the end of expansion is obtained. This analytical procedure is repeated until the pressures associated with the entire level history during outsurge, are predicted. Thus the outsurge is handled as a series of "stepped-open system" isentropic expansions. The mass of the system reduces after each expansion interval, i.e., at the end of each increment a quantity of mass which has entered the piping ceases to be part of the system of interest.

The following step-by-step procedure is used for computation during outsurge.

1. The initial thermodynamic properties of the tank contents are computed, such as system quality, average specific entropy and density. Thus, the starting point on the temperature-entropy diagram is determined.

2. The contents of the tank are considered to undergo an isentropic expansion associated with a small change in liquid level and new properties at the end of level increment are determined.

3. The system boundaries are redefined excluding the liquid which has left from the bottom of the tank and ceases to be part of the system of interest. Since some liquid has left, the system quality has increased which results in higher average specific entropy.

4. Steps 2 and 3 are repeated until the entire outsurge is completed.

It is seen that the analytical procedure generates a stair-step type of path on the temperature entropy diagram, descending and moving outward in the direction of the positive entropy axis. Initially there is a small vertical drop of temperature at constant entropy associated with isentropic expansion during level increment. This is followed by a horizontal move to a point of higher average entropy but unchanged temperature as the system boundaries are redefined before starting the next increment. Similar steps are associated with each additional increment in outsurge.

CHAPTER 3

COMPUTING PROCEDURES

The Insurge Problem

The computer programs utilized for all insurge and outsurge computation are written in FORTRAN IV. A print-out of these programs is included in the Appendix. All the symbols utilized as input to the computer program are included in the nomenclature. Variables which would normally begin with a letter lying between I and N in the alphabet are preceded by the letter A to meet the FORTRAN language requirements. All sub-programs and the main program utilize British Units, but the input and output can be easily changed to the desired units using conversion factors at the input and print-out stage.

The insurge program is divided into six parts which are discussed below.

Part 1

Orderly storage space is reserved for known properties as well as for those to be computed later in the program. Since the computer cannot handle zero as a subscript, the space reserved is one more in number than the number of time intervals. In the print-out the DIMENSION statement is given in a generalized form, but in the actual practice it has to be specified before the program can be executed.

All data required to conduct the entire computation is read in, for example, the initial pressure, total tank volume, diameter of the tank, density, specific heat and thermal conductivity of the wall material and liquid, thickness of the wall, etc. (see program). A 148 element digital array of constants is also read in, which is to be used by sub-programs for the computation of various thermodynamic properties. This array is included at the end of the Appendix. The insurge level history is also read in.

The surge tank for which the program is written is shown in Figure 2, but any tank geometry can be handled by this program with slight modifications. The value of the variable TYPE tells the computer whether to use light or heavy water thermodynamic properties. The program is written in such a way that if the value of the variable TYPE is greater than one, heavy water thermodynamic properties will be used.

Part 2

In this section some simple preliminary calculations are performed. Wall thickness and time interval are converted to feet and hours respectively. The volume per unit length (ft^3/in.) of the straight section of tank and the area per unit length of the tank as well as the area of the tank upper dome are evaluated. Thermal diffusivities of the water and the wall are evaluated. The properties, used for the evaluation of thermal diffusivities, are selected at approximately

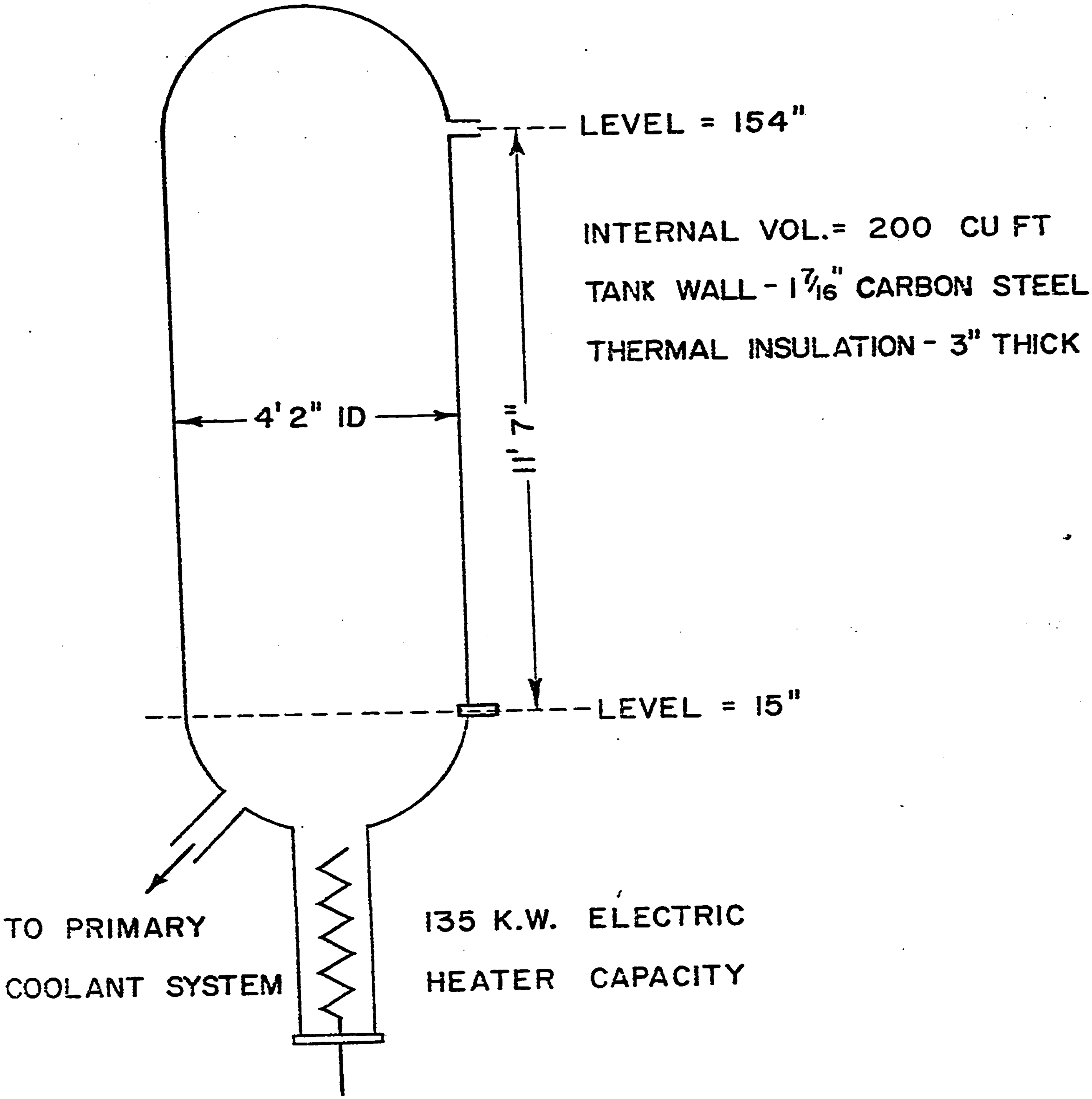

FIG. 2 SCHEMATIC DRAWING OF N.P.D. REACTOR PRIMARY COOLING SYSTEM STEAM SURGE TANK.

mean transient temperature and are assumed constant throughout the insurge.

Part 3

Total volumes of vapor are computed for the beginning of each time interval and are stored. They are set equal to half the tank volume, plus or minus the deviation from this value dictated by liquid level.

Part 4

Equations (2.5) and (2.7) are programmed in the form of sub-programs. Heat transfer constants for the walls and liquid are evaluated and stored, by using these sub-programs.

Part 5

Utilizing the appropriate sub-programs the initial thermodynamic properties for the beginning of first time interval are evaluated.

For light water the saturation temperature (in ^{o}F) is obtained from the known saturation pressure. Using these two properties the enthalpies of the liquid, the vapor, and hence that of evaporation are obtained. The modified gas constant R(P,T) is also obtained. In the CALL statement some quantities which are not of immediate interest, such as entropy, are also included to complete the statement. These quantities are there because they are used by the outsurge program.

For heavy water the saturation temperature (in $^{\circ}F$) is obtained from the known saturation pressure, but by using a different sub-program. Using the temperature of saturation, the three enthalpy quantities are called in one sub-program. Modified gas constant R(P,T) is obtained by using pressure and temperature of saturation and calling another sub-program. Finally, for either case, the liquid internal energy is set equal to the liquid enthalpy and the initial mass of vapor is obtained from the equation of state.

Part 6

This is the main part of the program. Solution for the properties of the vapor system at the end of each time interval is obtained here. The first step is to compute average wall area (cylindrical wall) and average total area surrounding the vapor during the increment. A pressure, P1, is assumed for the end of the interval. Now, based on this pressure, all of the saturation properties of interest such as saturation temperature, enthalpies of the liquid, the vapor and of evaporation are obtained, by utilizing the appropriate sub-programs. The difference between the saturation temperature and the initial saturation temperature TS(1), is stored. This difference is used for the computation of heat contents of the wall and liquid at the end of increment.

Using the above temperature difference the heat content per unit area, above the initial heat content, is easily evaluated for the wall and liquid. For the nth interval n temperature differences will be involved. In any case, the heat transferred from the vapor during the interval, based on the assumed pressure, is readily established. Heat transfer during any time interval is obtained by subtracting the heat contents per unit area at the end and beginning of time interval and multiplying this difference by the mean exposed area during the interval.

It is now necessary to compute the ambient vapor temperature compatible with the assumed pressure. The computation is started by setting the ambient temperature equal to the saturation temperature. Modified gas constant R(P,T) is obtained by calling appropriate sub-program and based on ambient temperature, i.e., saturation temperature at the start of computation and pressure P1. Computed temperature is then evaluated using equation (2.9). The first value obtained for the computed temperature is compared with the saturation temperature. One can easily show, using the perfect gas equation of state for simplicity, that if the assumed pressure is much too close to the pressure at the beginning of the interval the computed temperature may be less than saturation temperature. For any real process it must be equal or greater than saturation temperature, hence, if it is found to be less, the assumed pressure is rejected and computation is begun again with a higher assumed pressure.

When a pressure, for which the first computed temperature is greater than saturation temperature, is obtained the temperature iteration procedure can proceed.

It is known that the modified gas constant R(P,T) increases with temperature in the region near saturation. Because of this fact and due to the nature of equation (2.9), it follows that the corrected temperature will lie between the first permissible computed temperature and saturation temperature. Accordingly, the first computed temperature is given small negative increments and the iteration procedure described earlier in Chapter 2 is utilized to obtain the corrected value of temperature. It is mathematically possible for the iteration procedure to carry the corrected temperature down below saturation again. This can only happen if the assumed pressure is again much too low. In such a case provision has been made in the program to reject this pressure and assume a higher one.

Once a permissible assumed pressure and corresponding temperature is obtained, the final check is to test the energy balance through equation (2.8).

For carrying out the energy balance it is first necessary to evaluate the enthalpy of the vapor. The vapor will in general have some degree of superheat and the enthalpy and modified gas constant are evaluated utilizing the appropriate sub-programs and the assumed pressure and computed ambient temperature.

The mass of the vapor at the end of the time interval is obtained by using the modified gas constant.

Now the left hand side of the equation (2.8) can be evaluated. This is designated as error. The first time this error should be negative. If it is found to be positive, a provision has been made in the program to stop all the computations. This is because the pressure increment, DP, is too big. The programmer's response should be to use a smaller pressure increment.

The error is stored and consecutive higher values of pressure are assumed until the change in the sign of the error is obtained. Using the iteration technique discussed in Chapter 2, the pressure is then corrected to minimize the error. A final value of pressure, correct within prescribed limits, is obtained for the end of the interval. The solution for subsequent intervals is then obtained.

The Outsurge Problem

The computational procedure for the outsurge problem is a much simpler one since the theoretical model is much less involved. The computer program is divided into three parts and is described as follows:

Part 1

All input data required for the computation are read in here, such as the initial level, initial pressure, diameter of the tank, and the total tank volume, etc. The 148 element matrix of digital values is also read in for the use of sub-programs.

Part 2

In this part some preliminary calculations, to evaluate volume per unit length ($ft^3/in.$) of the straight section of tank, and initial liquid and vapor volumes, are performed.

Part 3

In this part the main computation is carried out. First the saturation temperature associated with the initial pressure is obtained using the appropriate sub-program. Initial values for specific volume and entropy, of the liquid and vapor are obtained using either pressure and saturation temperature for light water or saturation temperature alone for the heavy water. The entropy of evaporation, masses of liquid and vapor in the tank is then obtained. Using these quantities, system quality and the average system specific entropy are computed.

Next the initial level is given a small negative increment and the conditions at the end of this increment are considered. The new volume for the vapor phase at the end of level increment is obtained. This volume dictates a new and lower average specific density. A pressure, slightly below the initial pressure, is assumed for the end of the interval. With this pressure there is an associated liquid and vapor density. Following a sequence of steps virtually identical to those described for the beginning of the interval, a value is obtained for the system average specific entropy at the end of the interval. The difference between this and the initial entropy is designated as error. Using an iteration procedure the same as that described for the insurge problem, the assumed pressure is decreased in further steps until the error changes sign. The value of the pressure is then converged upon to give the associated error within prescribed limits.

Finally, the conditions obtained for the system at the end of the interval are utilized as 'initial' conditions for the subsequent interval. The procedure is repeated until the entire outsurge is solved.

The Computer Sub-Programs

The first two sub-programs compute the constants for the evaluation of heat content of the wall and liquid respectively at the end of time interval. Expressions for these constants are given by equations (2.5) and (2.7). The constants are evaluated only once for the entire insurge and stored.

The remaining sub-programs pertain to the evaluation of thermodynamic properties of light and heavy water respectively. They are provided in the Appendix and are described below, in that order.

Light Water Sub-Programs

The source of all light water sub-programs utilized here is to be found in reference [11]. They are valid over the entire range of pressure and temperature upto the critical values. These sub-programs are modified according to the needs. The evaluation of specific heat, in the sub-program SSWCH and SSVCH, is deleted. An additional calculation is performed in the sub-program SSVCH for the evaluation of modified gas constant R(P,T).

The two sub-programs for volume, entropy and enthalpy (called SSWCH and SSVCH) call a group of 5 auxiliary sub-programs between them (BETA4, SIGEP4, BETA3, SIGEP3, and ZERO). The TSAT sub-program calls PSAT for saturation values.

The sub-programs for water can be used in the sub-cooled or saturated phase. Similarly the vapor sub-programs can be used in the superheated or saturated phase. For saturation properties, in either phase, only one of either pressure or temperature is required, since the corresponding value of temperature or pressure respectively can be found and these used in the appropriate sub-program. For sub-cooled liquid or superheated steam, pressure and temperature are independent and hence both must be given as input.

Heavy Water Sub-Programs

The saturated heavy water sub-programs used here are given in reference [12]. These are valid over a range of pressure between one atmosphere and 2,240 lb/in.^{2} abs. There was some error found in the constants provided in reference [12] for the evaluation of vapor specific volume. Using the property values given in reference [13] new constants were evaluated. This sub-program appears in the Appendix in the corrected form. The sub-programs for the evaluation of entropy of saturated liquid and vapor were also developed using the property values tabulated in reference [13], and are given in the Appendix.

In the main computation the enthalpy and specific volume of slightly superheated heavy water vapor are needed. No experimental data for the properties of superheated heavy water vapor in the range of interest are available. Values for these properties are obtained here by means of an approximation which is considered to be admissible. Pressure and temperature, at which the properties are to be evaluated, are known. The properties of the heavy water vapor at the given pressure and associated saturation temperature are first obtained. The degree of superheat for the heavy water system is known. It is assumed that the change of properties due to this superheat is the same as it would be for a light water system of the same pressure and the same degree of superheat. This latter change is computed and added to the saturation values to obtain the properties in the superheated region. There is a sub-program in the heavy water sub-programs to evaluate the modified gas constant for both superheated and saturated vapor.

Finally, at the end of the Appendix, a listing of the 148 element digital array AK of constants, is given.

CHAPTER 4

RESULTS AND DISCUSSION

Comparison of Experimental and Analytical Results

The Insurge Problem

A series of experimental heavy water insurge tests were conducted on the surge tank of the N.P.D. (Nuclear Power Demonstration) reactor of Atomic Energy of Canada Ltd. The results are presented in reference [7]. In order to verify the accuracy of the theoretical model and the computing procedure described in Chapters 2 and 3 respectively, a number of experimental test runs are compared with predicted results based on the insurge level histories. The latter are obtained by executing the computer program on an IBM 360/65-OS. Computer at H-level.

The comparison for a typical test run is presented in Figure 3. It can be seen that the assumption of isentropic compression would lead to extremely large error for insurges of the magnitude shown. It is also obvious that very good agreement between experiment and predictions is obtained. The reason for the poor predictions, based on the isentropic model as the compression proceeds, is because of the fact that there is an increasing temperature gradient in the walls building up in the early part of the compression. The amount of work done on the steam during the later volume increments is not much different from that done during the earlier increments, however, the amount of heat transferred from the steam per interval is greatly increased. The predicitions based on the isentropic model for these insurges is so poor that they are not presented for further N.P.D. insurge tests reported here.

In Figure 4 the accumulated heat flow (predicted) to the walls and the liquid is presented as a function of time. It is seen that the heat flow from the steam per time interval increases rapidly for about 25 seconds. After this time the wall temperature gradients have steadied out sufficiently to keep the rate of heat loss to the walls about constant. The comparison between the accumulated heat flow to the walls and liquid is quite informative. It is seen that for all practical purposes the heat flow to the liquid could be neglected for geometries and pressures in the range under study here.

Two of the tests discussed here (Figure 7 and 8) were conducted while electric heaters in the liquid phase, of 15 KW capacity, were turned on. It is easily inferred from Figure 4 that these heaters would have no appreciable effect on the compression process.

In Figure 5 predicted values of ambient vapor temperature and saturation temperatures are plotted for the run of Figure 3. The accuracy of the computed ambient temperature will depend considerably on the accuracy with which the sensible heat transfer coefficient is selected. It can easily be shown, however, using the perfect gas law for simplicity and assuming the vapor to be polytropic, that the value of this coefficient has very little effect on the predicted pressure.

A typical level increment is considered. The work done on the vapor, and heat transferred from it, are determined by the rise in pressure. The difference in these two quantities dictate a value for internal energy of the vapor and condensate at the end of the interval. This internal energy would be equal to the product of the mass of vapor, the specific heat at constant volume and absolute temperature of the vapor if we neglect internal energy of condensate. Since the mass would vary inversely with the absolute temperature, the total internal energy and hence pressure would be independent of temperature.

The value of the sensible heat transfer coefficient will therefore be critical only if the degree of superheat attained is of interest. Drucker and Tong [1] used a value of 0.074 Btu/hr/ft^2/^{o}F for their work. It is shown in the literature that the sensible heat transfer coefficient for steady state free convection may be expressed as follows [14],

$$K = \frac{C\ K_f}{L}\ (G_r \times P_r)^m \qquad (4.1)$$

where

K_f = Vapor conductivity

L = Length of rectangular wall

G_r = Grashof No.

P_r = Prandtl No.

C and m are constants whose values depend on the system.

While the heat transfer problem of immediate interest is a transient one and the walls are cylindrical, it has been considered appropriate to use the Drucker-Tong value as a reference and to modify it for the N.P.D. system under study according to the relationship of equation (4.1). This practice has been followed in the work reported here and a value of K equal to 0.25 $Btu/hr/ft^2/^oF$ has been utilized.

The experimental data presented in Figure 6 are obtained through private communication with the author of reference [7], and are not contained in that reference. The data are believed to be the most accurate of all of that taken during the entire test series. It is seen that while the level history is far from being linearly related to time the computation procedure gives excellent agreement with experiment.

Some more experimental results are compared with the predicted values in Figures 7, 8 and 9. In the analysis in Figure 7 it has been necessary to depart slightly from the experimental level history. It has been discussed in Chapter 2 that there must be a monotonic increase in pressure with time if the computational procedure is to be utilized. Since this condition is not always satisfied in Figure 7, beyond the 70 second point in time, the level history was adjusted to that shown by the dashed line for the purpose of computation. This has contributed to some discrepancy between experiment and analysis beyond this point. Otherwise the agreement is quite good.

It is observed in Figures 8 and 9 that there is fairly good agreement for most of these insurges. The study of the experimental level and pressure curves reveals that there are some small anomalies in the experimental data. Without these anomalies, the discrepancies between experimental and predicted values would be even less.

In Figure 10 the experimental data from reference [2] are compared with the predicted pressures obtained using the computer program described here. This figure is presented to demonstrate the versatility of the program. The experimental data for this run was obtained with a small, low pressure tank using light water. It can be seen that the isentropic model is inappropriate and the agreement between experiment and analysis is very good. Therefore, the program has no difficulty in handling heavy or light water systems of high or low pressure ranges.

It is seen that near the end of the insurge the predicted pressures are slightly higher than the experimental. There are two factors in particular which tend to explain this behavior. First the tank is considered in the calculations to be perfectly insulated whereas in the actual experimental tests some heat is certain to be lost through the insulation. Secondly, in the calculations heat flow axially down the vessel wall is neglected. It is inevitable that near the end of the compression when the temperature of the vapor is relatively high there will exist a temperature gradient down the wall and some heat will be lost in this manner. Both of these conditions will contribute towards a small discrepancy near the end of the insurge but, the incorporation of these effects into the analysis is not warranted.

The Outsurge Problem

The comparison between the experimental and analytically predicted outsurge results for a typical N.P.D. surge tank test run is made in Figure 11. The outsurge level history is also included in the same figure. It has been shown in reference [6] that the much higher predicted pressures are obtained if the entire initial contents of the tank are assumed to undergo a closed isentropic expansion.

Very good agreement between the experimental and analytical data for almost the entire outsurge is obtained using the computational procedure described in Chapter 3. It can be seen that the predicted values are slightly lower than the experimental near the end of the outsurge. This can be explained by noting that no account for the heat-inflow from the tank walls has been made in the analysis.

There is some slight anomaly in the experimental data. The pressure curve tends to flatten out more quickly than would be expected on studying the level curve. The effect of heat in flow would be much more significant if the outsurge had to occur over a longer period of time. This can be taken into consideration by using the procedure described in the insurge problem. It is noted, that the computational technique described herein is highly appropriate for the prediction of outsurge pressure behavior for systems and pressure ranges of the type encountered in the N.P.D. surge tank.

Discussion and Conclusions

It is evident that the theoretical models and computational procedures described in this thesis provide a powerful means for predicting the performance of steam surge tanks during both insurge and outsurge of liquid. The analysis is virtually unique in that no empirical constants are required. Though the experimental data have been examined for a limited range, the included computer program can be used for analysis over a wide range of pressures. It is reasonable to expect that good agreement between the experimental and analytical values would be obtained over a fairly large range of pressure and for most steam surge tanks of interest.

Though the computer program has been written for the vertical cylindrical tank with hemispherical domes, there would not be any difficulty in introducing modifications to handle any particular geometry. Furthermore, while the study has been restricted to the performance of light and heavy water systems, the performance of any single component liquid-vapor system can be analyzed once the appropriate thermodynamic property sub-programs have been provided.

The work could be extended by considering the effect of in-spray of liquid droplets to the steam region. This in-spray is sometimes used to decrease the pressure rise during insurge. It has been shown in reference [2] that upon making certain assumptions, the heat lost to the droplets can be added to other heat losses in the analysis described here. A comparison between the experimental and the predicted values can be done, provided accurate experimental data are available for this purpose. The predicted values can be obtained by using the same computational procedure, but incorporating the appropriate modifications.

Another problem which can be considered for the extension of the present work involves tanks fabricated from laminated walls. There will not be any difficulty in making appropriate modifications to the analysis. Another area of interest which does not appear to have been explored involves the insurge and outsurge of liquid to systems where the vapors contain non-condensable gases. This problem may become of more interest to nuclear design people if non-condensable gases are used extensively in fuel channels to promote the heat transfer in nominally liquid cooled systems.

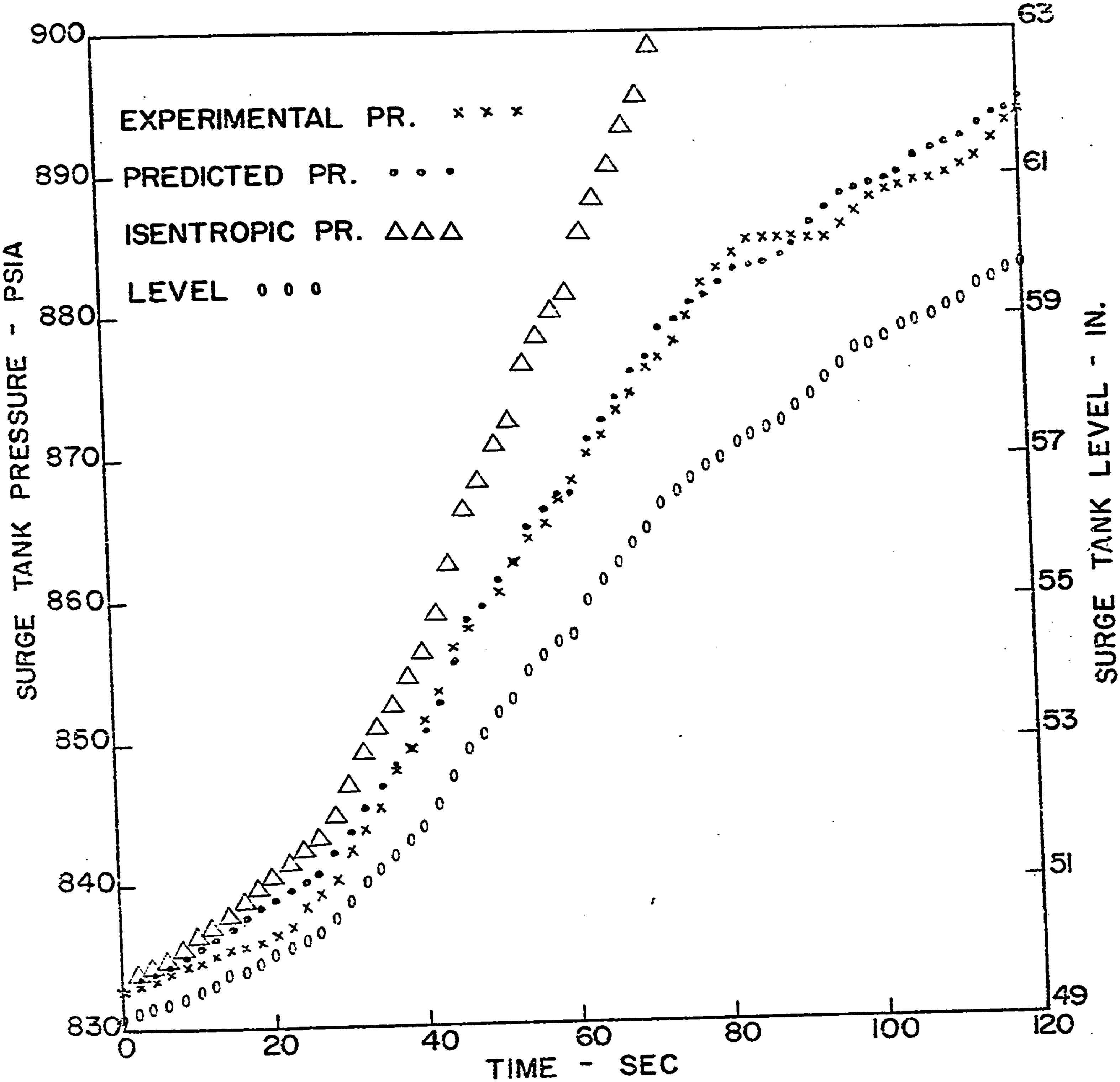

FIG. 3 COMPARISION BETWEEN EXPERIMENTAL AND ANALYTICALLY PREDICTED PRESSURE BEHAVIOUR. EXPERIMENTAL DATA FROM REF. 7, RUN 6.

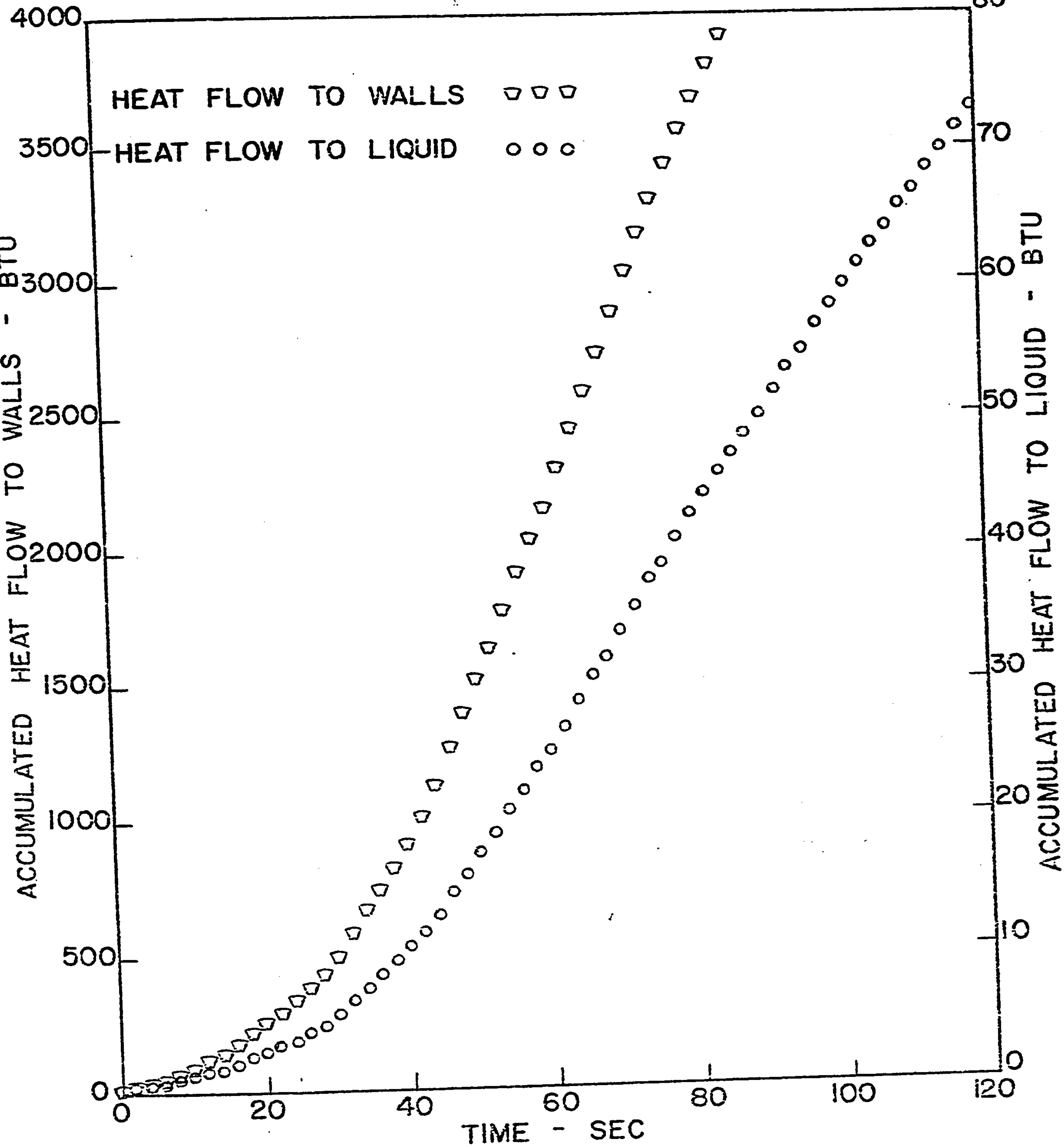

FIG. 4 ACCUMULATED HEAT FLOW TO WALLS AND LIQUID vs TIME, BASED ON THEORETICAL MODEL. PERTAINS TO INSURGE OF FIG. 3.

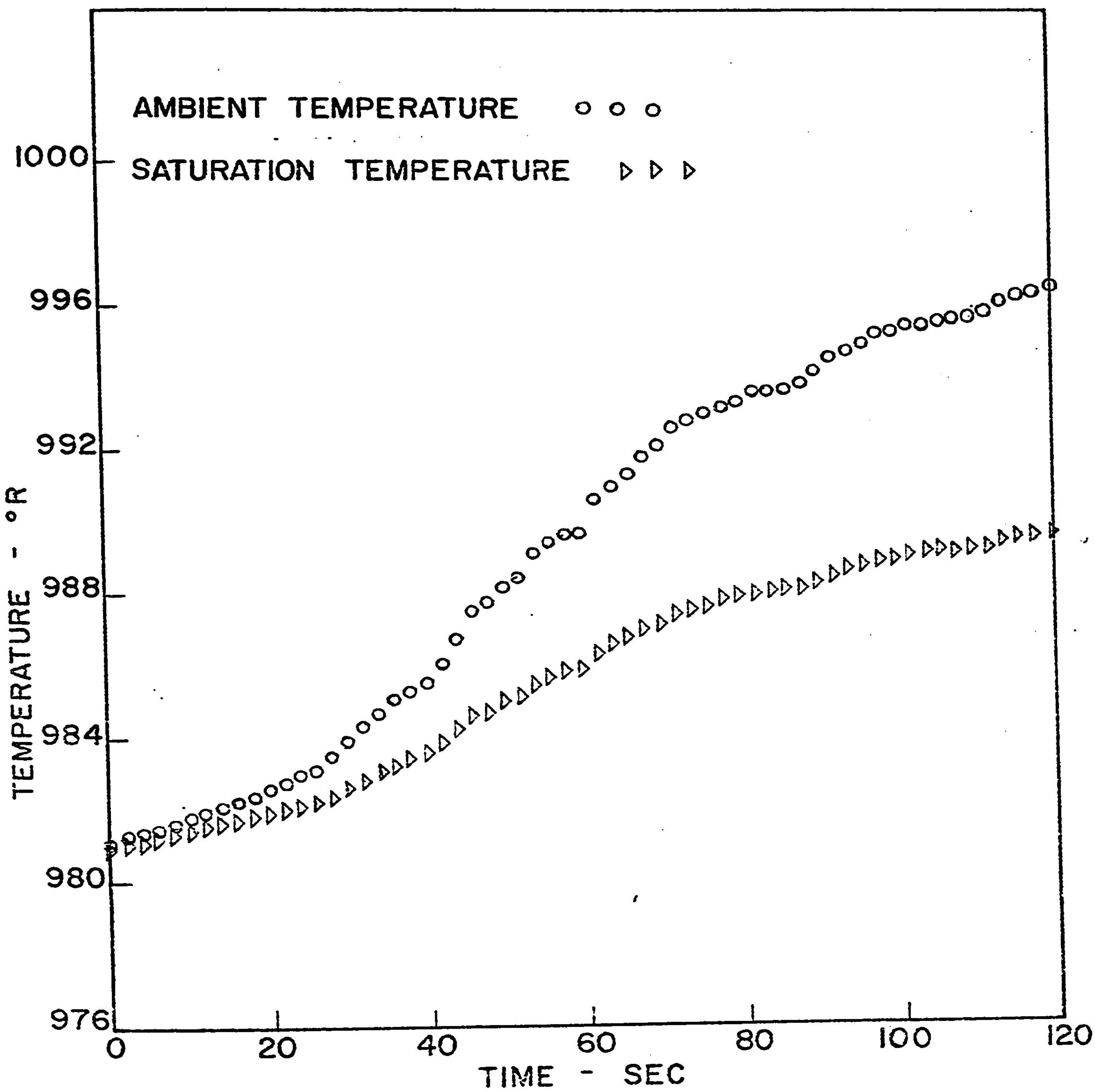

FIG. 5 COMPARISION BETWEEN AMBIENT TEMPERATURE AND SATURATION TEMPERATURE BASED ON THEORETICAL MODEL. PERTAINS TO INSURGE OF FIGURE 3.

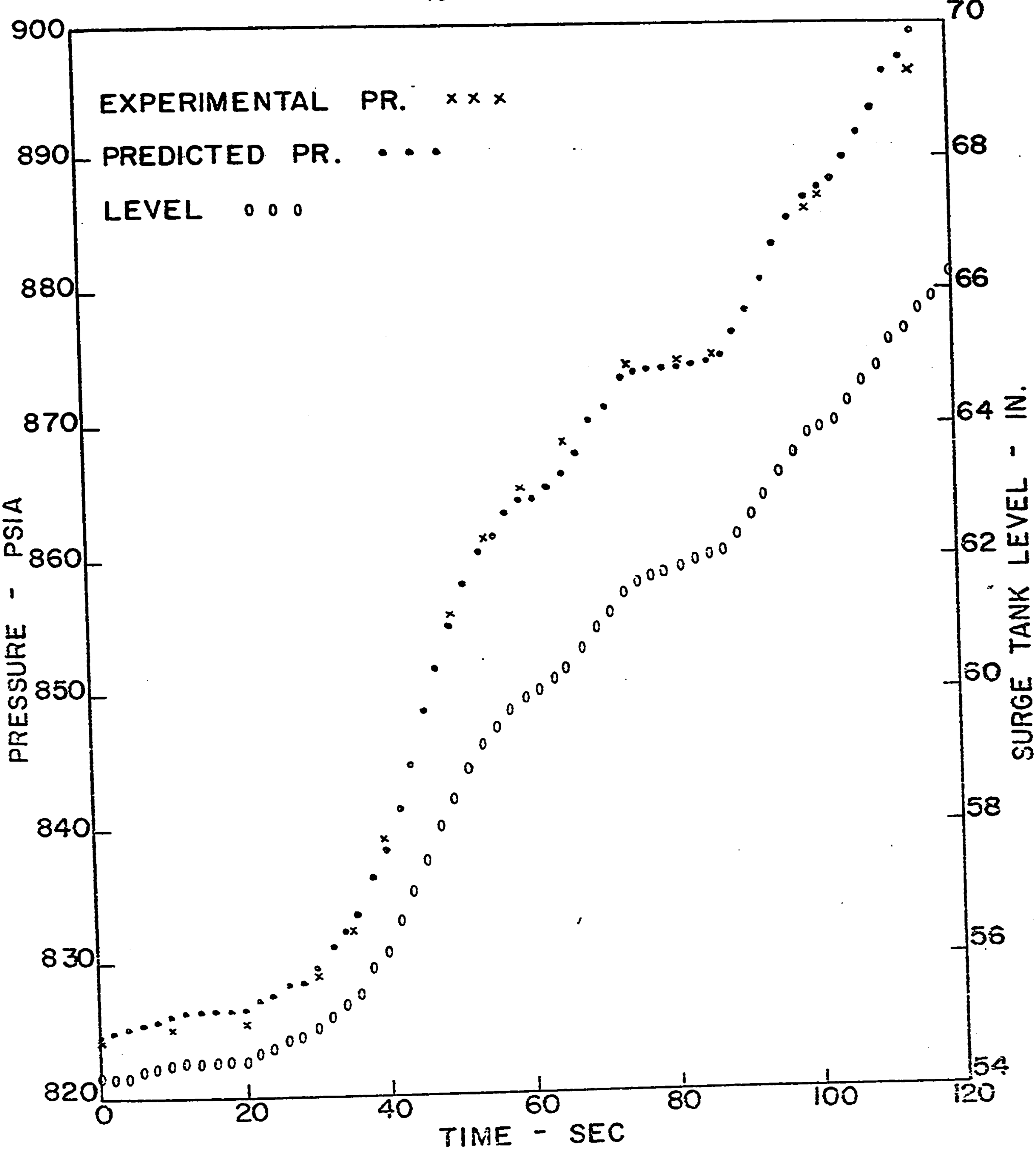

FIG. 6 COMPARISION BETWEEN EXPERIMENTAL AND ANALYTICALLY PREDICTED PRESSURE BEHAVIOUR. EXPERIMENTAL DATA PROVIDED BY A.E.C.L.

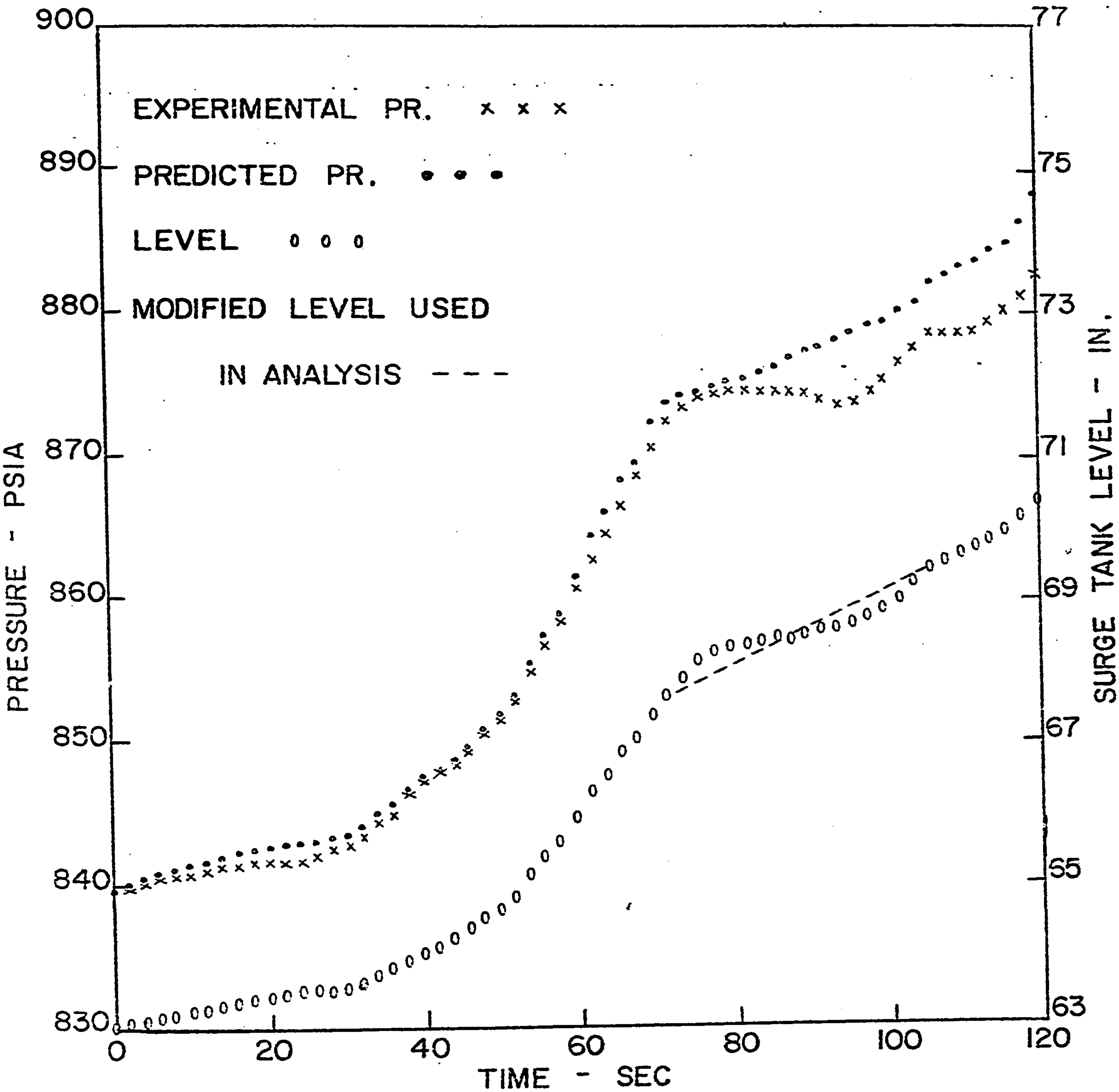

FIG. 7 COMPARISION BETWEEN EXPERIMENTAL AND ANALYTICALLY PREDICTED PRESSURE BEHAVIOUR. EXPERIMENTAL DATA FROM REF. 7, RUN 4.

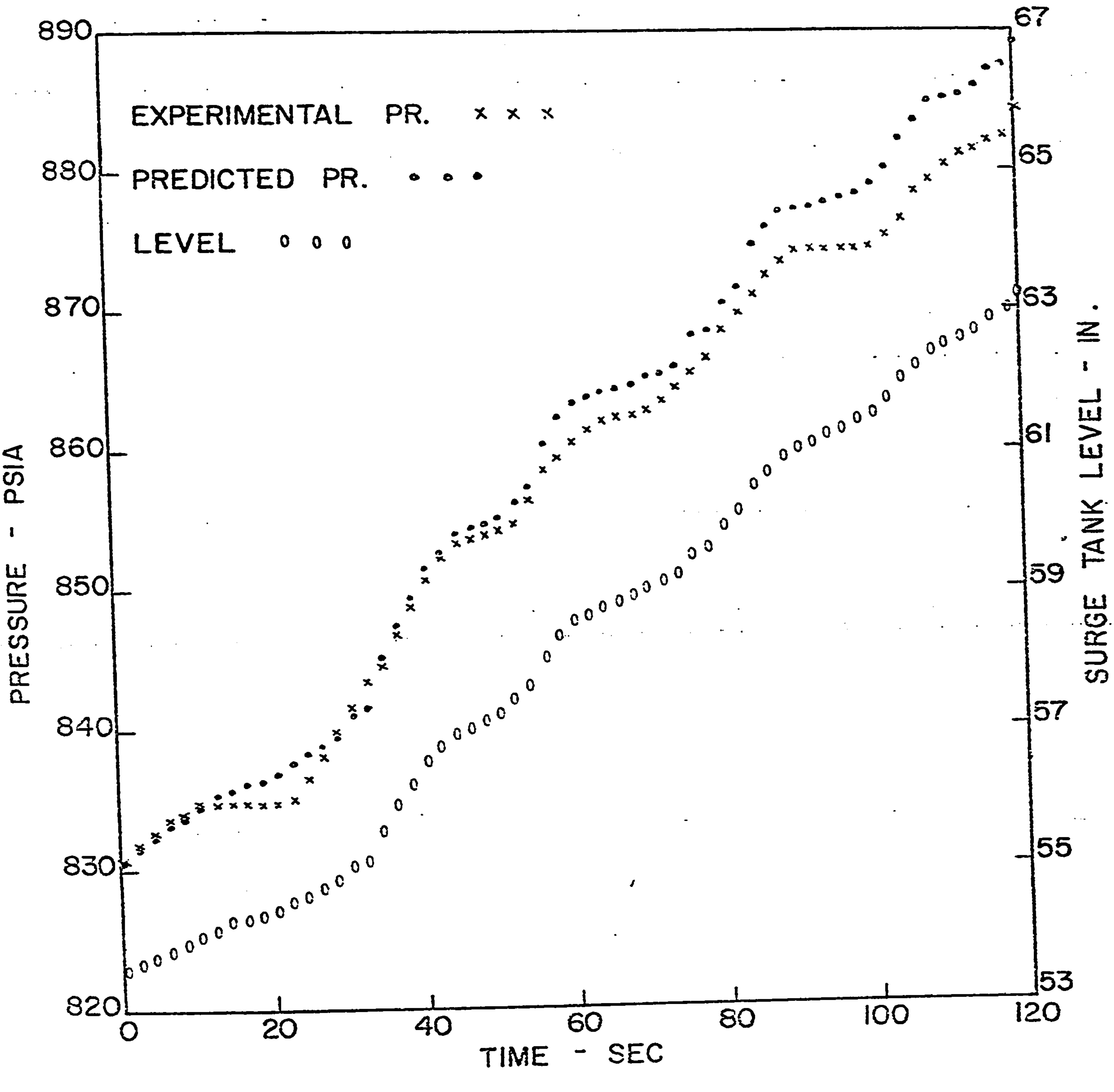

FIG. 8 COMPARISION BETWEEN EXPERIMENTAL AND ANALYTICALLY PREDICTED PRESSURE BEHAVIOUR. EXPERIMENTAL DATA FROM REF. 7, RUN 3.

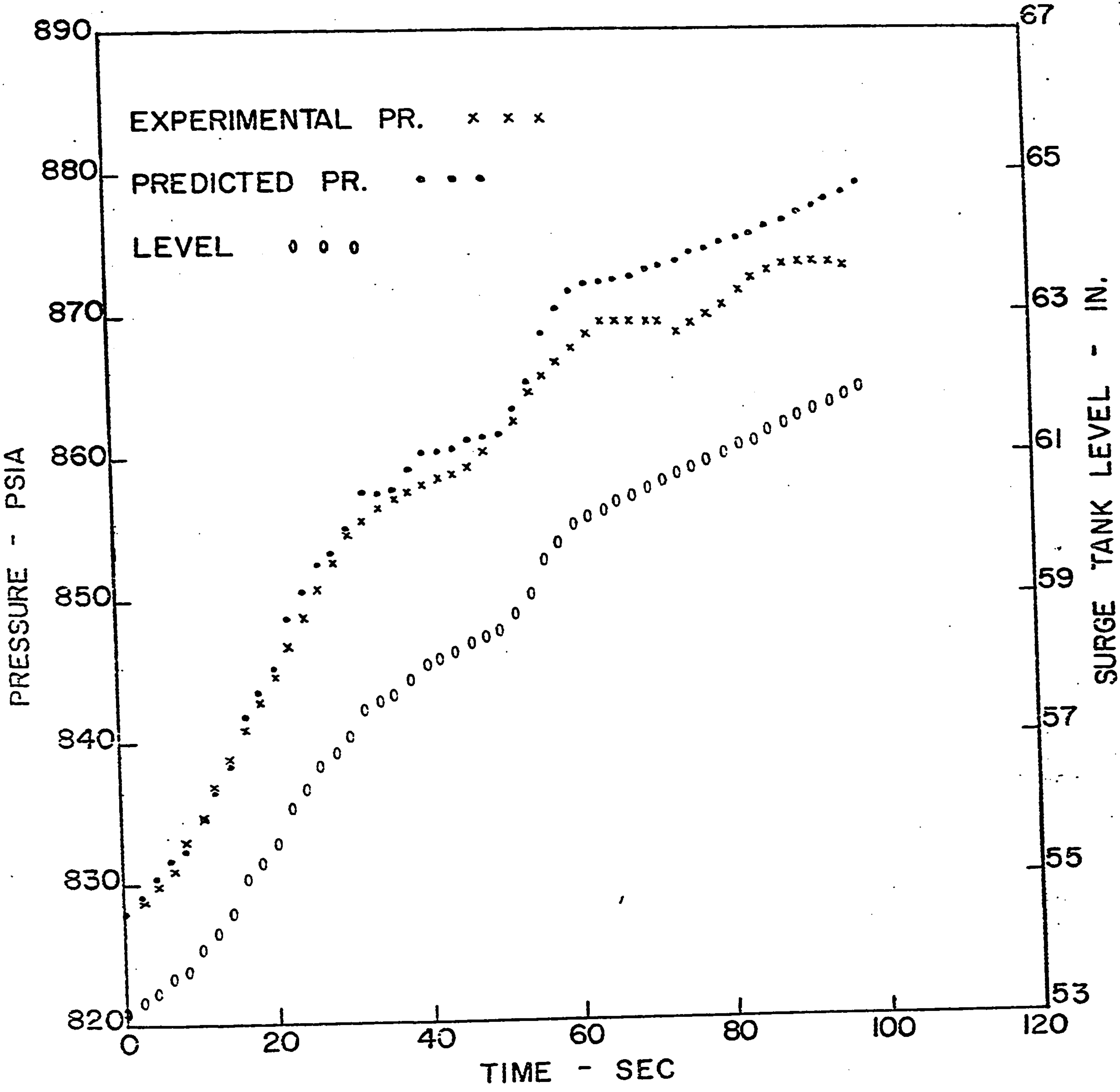

FIG. 9 COMPARISION BETWEEN EXPERIMENTAL AND ANALYTICALLY PREDICTED PRESSURE BEHAVIOUR. EXPERIMENTAL DATA FROM REF. 7, RUN 5.

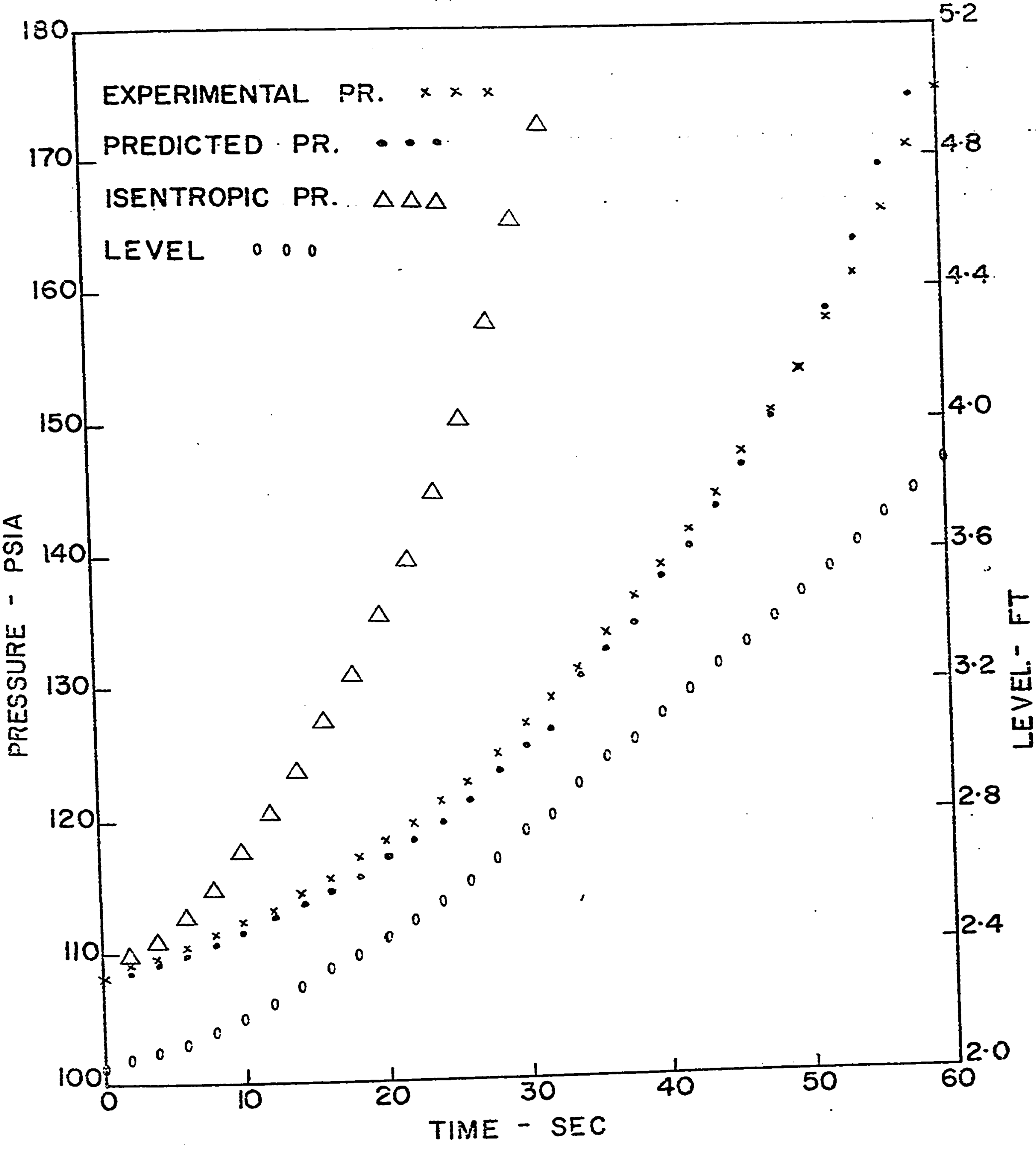

FIG. 10 COMPARISION BETWEEN EXPERIMENTAL AND ANALYTICALLY PREDICTED PRESSURE BEHAVIOUR. EXPERIMENTAL DATA FROM REF. 2, FIG. 3.

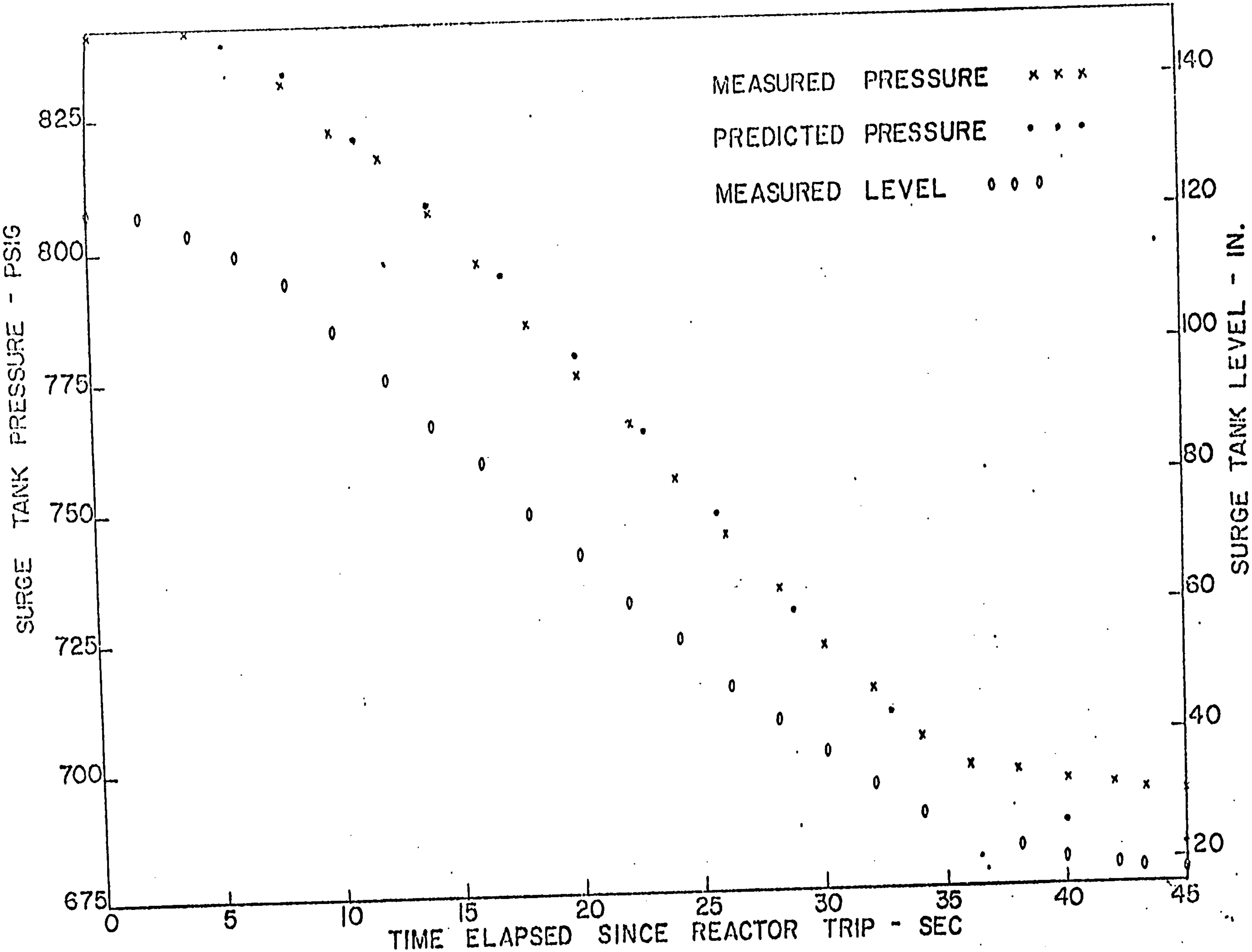

FIG. II COMPARISION BETWEEN EXPERIMENTAL AND ANALYTICALLY PREDICTED PRESSURE BEHAVIOUR FOR N.P.D. OUTSURGE TEST. DATA FROM REF. 6,FIG.2.

APPENDIX

```
C     TITLE-COMPUTATION OF STEAM SURGE TANK TRANSIENTS DURING INSURGE
C     PART 1-ENTER INPUT DATA
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION P(NU),ALEVEL(NU),QW(NU),QL(NU),TVOLU(NU),GW(NU),HC(NU),
     2TSF(NU),HW(NU),R(NU),H(NU),HFG(NU),TS(NU),T(NU),HS(NU),EF(NU),
     3AM(NU),V(NU),TF(NU)
      COMMON AK(148)
      READ NU,TYPE,DIA,VOLUME,ALM,ALW,CPWT,CONWT,ROWWT,CPW,CONW,ROWW,
     2THW,DT,CK,DP,DET,ALIM1,ALIM2
      READ P(1)
      READ (AK(I),I=1,148)
      READ (ALEVEL(I),I=1,NU)
C     PART 2-PRELIMINARY CALCULATIONS
      THW=THW/12.0
      DT=DT/3600.0
      PI=4.0*DATAN(1.0D00)
      VPUL=(PI*DIA*DIA)/(4.0*1728.0)
      AT=(PI*DIA*DIA)/(2.0*144.0)
      AL=(PI*DIA*DIA)/(4.0*144.0)
      TDIFWT=CONWT/(ROWWT*CPWT)
      TDIF=CONW/(ROWW*CPW)
      ALFA=2.0*CONW/THW
      QW(1)=0.0
      QL(1)=0.0
C     PART 3-CALCULATION OF VAPOR VOLUMES
      DO 10 J=1,NU
10    TVOLU(J)=VOLUME/2.0+(ALM-ALEVEL(J))*VPUL
C     PART 4-CALCULATION OF HEAT TRANSFER CONSTANTS
      DO 20 I=1,NU
      GW(I)=GWF(I,THW,PI,DT,TDIF,ALFA)
20    HC(I)=HCF(I,CPWT,PI,ROWWT,DT,TDIFWT)
C     PART 5-CALCULATION OF INITIAL THERMODYNAMIC PROPERTIES
      IF(TYPE.GT.1.0) GO TO 30
      TSF(1)=TSAT(P(1))
      CALL SSWCH(P(1),TSF(1),SPVOLW,SW,HW(1))
      CALL SSVCH(P(1),TSF(1),SPVOLV,R(1),SV,H(1))
      HFG(1)=H(1)-HW(1)
      GO TO 40
30    TSF(1)=TSATH(P(1))
      CALL HWFGG(TSF(1),HW(1),HFG(1),H(1))
      CALL GASCON(P(1),TSF(1),R(1))
40    TS(1)=TSF(1)+459.67
```

```
      T(1)=TS(1)
      HS(1)=H(1)
      EF(1)=HW(1)
      AM(1)=(P(1)*TVOLU(1))/(R(1)*T(1))
C     PART 6-MAIN CCMPUTATION
      DO 280 I=2,NU
      ICOUNT=0
      CTR3=0.0
      CTR4=0.0
      TVOLAV=(TVOLU(I)+TVOLU(I-1))/2.0
      AVELEV=(ALEVEL(I)+ALEVEL(I-1))/2.0
      AW=(ALW-AVELEV)*PI*DIA/144.0
      AR=AT+AL+AW
      P1=P(I-1)
50    P1=P1+DP
60    IF(TYPE.GT.1.0) GO TO 70
      TSF(I)=TSAT(P1)
      CALL SSWCH(P1,TSF(I),SPVOLW,SW,HW(I))
      CALL SSVCH(P1,TSF(I),SPVOLV,RR,SV,HS(I))
      HFG(I)=HS(I)-HW(I)
      GO TO 80
70    TSF(I)=TSATH(P1)
      CALL HWFGG(TSF(I),HW(I),HFG(I),HS(I))
80    TS(I)=TSF(I)+459.67
      EF(I)=HW(I)
      HFGAV=(HFG(I)+HFG(I-1))/2.0
      V(I)=TS(I)-TS(1)
C     CALCULATION OF HEAT CONTENT OF LIQUID AND WALL
      QW(I)=0.0
      QL(I)=0.0
      DO 90 N=2,I
      M=I+1
      QW(I)=QW(I)+V(N)*GW(M-N)
90    QL(I)=QL(I)+V(N)*HC(M-N)
C     CALCULATION OF HEAT TRANSFER DURING INTERVAL
      DQ=(QW(I)-QW(I-1))*(AW+AT)+(QL(I)-QL(I-1))*AL
C     ITERATION FOR TEMPERATURE COMPATIBLE WITH ASSUMED PRESSURE
      T1=TS(I)
      CTR=0.0
      CTR1=0.0
      CTR2=0.0
100   T11=T1-459.67
      IF(TYPE.GT.1.0) GO TO 110
      CALL SSVCH(P1,T11,SPVOLV,R(I),SV,H(I))
```

```
      GO TO 120
110   CALL GASCON(P1,T11,R(I))
120   A=CK*AR*DT/2.0
      B=A*(T(I-1)-TS(I)-TS(I-1))+HFGAV*AM(I-1)-DQ
      C=-(HFGAV*P1*TVOLU(I))/R(I)
      D=DSQRT(B*B-4.C*A*C)
      T2=(-B+D)/(2.0*A)
      IF(CTR.GT.0.0) GO TO 130
      IF(T2.LT.TS(I)) GO TO 50
      T1=T2
      CTR=1.0
      GO TO 100
130   ERRR=T1-T2
      IF(CTR1.GT.0.0) GO TO 150
      CTR1=1.0
140   ERRRO=ERRR
      T1=T1-DET
      IF(T1.LT.TS(I)) GO TO 50
      GO TO 100
150   IF(CTR2.GT.0.0) GO TO 160
      IF((ERRR*ERRRO).GT.0.0) GO TO 140
      ERRA=ERRR
      TA=T1
      ERRB=ERRRO
      TB=T1+DET
      CTR2=1.0
      GO TO 180
160   IF((ERRR*ERRA).LT.0.0) GO TO 170
      ERRA=ERRR
      TA=T1
      GO TO 180
170   ERRB=ERRR
      TB=T1
180   T1=TA+(TB-TA)*DABS(ERRA)/DABS(ERRB-ERRA)
      IF(DABS(ERRR).GT.ALIM1) GO TO 100
      T(I)=T1
      TF(I)=T(I)-459.67

C     ENERGY BALANCE AND EVALUATION OF ERROR

      IF(TYPE.GT.1.0) GO TO 190
      CALL SSVCH(P1,TF(I),SPVOLV,R(I),SV,H(I))
      GO TO 200
190   CALL GASCON(P1,TF(I),R(I))
      CALL HSUPH(P1,TF(I),H(I))
200   AM(I)=(P1*TVOLU(I))/(R(I)*T(I))
      EFAV=(EF(I)+EF(I-1))/2.0
      E1=(AM(I)*H(I)-AM(I-1)*H(I-1))
      E2=DQ
      E3=TVOLAV*(P1-P(I-1))*144.0/778.0
      E4=EFAV*(AM(I)-AM(I-1))
      ERR=E1+E2-E3-E4
```

```
      IF(ICOUNT.GT.0) GO TO 210
      ICOUNT=ICOUNT+1
      IF(ERR) 210,210,290
210   IF(CTR3.GT.0.0) GO TO 230
      CTR3=1.0
220   ERRO=ERR
      GO TO 50
230   IF(CTR4.GT.0.0) GO TO 250
      IF((ERR*ERRO).GT.0.0) GO TO 220
C     CALCULATION OF CORRECTED PRESSURE
      ERA=ERRO
      PA=P1-DP
      ERB=ERR
      PB=P1
      CTR4=1.0
240   P1=PA+(PB-PA)*DABS(ERA)/DABS(ERB-ERA)
      GO TO 60
250   IF((ERR*ERA).GT.0.0) GO TO 260
      ERB=ERR
      PB=P1
      GO TO 270
260   ERA=ERR
      PA=P1
270   IF(DABS(ERR).GT.ALIM2) GO TO 240
      P(I)=P1
280   CONTINUE
290   RETURN
      END
```

```
C     TITLE-COMPUTATION OF STEAM SURGE TANK TRANSIENTS DURING OUTSURGE
C     PART 1-ENTER INPUT DATA
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON AK(148)
      READ TYPE,ALO,PO,DP,DL,DIA,VOLUME,ALM,ALLIM,ALIM
      READ (AK(I),I=1,148)
C     PART 2-PRELIMINARY CALCULATIONS
      PI=4.0*DATAN(1.0D00)
      VPUL=(PI*DIA*DIA)/(4.0*1728.0)
      VLO=VOLUME/2.0+VPUL*(ALO-ALM)
      VVO=VOLUME-VLO
C     PART 3-MAIN COMPUTATION
```

```
C     CALCULATION OF INITIAL THERMODYNAMIC PROPERTIES

10    CTR1=0.0
      CTR2=0.0
      IF(TYPE.GT.1.0) GO TO 20
      TSFO=TSAT(PO)
      CALL SSWCH(PO,TSFO,VFO,SFO,HW)
      CALL SSVCH(PO,TSFO,VGO,R,SGO,HS)
      GO TO 30
20    TSFO=TSATH(PO)
      VFO=VFHS(TSFO)
      VGO=VGHS(TSFO)
      SFO=SFHS(TSFO)
      SGO=SGHS(TSFO)
30    SFGO=SGO-SFO
      AMLO=VLO/VFO
      AMVO=VVO/VGO
      QO=AMVO/(AMVO+AMLO)
      SO=SFO+QO*SFGO

C     CALCULATION OF FINAL THERMODYNAMIC PROPERTIES AND ERROR

      AL1=ALO-DL
      IF(AL1.LT.ALLIM) GO TO 130
      VV1=VVO+(ALO-AL1)*VPUL
      P1=PO
40    P1=P1-DP
50    IF(TYPE.GT.1.0) GO TO 60
      TSF1=TSAT(P1)
      CALL SSWCH(P1,TSF1,VF1,SF1,HW)
      CALL SSVCH(P1,TSF1,VG1,R,SG1,HS)
      GO TO 70
60    TSF1=TSATH(P1)
      VG1=VGHS(TSF1)
      SF1=SFHS(TSF1)
      SG1=SGHS(TSF1)
70    SFG1=SG1-SF1
      AMV1=VV1/VG1
      Q1=AMV1/(AMVO+AMLO)
      S1=SF1+Q1*SFG1
      ERR=SO-S1
      IF(CTR1.GT.0.0) GO TO 90
      CTR1=1.0
80    ERRO=ERR
      GO TO 40
90    IF(CTR2.GT.0.0) GO TO 100
      IF((ERR*ERRO).GT.0.0) GO TO 80

C     CALCULATION OF CORRECTED PRESSURE

      ERA=ERR
      PA=P1
```

```
      ERB=ERRO
      PB=P1+DP
      CTR2=1.0
      GO TO 120
100   IF((ERR*ERA).LT.0.0) GO TO 110
      ERA=ERR
      PA=P1
      GO TO 120
110   ERB=ERR
      PB=P1
120   P1=PA+(PB-PA)*DABS(ERA)/DABS(ERB-ERA)
      IF(DABS(ERR).GT.ALIM) GO TO 50
      P=P1
      PO=P
      ALO=AL1
      VVO=VV1
      VLO=VOLUME-VVO
      GO TO 10
130   RETURN
      END


C     PART 7-LISTING OF SUBPROGRAMS

      FUNCTION GWF(I,THW,PI,DT,TDIF,ALFA)

C     THIS SUBPROGRAM CALCULATES HEAT TRANSFER CONSTANTS FOR WAL-

      IMPLICIT REAL*8(A-H,O-Z)
      J=I-1
      IF(J.GT.0) GO TO 60
      CTR=0.0
      SUM=0.0
      X=0.0
10    AN=((2.0*X+1.0)*(2.0*X+1.0))*PI*PI*TDIF/(4.0*THW*THW)
      ANS=AN*DT
      IF(ANS.GT.170.0) GO TO 20
      X1=(1.0-1.0/DEXP(ANS))/AN
      GO TO 30
20    X1=1/AN
30    X1=(1.0/AN)*(DT-X1)
      SUM=SUM+X1
      IF(CTR.EQ.1.0) GO TO 40
      XO=X1
      X=X+1.0
      CTR=CTR+1.0
      GO TO 10
40    X=X+1.0
      IF(DABS(X1/SUM).LE.0.0001) GO TO 50
      GO TO 10
50    SUM=SUM*ALFA/DT
```

```
      GWF=SUM
      GO TO 100
60    CTR=0.0
      SUM=0.0
      X=0.0
70    AN=((2.0*X+1.0)*(2.0*X+1.0))*PI*PI*TDIF/(4.0*THW*THW)
      ANS=AN*DT
      X1=(DEXP(ANS)+1.0/DEXP(ANS)-2.0)/(AN*AN)
      ARG=J*ANS
      IF(ARG.GT.170.0) GO TO 90
      X1=(1.0/DEXP(ARG))*X1
      SUM=SUM+X1
      IF(CTR.EQ.1.0) GO TO 80
      X=X+1.0
      CTR=CTR+1.0
      GO TO 70
80    X=X+1.0
      IF(DABS(X1/SUM).LE.0.001) GO TO 90
      GO TO 70
90    SUM=SUM*ALFA/DT
      GWF=SUM
100   RETURN
      END

      FUNCTION HCF(I,CPWT,PI,ROWWT,DT,TDIFWT)
C     THIS SUBPROGRAM CALCULATES HEAT TRANSFER CONSTANTS FOR LIQUID
      IMPLICIT REAL*8(A-H,O-Z)
      J=I-1
      IF(J.GT.0) GO TO 10
      A=4.0*ROWWT*CPWT/3.0
      B=TDIFWT*DT/PI
      C=DSQRT(B)
      HCF=A*C
      GO TO 20
10    A=4.0*ROWWT*CPWT/3.0
      B=TDIFWT*DT/PI
      C=DSQRT(B)
      D=(J-1)**1.5+(J+1)**1.5-2.0*(J**1.5)
      HCF=A*C*D
20    RETURN
      END

C     LIGHT WATER SUBPROGRAMS

      FUNCTION TSAT(P)
C     THIS SUBPROGRAM FINDS SATURATION TEMPERATURE IN DEGREES F FROM
C     PRESSURE IN PSIA FOR LIGHT WATER
```

```
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON AK(148)
      Y=P
      X0=117.0936*P**.222536
      EPS=1D-07*P
      IT=0
      Y0=PSAT(X0,AK)
      IF(DABS(Y-Y0).LE.EPS) GO TO 106
      X1=X0+X0*5D-5
      Y1=PSAT(X1,AK)
      DIF1=Y-Y1
      SLOPE=(Y1-Y0)/(X1-X0)
      X2=X0
100   Y2=PSAT(X2,AK)
      DIF2=Y-Y2
      IF(DABS(DIF2).LE.EPS) GO TO 107
      IT=IT+1
      IF(IT.GT.30) GO TO 108
      SLOPE=(Y2-Y1)/(X2-X1)
      IF(DIF1*DIF2)101,101,105
101   X3=(X1+X2)/2.0
      Y3=PSAT(X3,AK)
      DIF3=Y-Y3
      IF(DABS(DIF3).LE.EPS) GO TO 109
      IF(DIF1*DIF3)102,102,103
102   DIF2=DIF3
      Y2=Y3
      X2=X3
103   IF(DIF2*DIF3)104,104,100
104   DIF1=DIF3
      Y1=Y3
      X1=X3
      GO TO 100
105   X1=X2
      Y1=Y2
      DIF1=DIF2
      X2=X1+DIF1/SLOPE
      GO TO 100
106   TSAT=X0
      RETURN
107   TSAT=X2
      RETURN
108   TSAT=X0
      RETURN
109   TSAT=X3
      RETURN
      END

      FUNCTION PSAT(TF)
C     THIS SUBPROGRAM FINDS LIGHT WATER SATURATION PRESSURE IN PSIA AS A
C     FUNCTION OF TEMPERATURE IN DEGREES F
```

```
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON AK(148)
      PCON=2.212D7*2.54*2.54D-4/(9.80655*0.45359237)
      TCON=647.3*1.8
      THETA=(TF+459.67)/TCON
      THET=1.0-THETA
      SIGK=0.0
      DO 10  J=1,5
10    SIGK=SIGK+AK(J)*(THET**J)
      A=1.0+AK(6)*THET+AK(7)*(THET**2.0)
      AA=SIGK/(THETA*A)
      B=AK(8)*(THET**2.0)+AK(9)
      BB=THET/B
      BRAK=AA-BB
      BK=DEXP(BRAK)
      PSAT=BK*PCON
      RETURN
      END

      SUBROUTINE SSWCH(P,TF,VOL,S,H)

C     THIS SUBPROGRAM CALCULATES THE SPECIFIC VOLUME,ENTROPY,ENTHALPY OF
C     LIQUID LIGHT WATER AS FUNCTIONS OF PRESSURE IN PSIA AND
C     TEMPERATURE IN DEGREES F

      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER V
      COMMON AK(148)
      PCON=2.212D7*2.54*2.54D-4/(9.80665*0.45359237)
      TCON=647.3*1.8
      VCON=3.17D-03*.45359237/(.3048**3)
      SCON=2.212D07*3.17D-03/(647.3*4186.8)
      HCON=2.212D07*3.17D-03/2326.0
      T=TF+459.67
      BETA=P/PCON
      THETA=T/TCON
      THET=1.0-THETA
      SIGK=0.0
      DO 100  J=1,5
100   SIGK=SIGK+AK(J)*(THET**J)
      A=1.0+AK(6)*THET+AK(7)*(THET**2.0)
      AA=SIGK/(THETA*A)
      B=AK(8)*(THET**2.0)+AK(9)
      BB=THET/B
      BRAK=AA-BB
      BK=DEXP(BRAK)
      IF(BK-BETA.LE.1D-7) GO TO 102
101   VOL=1.0D24
      S=1.0D24
      H=1.0D24
      RETURN
102   THET1=0.9626911787
```

```
      IF(THETA.LE.THET1) GO TO 200
      IF(THETA.GT.1.0) GO TO 101
      DF=0.25
      IF(THETA.LT.1.0) GO TO 103
      GO TO 104
103   P1=BK-2D-7
      GO TO 105
104   P1=1.0
105   IF(BETA.LT.P1) GO TO 106
      GO TO 107
106   V0=0.3*(TF+459.67)/P
      GO TO 108
107   V0=(0.077+92.8/P)*(TF-482.0)/(TF+58.0)
108   CHI4=V0/VCON
      ICOUNT=0
      V2=V0
109   B3CHI=BETA3(CHI4,THETA)
      B4CHI=BETA4(CHI4,THETA)
      BET4=B3CHI+B4CHI
      ICOUNT=ICOUNT+1
      IF(ICOUNT.GT.50) RETURN
      IF(DABS((BETA-BET4)/BETA).GT.1D-07) GO TO 110
      GO TO 116
110   P2=BET4*PCON
      IF(ICOUNT.EQ.1) GO TO 111
      GO TO 112
111   P1=P2
      DELV=DF*V0*(P1-P)/P
      V1=V0+DELV
      CHI4=V1/VCON
      GO TO 109
112   IF((P-P2)*(P-P1))113,113,114
113   DF=0.6*DF
      GO TO 115
114   DF=1.5*DF
115   DELV=DF*(V2-V1)*(P-P2)/(P2-P1)
      V1=V2
      V2=V1+DELV
      CHI4=V2/VCON
      P1=P2
      GO TO 109
116   VOL=CHI4*VCON
      CALL SIGEP3(CHI4,THETA,SIG3,EPS3)
      CALL SIGEP4(CHI4,THETA,SIG4,EPS4)
      S=(SIG3+SIG4)*SCON
      H=(EPS3+EPS4)*HCON
      RETURN
C     THIS ENDS SUBREGION 4-FOLLOWING IS SUBREGION 1
200   Y=1.0-AK(33)*THETA**2-AK(34)/THETA**6
      Z=Y+DSQRT(AK(35)*Y**2-2*AK(36)*THETA+2*AK(37)*BETA)
      Y1=-2*AK(33)*THETA+6*AK(34)*THETA**(-7)
      FRAC=-5.0/17.0
```

```
      CHI=AK(21)*AK(37)*Z**FRAC+AK(22)+AK(23)*THETA+AK(24)*THETA**2
     2+AK(25)*(AK(38)-THETA)**10+AK(26)/(AK(39)+THETA**19)
     3-(AK(27)+2*AK(28)*BETA+3*AK(29)*BETA**2)/(AK(40)+THETA**11)
     4-AK(30)*THETA**18*(AK(41)+THETA**2)*(-3*(AK(42)+BETA)**(-4)
     5+AK(43))+3*AK(31)*(AK(44)-THETA)*BETA**2
     6+4*AK(32)*BETA**3/THETA**20
      VOL=CHI*VCON
      SIG=0.0
      DO 201 I=12,20
201   SIG=SIG+(I-11)*AK(I)*THETA**(I-12)
      SIG1=AK(10)*DLOG(THETA)-SIG+AK(21)*((5.0*Z/12.0-(AK(35)-1)*Y)*Y1
     2+AK(36))*Z**FRAC+(-AK(23)-2*AK(24)*THETA+10*AK(25)*(AK(38)-THETA)
     3**9+19*AK(26)*(AK(39)+THETA**19)**(-2)*THETA**18)*BETA-11*(AK(40)
     4+THETA**11)**(-2)*THETA**10*(AK(27)*BETA+AK(28)*BETA**2+AK(29)*
     5BETA**3)+AK(30)*THETA**17*(18*AK(41)+20*THETA**2)*((AK(42)+BETA)
     6**(-3)+AK(43)*BETA)+AK(31)*BETA**3+20*AK(32)*BETA**4/THETA**21
      S=SIG1*SCON
      SIG=0.0
      DO 202 I=11,20
202   SIG=SIG+(I-12)*AK(I)*THETA**(I-11)
      EPS=AK(10)*THETA-SIG+AK(21)*(Z*(17.0*(Z/29.0-Y/12.0)+5.0*THETA*Y1/
     2     12.0)+AK(36)*THETA-(AK(35)-1)*THETA*Y*Y1)*Z**FRAC
     3+(AK(22)-AK(24)*THETA**2+AK(25)*(9*THETA+AK(38))*(AK(38)-THETA)**9
     4+AK(26)*(20*THETA**19+AK(39))*(AK(39)+THETA**19)**(-2))*BETA
     5-(12*THETA**11+AK(40))*(AK(40)+THETA**11)**(-2)*(AK(27)*BETA+
     6AK(28)*BETA**2+AK(29)*BETA**3)+AK(30)*THETA**18*(17*AK(41)+19*
     7THETA**2)*((AK(42)+BETA)**(-3)+AK(43)*BETA)+AK(31)*AK(44)*BETA**3+
     821*AK(32)*THETA**(-20)*BETA**4
      H=EPS*HCON
      RETURN
      END

      SUBROUTINE SSVCH(P,TF,VOL,R,S,H)
C     THIS SUBPROGRAM CALCULATES THE SPECIFIC VOLUME,GAS CONSTANT,
C     ENTROPY,ENTHALPY FOR SATURATED OR SUPERHEATED LIGHT WATER VAPOR
C     FROM PRESSURE IN PSIA AND TEMPERATURE IN DEGREES F

      IMPLICIT REAL*8(A-H,O-Z)
      REAL L1,L2,I1,NUM
      INTEGER V
      DIMENSION N(8),L(8),Z(8,3),X(8,2),SIG(14),F(3,3),G(3,3)
      COMMON AK(148)
      PCON=2.212D7*2.54*2.54D-4/(9.80665*0.45359237)
      TCON=647.3*1.8
      VCON=3.17D-03*.45359237/(.3048**3)
      SCON=2.212D07*3.17D-03/(647.3*4186.8)
      HCON=2.212D07*3.17D-03/2326.0
      T=TF+459.67
      BETA=P/PCON
      THETA=T/TCON
      THET1=0.9626911787
```

```
      THET=1.0-THETA
      SIGK=0.0
      DO 100 J=1,5
100   SIGK=SIGK+AK(J)*(THET**J)
      A=1.0+AK(6)*THET+AK(7)*THET*THET
      AA=SIGK/(THETA*A)
      B=AK(8)*THET*THET+AK(9)
      BB=THET/B
      BRAK=AA-BB
      BK=DEXP(BRAK)
      L1=-34.17061978
      L2=19.31380707
      BETL=15.74373327+L1*THETA+L2*THETA**2
      BETL1=L1+2*L2*THETA
      BETL2=2*L2
      N(1)=2
      N(2)=3
      N(3)=2
      N(4)=2
      N(5)=3
      N(6)=2
      N(7)=2
      N(8)=2
      Z(1,1)=13.0
      Z(2,1)=18.0
      Z(3,1)=18.0
      Z(4,1)=25.0
      Z(5,1)=32.0
      Z(6,1)=12.0
      Z(7,1)=24.0
      Z(8,1)=24.0
      Z(1,2)=3.0
      Z(2,2)=2.0
      Z(3,2)=10.0
      Z(4,2)=14.0
      Z(5,2)=28.0
      Z(6,2)=11.0
      Z(7,2)=18.0
      Z(8,2)=14.0
      Z(2,3)=1.0
      Z(5,3)=24.0
      L(6)=1
      L(7)=1
      L(8)=2
      X(6,1)=14.0
      X(7,1)=19.0
      X(8,1)=54.0
      X(8,2)=27.0
      B=AK(76)
      XO=DEXP(B*(1.0-THETA))
      I1=4.260321148
      IF(THETA.GE.THET1) GO TO 102
```

```
      IF(BETA-BK.LE.1D-7) GO TO 200
101   VOL=1.0D24
      R=1.0D24
      S=1.0D24
      H=1.0D24
      RETURN
102   IF(BETA.LE.BETL) GO TO 200
      IF(THETA.GE.1.0) GO TO 103
      IF(BETA-BK.GT.1D-7) GO TO 101
103   DF=0.25
      IF(THETA.LT.1.0) GO TO 104
      GO TO 105
104   P1=BK+2D-7
      GO TO 106
105   P1=1.0
106   IF(BETA.LT.P1) GO TO 107
      GO TO 108
107   V0=0.3*(TF+459.67)/P
      GO TO 109
108   V0=(0.077+92.8/P)*(TF-482.0)/(TF+58.0)
109   CHI3=V0/VCON
      ICOUNT=0
      V2=V0
110   BET3=BETA3(CHI3,THETA)
      ICOUNT=ICOUNT+1
      IF(ICOUNT.GT.50) RETURN
      IF(DABS((BETA-BET3)/BETA).GT.1D-07) GO TO 111
      GO TO 117
111   P2=BET3*PCON
      IF(ICOUNT.EQ.1) GO TO 112
      GO TO 113
112   P1=P2
      DELV=DF*V0*(P1-P)/P
      V1=V0+DELV
      CHI3=V1/VCON
      GO TO 110
113   IF((P-P2)*(P-P1))114,114,115
114   DF=0.6*DF
      GO TO 116
115   DF=1.5*DF
116   DELV=DF*(V2-V1)*(P-P2)/(P2-P1)
      V1=V2
      V2=V1+DELV
      CHI3=V2/VCON
      P1=P2
      GO TO 110
117   VOL=CHI3*VCON
      R=P*VOL/T
      CALL SIGEP3(CHI3,THETA,S3,EPS3)
      S=S3*SCON
      H=EPS3*HCON
      RETURN
```

```
C     THIS ENDS SUBREGION 3-FOLLOWING IS SUBREGION 2
200   I=50
      J=76
      CALL ZERO(SIG,14)
      DO 202 MU=1,5
      SIG(1)=0.0
      NMU=N(MU)
      DO 201 V=1,NMU
      I=I+1
201   SIG(1)=SIG(1)+AK(I)*XO**Z(MU,V)
202   SIG(2)=SIG(2)+MU*BETA**(MU-1)*SIG(1)
      DO 205 MU=6,8
      SIG(3)=0.0
      SIG(4)=0.0
      NMU=N(MU)
      DO 203 V=1,NMU
      I=I+1
203   SIG(4)=SIG(4)+AK(I)*XO**Z(MU,V)
      NUM=(MU-2)*BETA**(1-MU)*SIG(4)
      LMU=L(MU)
      DO 204 LAM=1,LMU
      J=J+1
204   SIG(3)=SIG(3)+AK(J)*XO**X(MU,LAM)
      DEN=(BETA**(2-MU)+SIG(3))**2
205   SIG(5)=SIG(5)+NUM/DEN
      DO 206 V=1,7
      I=I+1
206   SIG(6)=SIG(6)+AK(I)*XO**(V-1)
      CHI=I1*THETA/BETA-SIG(2)-SIG(5)+I1*(BETA/BETL)**10*SIG(6)
      VOL=CHI*VCON
      R=P*VOL/T
      CALL ZERO (SIG,14)
      I=45
      J=76
      DO 207 V=1,5
      I=I+1
      SIG(9)=SIG(9)+(V-2)*AK(I)*THETA**(V-1)
207   SIG(1)=SIG(1)+(V-1)*AK(I)*THETA**(V-2)
      DO 209 MU=1,5
      SIG(2)=0.0
      SIG(10)=0.0
      NMU=N(MU)
      DO 208 V=1,NMU
      I=I+1
      SIG(10)=SIG(10)+AK(I)*(1+Z(MU,V)*B*THETA)*XO**Z(MU,V)
208   SIG(2)=SIG(2)+Z(MU,V)*AK(I)*XO**Z(MU,V)
      SIG(11)=SIG(11)+BETA**MU*SIG(10)
209   SIG(3)=SIG(3)+BETA**MU*SIG(2)
      DO 212 MU=6,8
      SIG(4)=0.0
      SIG(5)=0.0
      SIG(6)=0.0
```

```
      SIG(12)=0.0
      LMU=L(MU)
      DC 210 LAM=1,LMU
      J=J+1
      TERM=AK(J)*XO**X(MU,LAM)
      SIG(5)=SIG(5)+TERM
210   SIG(6)=SIG(6)+TERM*X(MU,LAM)
      DENOM=BETA**(2-MU)+SIG(5)
      NMU=N(MU)
      DO 211 V=1,NMU
      I=I+1
      SIG(12)=SIG(12)+AK(I)*XO**Z(MU,V)*(1+Z(MJ,V)*B*THETA-B*THETA*
     2SIG(6)/DENOM)
211   SIG(4)=SIG(4)+AK(I)*XO**Z(MU,V)*(Z(MU,V)-SIG(6)/DENOM)
      SIG(13)=SIG(13)+SIG(12)/DENOM
212   SIG(7)=SIG(7)+SIG(4)/DENOM
      DO 213 V=1,7
      I=I+1
      SIG(14)=SIG(14)+(1+THETA*(10*BETL1/BETL+(V-1)*B))*AK(I)*XO**(V-1)
213   SIG(8)=SIG(8)+(10*BETL1/BETL+(V-1)*B)*AK(I)*XO**(V-1)
      S2=-I1*DLOG(BETA)+AK(45)*DLOG(THETA)-SIG(1)-B*SIG(3)-B*SIG(7)+
     2BETA*(BETA/BETL)**10*SIG(8)
      S=S2*SCON
      EPS=AK(45)*THETA-SIG(9)-SIG(11)-SIG(13)+BETA*(BETA/BETL)**1)*
     2SIG(14)
      H=EPS*HCON
      RETURN
      END

      FUNCTION BETA4(CHI,THETA)

C     THIS SUBPROGRAM IS CALLED BY SSWCH

      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER V
      COMMON AK(148)
      THET1=0.9626911787
      THET=1.0-THET1
      YT=(1.0-THETA)/THET
      I=135
      SIGMA1=0.0
      SIGMA2=0.0
      DO 100 MU=3,4
      DO 100 V=1,5
      I=I+1
100   SIGMA1=SIGMA1+(V-1)*AK(I)*YT**MU*CHI**(-V)
      DO 101 V=1,3
      I=I+1
101   SIGMA2=SIGMA2+(V-1)*AK(I)*CHI**(V-2)
      BETA4=SIGMA1-YT**32*SIGMA2
      RETURN
      END
```

```
      SUBROUTINE SIGEP4(CHI,THETA,SIG,EPS)
C     THIS SUBPROGRAM IS CALLED BY SSWCH
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER V
      COMMON AK(148)
      THET1=0.9626911787
      THET=1.0-THET1
      Y=(1.0-THETA)/THET
      S1=0.0
      S2=0.0
      S3=0.0
      S4=0.0
      I=135
      DO 100 MU=3,4
      DO 100 V=1,5
      I=I+1
      S1=S1+MU*AK(I)*Y**(MU-1.0)/CHI**(V-1)
100   S3=S3+AK(I)*((1.0-MU+(V-1))*Y+MU/THET)*Y**(MU-1.0)/CHI**(V-1)
      DO 101 V=1,3
      I=I+1
      S2=S2+AK(I)*CHI**(V-1)
101   S4=S4+AK(I)*((31.0+(V-1))*Y-32.0/THET)*CHI**(V-1)
      SIG=(S1+32.0*Y**31*S2)/THET
      EPS=S3-Y**31*S2
      RETURN
      END
      FUNCTION BETA3(CHI,THETA)
C     THIS SUBPROGRAM IS CALLED BY SSWCH AND SSVCH
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER V
      DIMENSION COEF(4)
      COMMON AK(148)
      I=82
      SIGMA=0.0
      DO 100 V=2,11
      I=I+1
100   SIGMA=SIGMA+(1.0-V)*AK(I)*CHI**(-V)
      COEF(1)=AK(82)+SIGMA+AK(93)/CHI
      I=94
      SIGMA=0.0
      DO 101 V=2,6
      I=I+1
101   SIGMA=SIGMA+(1.0-V)*AK(I)*CHI**(-V)
      COEF(2)=AK(94)+SIGMA+AK(100)/CHI
      I=101
      SIGMA=0.0
      DO 102 V=2,7
```

```
      I=I+1
102   SIGMA=SIGMA+(1.0-V)*AK(I)*CHI**(-V)
      COEF(3)=AK(101)+SIGMA+AK(108)/CHI
      I=109
      SIGMA=0.0
      DO 103 V=2,9
      I=I+1
103   SIGMA=SIGMA+(1.0-V)*AK(I)*CHI**(-V)
      COEF(4)=AK(109)+SIGMA+AK(118)/CHI
      I=121
      SIGMA=0.0
      DO 104 V=1,5
      I=I+1
104   SIGMA=SIGMA+AK(I)*THETA**(-1-V)
      BET3=0.0
      DO 105 I=1,4
105   BET3=BET3-COEF(I)*(THETA-1.0)**(I-1)
      BETA3=BET3+5.0*AK(120)/CHI**6/THETA**23*(THETA-1.0)-6*CHI**5*SIGMA
      RETURN
      END

      SUBROUTINE SIGEP3(CHI,THETA,SIG,EPS)

C     THIS SUBPROGRAM IS CALLED BY SSWCH AND SSVCH

      IMPLICIT REAL*8(A-H,O-Z)
      REAL LNX
      INTEGER V
      DIMENSION COEF(4)
      COMMON AK(148)
      LNX=DLOG(CHI)
      THETM1=THETA-1.0
      I=94
      S=0.0
      DO 100 V=2,6
      I=I+1
100   S=S+AK(I)*CHI**(1-V)
      COEF(1)=AK(94)*CHI+S+AK(100)*LNX+AK(121)
      I=101
      S=0.0
      DO 101 V=2,7
      I=I+1
101   S=S+AK(I)*CHI**(1-V)
      COEF(2)=AK(101)*CHI+S+AK(108)*LNX
      I=109
      S=0.0
      DO 102 V=2,9
      I=I+1
102   S=S+AK(I)*CHI**(1-V)
      COEF(3)=AK(109)*CHI+S+AK(118)*LNX
      I=121
      S=0.0
```

```
      DO 103 V=1,5
      I=I+1
103   S=S+(V+1)*AK(I)*THETA**(-2-V)
      COEF(4)=(AK(119)+AK(120)/CHI**5)*(22.0/THETA**23-23.0/THETA**24)-
     2AK(121)*DLOG(THETA)+CHI**6*S
      I=126
      S=0.0
      DO 104 V=1,9
      I=I+1
104   S=S+V*AK(I)*THETM1**(V-1)
      SIG=-COEF(1)-2*COEF(2)*THETM1-3*COEF(3)*THETM1**2+COEF(4)-S
      S1=0.0
      S2=0.0
      S3=0.0
      I=82
      DO 105 V=2,11
      I=I+1
105   S1=S1+V*AK(I)*CHI**(1-V)
      I=94
      DO 106 V=2,6
      I=I+1
      TERM=AK(I)*CHI**(1-V)
      S2=S2+TERM
106   S3=S3+(V-1)*TERM
      COEF(1)=AK(81)-AK(93)-AK(121)-AK(94)*CHI+S1-S2+
     2(AK(93)-AK(100))*LNX
      S1=0.0
      S2=0.0
      I=101
      DO 107 V=2,7
      I=I+1
      TERM=AK(I)*CHI**(1-V)
      S1=S1+TERM
107   S2=S2+(V-2)*TERM
      COEF(2)=-AK(100)-AK(121)-(AK(94)+2*AK(101))*CHI+S3-2*S1-2*AK(108)*
     2LNX
      S1=0.0
      S3=0.0
      I=109
      DO 108 V=2,9
      I=I+1
      TERM=AK(I)*CHI**(1-V)
      S1=S1+TERM
108   S3=S3+(V-3)*TERM
      COEF(3)=-AK(108)-(2*AK(101)+3*AK(109))*CHI+S2-3*S1-
     2(AK(108)+3*AK(118))*LNX
      COEF(4)=-AK(118)-3*AK(109)*CHI+S3-2*AK(118)*LNX
      S1=0.0
      S2=0.0
      I=121
      DO 109 V=1,5
      I=I+1
```

```
109   S1=S1+(V-4)*AK(I)*THETA**(-1-V)
      I=126
      DO 110 V=1,9
      I=I+1
110   S2=S2+AK(I)*(1+(V-1)*THETA)*(THETA-1)**(V-1)
      EPS=COEF(1)+COEF(2)*THETM1+COEF(3)*THETM1**2+COEF(4)*THETM1**3+
     2(23*AK(119)+28*AK(120)/CHI**5)/THETA**22-
     3(24*AK(119)+29*AK(120)/CHI**5)/THETA**23+CHI**6*S1-S2
      RETURN
      END

      SUBROUTINE ZERC(A,N)

C     THIS SUBPROGRAM IS CALLED BY SSVCH

      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(N)
      DO 100 I=1,N
100   A(I)=0.0
      RETURN
      END


C     HEAVY WATER SUBPROGRAMS

      FUNCTION TSATH(P)

C     THIS SUBPROGRAM CALCULATES THE SATURATION TEMPERATURE OF HEAVY
C     WATER IN DEGREES F FROM PRESSURE IN PSIA

      IMPLICIT REAL*8(A-H,O-Z)
      IF(P.LT.14.0D00) GO TO 10
      IF(P.GT.2500.0D00) GO TO 10
      A1=-6.58561091040D+00
      A2=+1.87240384107D+01
      A3=-1.29574409864D+01
      A4=+5.10086616666D+00
      A5=-1.23565803067D+00
      A6=+1.88794263773D-01
      A7=-1.77857078269D-02
      A8=+9.45540387910D-04
      A9=-2.17388691161D-05
      Y=DLOG(P)
      TT=A1+A2*Y+A3*(Y**2.0)+A4*(Y**3.0)+A5*(Y**4.0)+A6*(Y**5.0)
     2+A7*(Y**6.0)+A8*(Y**7.0)+A9*(Y**8.0)
      TSATH=DEXP(TT)
      GO TO 20
10    TSATH=1.0D24
20    RETURN
      END
```

```
      SUBROUTINE HWFGG(T,HW,HFG,HG)
C     THIS SUBPROGRAM CALCULATES THE ENTHALPY OF SATURATED HEAVY WATER
C     LIQUID,ENTHALPY OF SATURATED HEAVY WATER VAPOR,ENTHALPY OF
C     EVAPORATION,FROM TEMPERATURE IN DEGREES F
      IMPLICIT REAL*8(A-H,O-Z)
      IF(T.GT.650.0DC0) GO TO 10
      IF(T.LT.38.87DC0) GO TO 10
      A1=+1.09756189545D+00
      A2=-3.65834284890D-03
      A3=+5.99232807099D-05
      A4=-5.28096826462D-07
      A5=+2.68896315218D-09
      A6=-8.20701662323D-12
      A7=+1.48661726141D-14
      A8=-1.46721315339D-17
      A9=+6.06444994345D-21
      T1=300.0D00
      H0=260.82D00
      HH=A1*T1+A2*T1**2.0/2.0+A3*T1**3.0/3.0+A4*T1**4.0/4.0
     2+A5*T1**5.0/5.0+A6*T1**6.0/6.0+A7*T1**7.0/7.0+A8*T1**8.0/8.0
     3+A9*T1**9.0/9.0
      HR=A1*T+A2*T**2.0/2.0+A3*T**3.0/3.0+A4*T**4.0/4.0+A5*T**5.0/5.0+
     2A6*T**6.0/6.0+A7*T**7.0/7.0+A8*T**8.0/8.0+A9*T**9.0/9.0
      HW=H0+HR-HH
      HFG=FHFG(T)
      HG=HW+HFG
      GO TO 20
10    HW=1.0D24
      HFG=1.0D24
      HG=1.0D24
20    RETURN
      END

      FUNCTION FHFG(T)
C     THIS SUBPROGRAM CALCULATES ENTHALPY OF EVAPORATION OF HEAVY WATER
C     VAPOR FROM TEMPERATURE IN DEGREES F
      IMPLICIT REAL*8(A-H,O-Z)
      IF(T.LT.38.87D00) GO TO 10
      IF(T.GT.676.0D00) GO TO 10
      A1=+1.02241411330D+03
      A2=-6.80619179830D-01
      A3=+1.28538007346D-03
      A4=-8.32005197703D-06
      A5=+1.43628092040D-08
      A6=+5.11995932468D-11
      A7=-2.63108288895D-13
      A8=+4.01240243092D-16
      A9=-2.14120030794D-19
```

```
      FHFG=A1+A2*T+A3*T**2.0+A4*T**3.0+A5*T**4.0+A6*T**5.0+A7*T**5.0
     2+A8*T**7.0+A9*T**8.0
      GO TO 20
10    FHFG=1.0D24
20    RETURN
      END

      SUBROUTINE GASCON(P,T,R)

C     THIS SUBPROGRAM CALCULATES THE GAS CONSTANT FOR SATJRATED OR
C     SUPERHEATED HEAVY WATER VAPOR FROM PRESSURE IN PSIA AND
C     TEMPERATURE IN DEGREES F

      IMPLICIT REAL*8(A-H,O-Z)
      TSATU=TSATH(P)
      IF(T.GT.TSATU) GO TO 10
      V=VGHS(T)
      TDR=T+459.67
      R=P*V/TDR
      GO TO 20
10    CALL VGHSUP(P,T,V)
      TDR=T+459.67
      R=P*V/TDR
20    RETURN
      END

      FUNCTION VGHS(T)

C     THIS SUBPROGRAM CALCULATES THE SPECIFIC VOLUME OF SATURATED HEAVY
C     WATER VAPOR FRCM TEMPERATURE IN DEGREES F

      IMPLICIT REAL*8(A-H,O-Z)
      IF(T.LT.200.0D00) GO TO 20
      IF(T.GT.700.0D00) GO TO 20
      IF(T.GT.450.0D00) GO TO 10
      A1=+2.62026119913D+03
      A2=-5.36239564980D+01
      A3=+4.98816254589D-01
      A4=-2.71660775487D-03
      A5=+9.39161072329D-06
      A6=-2.09832794292D-08
      A7=+2.94718902985D-11
      A8=-2.37253980530D-14
      A9=+8.36435551823D-18
      VGHS=A1+A2*T+A3*T**2.0+A4*T**3.0+A5*T**4.0+A6*T**5.0+A7*T**5.0
     2+A8*T**7.0+A9*T**8.0
      GO TO 30
10    A1=+0.964882897923569D+02
      A2=-0.7407490357647129D+00
      A3=+0.225084857823848 6D-02
      A4=-0.304714124543416 4D-05
      A5=+0.711275297921725 6D-09
```

```
      A6=+0.2931668190719946D-11
      A7=-0.3395243546479802D-14
      A8=+0.1278556244024743D-17
      A9=-0.8695366316325546D-22
      VGHS=A1+A2*T+A3*T**2.0+A4*T**3.0+A5*T**4.0+A6*T**5.0+A7*T**5.0
     2+A8*T**7.0+A9*T**8.0
      GO TO 30
20    VGHS=1.0D24
30    RETURN
      END

      SUBROUTINE VGHSUP(P,T,VSUPH)

C     THIS SUBPROGRAM CALCULATES THE SPECIFIC VOLUME OF SUPERHEATED
C     HEAVY WATER VAPOR FROM PRESSURE IN PSIA AND TEMPERATURE IN
C     DEGREES F

      IMPLICIT REAL*8(A-H,O-Z)
      TSL=TSAT(P)
      TSH=TSATH(P)
      SUPHET=T-TSH
      TL=TSL+SUPHET
      CALL SSVCH(P,TSL,VOLSAT,RE,S,HSL)
      CALL SSVCH(P,TL,VOLSUP,RE,S,HL)
      VOLSH=VGHS(TSH)
      VSUPH=VOLSH+VOLSUP-VOLSAT
      RETURN
      END

      SUBROUTINE HSUPH(P,T,HSUPHV)

C     THIS SUBPROGRAM CALCULATES THE ENTHALPY OF SUPERHEATED HEAVY WATER
C     VAPOR FROM PRESSURE IN PSIA AND TEMPERATURE IN DEGREES F

      IMPLICIT REAL*8(A-H,O-Z)
      TSL=TSAT(P)
      TSH=TSATH(P)
      SUPHET=T-TSH
      TL=TSL+SUPHET
      CALL SSVCH(P,TSL,VOL,RRR,S,HSL)
      CALL SSVCH(P,TL,VOL,RRR,S,HL)
      CALL HWFGG(TSH,HWW,HFGG,HSH)
      HSUPHV=HSH+HL-HSL
      RETURN
      END

      FUNCTION VFHS(T)

C     THIS SUBPROGRAM CALCULATES THE SPECIFIC VOLUME OF SATURATED HEAVY
C     WATER LIQUID FROM TEMPERATURE IN DEGREES F

      IMPLICIT REAL*8(A-H,O-Z)
```

```
      IF(T.LT.50.0D00) GO TO 10
      IF(T.GT.700.0D00) GO TO 10
      A1=+5.3324332193CD+01
      A2=+7.1038074522OD-01
      A3=-1.2068356519 7D-02
      A4=+1.02825317618D-04
      A5=-4.96776568262D-07
      A6=+1.40552776986D-09
      A7=-2.30150062395D-12
      A8=+2.01527475558D-15
      A9=-7.29128246400D-19
      D=A1+A2*T+A3*T**2.0+A4*T**3.0+A5*T**4.0+A6*T**5.0+A7*T**6.0
     2+A8*T**7.0+A9*T**8.0
      VFHS=1.0/D
      GO TO 20
10    VFHS=1.0D24
20    RETURN
      END

      FUNCTION SFHS(T)

C     THIS SUBPROGRAM CALCULATES THE SPECIFIC ENTROPY OF SATURATED HEAVY
C     WATER LIQUID FROM TEMPERATURE IN DEGREES F

      IMPLICIT REAL*8(A-H,O-Z)
      IF(T.LT.200.0D00) GO TO 10
      IF(T.GT.650.0D00) GO TO 10
      A1=+0.287831799118848 2D+01
      A2=-0.634730265806833 0D-01
      A3=+0.619540127356233 2D-03
      A4=-0.328331547445883 0D-05
      A5=+0.106010178976482 3D-07
      A6=-0.214203017687505 7D-10
      A7=+0.264974341101346 7D-13
      A8=-0.183716193723406 9D-16
      A9=+0.547363388032233 6D-20
      SFHS=A1+A2*T+A3*T**2.0+A4*T**3.0+A5*T**4.0+A6*T**5.0+A7*T**6.0
     2+A8*T**7.0+A9*T**8.0
      GO TO 20
10    SFHS=1.0D24
20    RETURN
      END

      FUNCTION SGHS(T)

C     THIS SUBPROGRAM CALCULATES THE SPECIFIC ENTROPY OF SATURATED HEAVY
C     WATER VAPOR FROM TEMPERATURE IN DEGREES F

      IMPLICIT REAL*8(A-H,O-Z)
      IF(T.LT.200.0D00) GO TO 10
      IF(T.GT.650.0D00) GO TO 10
      A1=-0.217789537695950 7D+01
```

```
      A2=+0.864393956550905OD-01
      A3=-0.794509261580329 5D-03
      A4=+0.39673701620437 13D-05
      A5=-0.12013411673397 06D-07
      A6=+0.2271032544161674D-10
      A7=-0.262528972774311 4D-13
      A8=+0.170050703576580 7D-16
      A9=-0.47367962268690 78D-20
      SGHS=A1+A2*T+A3*T**2.0+A4*T**3.0+A5*T**4.0+A6*T**5.0+A7*T**6.0
     2+A8*T**7.0+A9*T**8.0
      GO TO 20
10    SGHS=1.0D24
20    RETURN
      END
```

LISTING OF DIGITAL ARRAY AK(148),(ROW-WISE STORAGE)

-0.7691234564D 01	-0.2608023696D 02	-0.1681706546D 03	0.6423285504D 02
-0.1189646225D 03	0.4167117320D 01	0.2097506760D 02	0.1000000000D 10
0.6000000000D 01	0.6824687741D 04	-0.5422063673D 03	-0.2096556205D 05
0.3941286787D 05	-0.6733277739D 05	0.9902381028D 05	-0.1093911774D 06
0.8590841667D 05	-0.4511168742D 05	0.1418138926D 05	-0.2017271113D 04
0.7982692717D 01	-0.2616571843D-01	0.1522411790D-02	0.2284279054D-01
0.2421647003D 03	0.1269716088D-09	0.2074838328D-06	0.2174020350D-07
0.1105710498D-08	0.1293441934D 02	0.1308119072D-04	0.6047526338D-13
0.8438375405D 00	0.5362162162D-03	0.1720000000D 01	0.7342278489D-01
0.4975858870D-01	0.6537154300D 00	0.1150000000D-05	0.1510800000D-04
0.1418800000D 00	0.7002753165D 01	0.2995284926D-03	0.2040000000D 00
0.1683599274D 02	0.2856067796D 02	-0.5438923329D 02	0.4330662834D 00
-0.6547711697D 00	0.8565182058D-01	0.6670375913D-01	0.1388983801D 01
0.8390104328D-01	0.2614670893D-01	-0.3373439453D-01	0.4520918904D 00
0.1069036614D 00	-0.5975336707D 00	-0.8847535804D-01	0.5958051609D 00
-0.5159303373D 00	0.2075021122D 00	0.1190510271D 00	-0.9867174132D-01
0.1683998803D 00	-0.5809438001D-01	0.6552390126D-02	0.5710218649D-03
0.1936587558D 03	-0.1388522425D 04	0.4126607219D 04	-0.6508211677D 04
0.5745984054D 04	-0.2693088365D 04	0.5235718523D 03	0.7633333333D 00
0.4006073948D 00	0.8636081627D-01	-0.8532322921D 00	0.3460208651D 00
-0.6839900000D 01	-0.1722604200D-01	-0.7771750390D 01	0.4204607520D 01
-0.2768070380D 01	0.2104197070D 01	-0.1146495880D 01	0.2231380350D 00
0.1162503630D 00	-0.8209005440D-01	0.1941292390D-01	-0.1694705760D-02
-0.4311577033D 01	0.7086360850D 00	0.1236794550D 02	-0.1203890040D 02
0.5404374220D 01	-0.9938650430D 00	0.6275231820D-01	-0.7747430160D 01
-0.4298850920D 01	0.4314305380D 02	-0.1416193130D 02	0.4041724590D 01
0.1555463260D 01	-0.1665689350D 01	0.3248811580D 00	0.2936553250D 02
0.7948418420D-05	0.8088597470D 02	-0.8361533800D 02	0.3586365170D 02
0.7518959540D 01	-0.1261606400D 02	0.1097174520D 01	0.2121454920D 01
-0.5465295660D 00	0.8328754130D 01	0.2759717760D-05	-0.5090739350D-03
0.2106363320D 03	0.5528935335D-01	-0.2336365955D 00	0.3697071420D 00
-0.2596415470D 00	0.6828087013D-01	-0.2571600553D 03	-0.1518783715D 03
0.2220723208D 02	-0.1802039570D 03	0.2357096220D 04	-0.1462335598D 05
0.4542916630D 05	-0.7053556432D 05	0.4381571428D 05	-0.1717616747D 01
0.3526389875D 01	-0.2690899373D 01	0.9070932505D 00	-0.1133791155D 00
0.1301023613D 01	-0.2642777743D 01	0.1996765362D 01	-0.6661557013D 00
0.8270860589D-01	0.3426663535D-03	-0.1236521258D-02	0.1155018309D-02

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École des études supérieures/School of Graduate Studies

Title of thesis THE ANALYSIS AND COMPUTATION OF STEAM SURGE TANK DYNAMICS FOR LIGHT AND HEAVY WATER SYSTEMS

Name of candidate GUPTA, Rakesh Kumar

Degree M.A.Sc. Department Mechanical Engineering

Date of defence - April 10th, 1973

We, the undersigned, certify that we have approved this thesis and that the candidate has defended it successfully.

J.T. Rogers (Signature of Examiners)

M. Carver

W.D. Gilbert

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(Dean of Graduate Studies)

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Date: April 10th, 1973

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