COMPUTER MODEL OF A NUCLEAR REACTOR PRIMARY COOLANT PUMP

by

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ABSTRACT

The performance of a reactor coolant pump should be modeled accurately so that it made be used in a reactor plant computer to provide information for the operator.

This study develops techniques to represent the gross performance of a coolant pump. Dimensionless quantities are used to describe the characteristic curves of a pump.

Also, in order to calculate flow transients, the hydraulic characteristics of the various flow paths are also modeled.

To test these models,a computer program is used to incorporate the pump model and the flow model to predict the reactor vessel flow during transients. Two specific applications of the computer program are shown at the end of the report.

Thesis Supervisor: John E. Meyer

Title: Professor of Nuclear Engineering

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1. INTRODUCTION

This study develops techniques to represent the gross performance of a coolant pump. Many existing works on pumps do not give detailed information on how the pump can be modeled. Valid pump models can be used in many ways to predict flow values during a plant flow transient.

One of these ways is to use the model on a plant computer. Computed output can supplement sensor measurements and provide better information for the operator(e.g. in the manner of Ray(1)).

To represent the performance of a pump, dimensionless quantities are used to describe characteristic curves of the pump. These curves are the head-capacity curve, the brake horsepower curve, and the net positive suction head curve. An equation that represents each curve is developed for one or more typical cases.

There is one more group of features that must be modeled in order to calculate flow transients. The hydraulic characteristics (friction, shock, and inertia) of the various flow paths must be described.

To test these models, a computer program is used to incorporate the pump model and the flow model to predict the mass flow through the reactor during transients. The transient considered is loss of power to the pump motor with a consequent loss of coolant flow through the core. Two specific applications of the computer program are shown at the end of the report(Chapter 6).

2.PUMP BEHAVIOR

2.1.General Description

A nuclear reactor primary coolant pump provides the means for forced circulation of coolant. In this case, the pump is connected to the primary loop of a pressurized water reactor (PWR). The water coolant is transferred from the reactor core to the steam generator and returned.

The pump's main components are an electric motor, a pump impeller, and a mechanical seals region. The electric motor is located at the top of the pump. Electrical current is supplied to the motor at high voltage and three phases. The motor converts this electrical power into the rotation of the pump impeller. The impeller rotation causes coolant flow through the coolant loop and a pressure rise across the pump.

The mechanical power associated with the impeller rotation is described by the brake horsepower (BHP) curve. The BHP curve describes the amount of torque and consequently the power needed to keep the impeller rotating at a specified speed. The power (pressure drop/flow) imparted to the fluid is described by the head-capacity (h-c) curve. The h-c curve shows how much pressure drop and consequently the power imparted to the fluid at a certain mass flow through the pump . The difference between the BHP and the h-c curve largely represents losses in the fluid flow through the pump.

There are two requirements on the pump during normal operation. The first is that the pump must provide enough pressure drop/flow to overcome all losses in one complete trip around the loop. These losses are due to friction and shock effects when the fluid moves through each component of the loop. The second requirement is that pump pressure entering the pump impeller must never be less than the fluid vapor pressure. If this occurs, some of the fluid will vaporize in the pump - is called cavitation. Cavitation can cause a decrease in the head supplied at a given flow and the bubble collapse can cause damage to the pump impeller.

2.2.Dimensional Analysis

There are only a few reports, Fuls(2) and Tong(3), that describe in detail how to represent the performance of a pump. Most reports, Burgreen(4) and Boyd(5), describe the performance of the pump using affinity laws but they do not give much detail about the derivation of these laws.

The main reference used in this section is the report by Fuls(2). In his report he describes the use of dimensionless quantities to represent the characteristic curves of the pump. Three of these quantities are:

$$\Pi_1 = \frac{\rho W}{uD} \qquad (2.2a)$$

$$\Pi_2 = \frac{W}{\rho w D^3} \qquad (2.2b)$$

$$\Pi_3 = \frac{P}{\rho w^2 D^2} \qquad (2.2c)$$

where

ρ = density (kg/m ^{3})

W = mass flow (kg/s)

u = viscosity (Pa·s)

D = pump impeller diameter (m)

Δp = pressure rise through the pump (densityxhead) (Pa)

w = pump speed (rad/s)

For this case the principles of dimensional analysis can be stated:

a)consider a class of pumps for which all geometrical features - lengths, radii, etc., - are scaled to be directly proportional to the impeller diameter;

b)for these pumps assume that only the quantities listed after equation 2.2a need be specified to completely define pump operation; and

c)if this assumption is valid, then for its range of validity and for all the pumps in this class, Π_3 is a unique function of Π_1 and Π_2 .

This is a very useful result and gives the so called affinity laws, Fuls(2), of pump performance. Furthermore for many fluids (excluding tars, etc.) the effect of variation in (Reynolds number)Π_1 is unimportant. This is a good approximation for liquid water and is adopted.

2.3.Head - Capacity Curve

To represent the head-capacity curve we use the two remaining dimensionless quantities (after dropping Reynolds number dependence):

$$\pi_2 = \frac{W}{\rho w D^3}$$

$$\pi_3 = \frac{\Delta p}{\rho w^2 D^2}$$

where

W = mass flow

w = pump speed

Δp = pressure rise through the pump

D = pump impeller diameter

ρ = density

(Note - when we talk about head-flow we mean pressure rise-flow)

An additional simplification is employed when we consider the operation of many states of a single pump (one pump diameter). Consider one of these states to be a "rated condition" (subscript R). Also note that multipling each π quantity by a constant does not change the dimensional analysis conclusions.

Therefore dividing π_2 by π_{2R} and π_3 by π_{3R} where R is the rated value of the mass flow, density, pump speed, and pressure rise, we arrive at:

$$\pi_{2R} = \frac{W_R}{\rho_R w_R D^2}$$

$$\pi_{3R} = \frac{\Delta p_R}{\rho_R w_R^2 D^2}$$

The resulting variables are Y and x, where:

$$Y_p = \frac{\Pi_3}{\Pi_{3R}} = \frac{(\Delta p)(\rho_R)(w_R)^2}{(\Delta p_R)(\rho)(w)^2} \qquad (2.3a)$$

$$x = \frac{\Pi_2}{\Pi_{2R}} = \frac{(W)(\rho_R)(w_R)}{(W_R)(\rho)(w)} \qquad (2.3b)$$

The relationship between Y_p and x is

$$Y_p = g(x) \qquad (2.3c)$$

where g(x) is determined by the given head-capacity curve (obtained by a pump test).

2.4. Brake Horsepower Curve and Motor Torques

To represent the brake horsepower (BHP) curve, we developed a dimensionless quantity not mentioned in Fuls'(2) report. This term is:

$$\Pi_5 = \frac{P}{\rho w^3 D^5} \qquad (2.4a)$$

where

P = power input to the pump(commonly called brake horsepower)(W)

ρ = density

w = pump speed

D = pump impeller diameter

(Note: when we talk about brake horsepower we use Watts to represent it).

Power divided by pump speed is equal to torque. Therefore π_5 is equivalent to:

$$\pi_5 = \frac{T_b}{\rho w^2 D^5} \qquad (2.4b)$$

where

T_b = brake horsepower torque (N m)

We divide π_5 by its rated value π_{5R} which is:

$$\pi_{5R} = \frac{T_{bR}}{\rho_R w_R^2 D^5}$$

$$Y_T = \frac{\pi_5}{\pi_{5R}} = \frac{(T_b)(w_R)^2(\rho_R)}{(T_{bR})(w)^2(\rho)} \qquad (2.4c)$$

Y_T is again considered to be a function of only one variable -x- where x is defined by equation (2.3b).

The relationship between Y_T and x is:

$$Y_T = f(x) \qquad (2.4d)$$

where f(x) is defined by the given BHP curve.

The brake horsepower is also used to calculate the pump efficiency. Pump efficiency describes how much of the mechanical power associated with impeller rotation (BHP) is actually imparted to the fluid. To determine pump efficiency, first convert the value of pressure rise through the pump to power. We multiply pressure rise by the fluid mass flow through the pump and also divide by the fluid density. This gives the power imparted to the fluid and we divide this value by the BHP value(at that mass flow) to obtain the pump efficiency at a given mass flow.

Equations (2.4a)-(2.4d) provide information on obtaining T_b (brake horsepower torque). This is the torque requirement to cause the impeller shaft to move the current value of mass flow rate with the current pump pressure rise. Two other torques act on the rotating parts; T_e - electric torque provided by the electric motor; and T_w - windage and bearing loss torque.

The electric torque for a 3 phase induction motor is depicted in figure 2.4.1. This figure show how the electric torque varies with pump impeller speed; from start speed to rated speed.

From Smith(6), the equation for rated electric torque for a 3 phase induction motor is:

$$T_{eR} = \frac{3I_2^2R_2}{sw_S} \qquad (2.4e)$$

where

I_2 = electric current in rotor

R_2 = resistance of rotor

w_S = synchronous pump speed

$s = \text{slip} = \frac{w_S - w}{w_S}$

When electrical power is turned off or lost to an induction motor, magnetic flux is trapped in the rotor. As the rotor continues to turn, the trapped flux generates

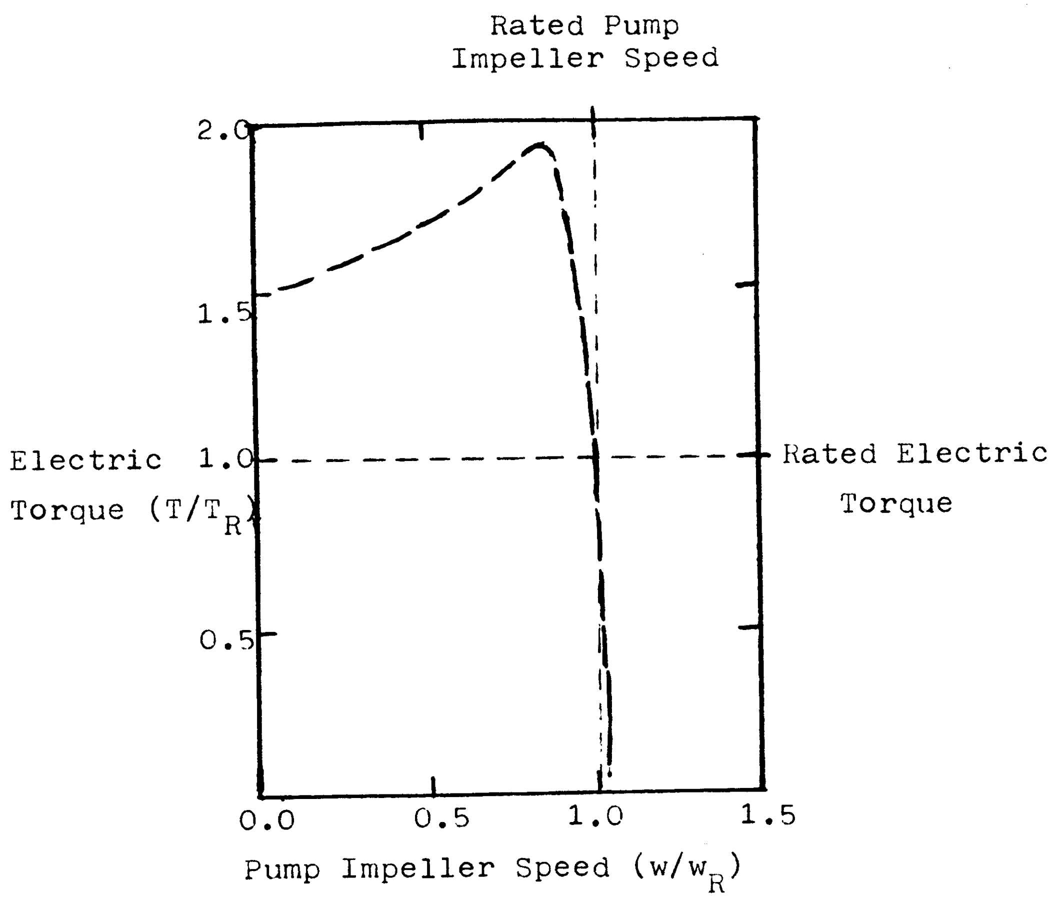


Figure 2.4.1 Electric Torque vs. Pump Impeller Speed (ref.-Smith(6))

currents in the stator. The induced stator currents(called eddy currents) produces a retardation torque on the rotor. Therefore the rotor begins to slow down and the electric torque decays. The formula for the electric torque for loss of electric current to the pump motor, from Boyd(5), is:

$$T_e = T_{eR}(e^{-t/tau})^2 \frac{(w)}{(w_R)} \qquad (2.4f)$$

where

t = time (s)

tau = time decay constant of electric torque (s)

From Fuls'(2) report, the electric torque is assumed to go instantaneously to zero. Therefore the value of tau is very small. I have also made this assumption and have used tau equal to 10^{-7} second for the examples in Chapter 6.

The windage and bearing loss torque are due to the bearings limiting the motion of the pump shaft. There are an upper and a lower guide bearing which limits radial shaft motion and an upward and a downward thrust bearing which limits axial shaft motion. The location of the bearings is shown in figure 2.4.2. From Fuls(2), the formula for windage and bearing loss torque is:

$$\begin{aligned} T_w &= T_{wR}(w/w_R)^2 && w>.19w_R \\ &= .035T_{wR} && 0<w<.19w_R \\ &= .1T_{wR} && w = 0 \end{aligned} \qquad (2.4g)$$

where

T_{wR} = rated windage and bearing loss torque (N·m).

The torque equation describes how the pump speed varies with the electric torque, the brake horsepower torque, and the windage and bearing loss torque.

$$I_p \frac{dw}{dt} = T_e - T_w - T_b \qquad (2.4h)$$

I_p = moment of inertia of rotating parts (kg·m^2)

w = pump speed

t = time

T_e = electric torque (N·m)

T_b = brake horsepower torque (N·m)

T_w = windage and bearing torque (N·m)

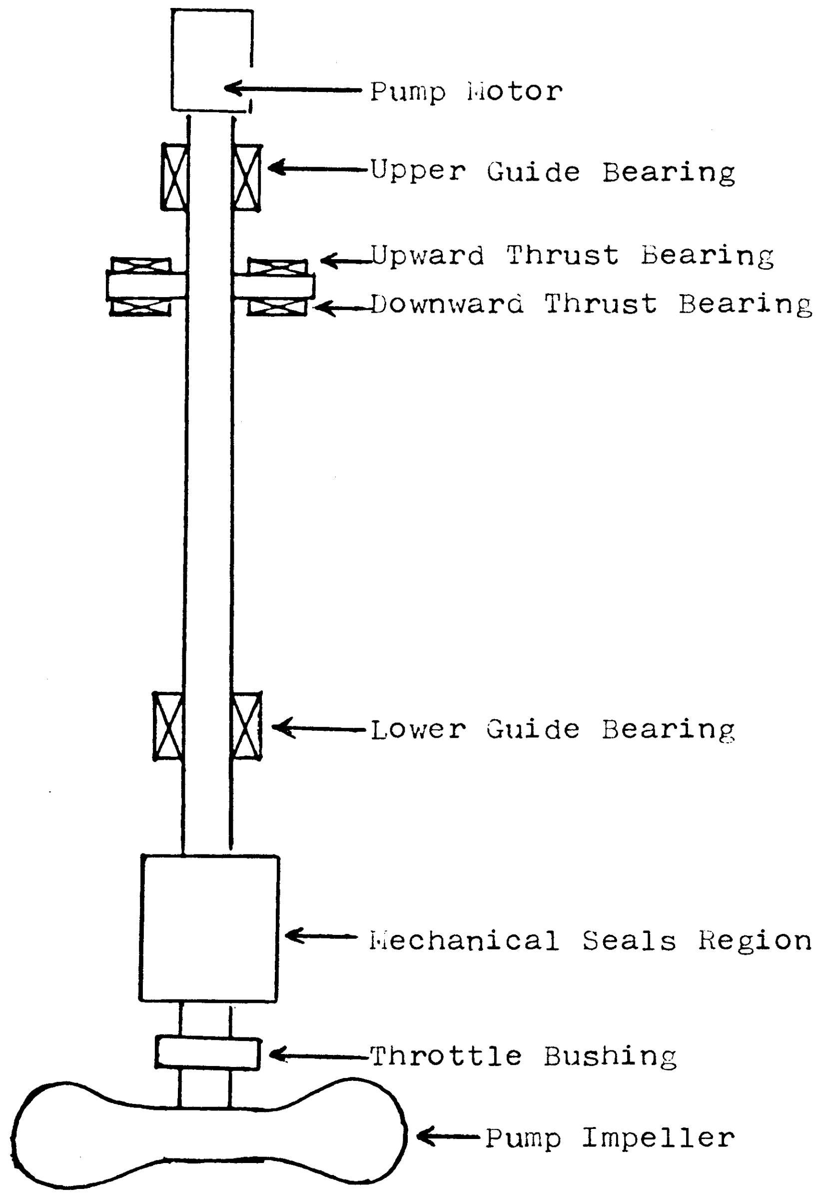


Figure 2.4.2 Location of Bearings
(ref.-Maine Yankee(7))

2.5. Net Positive Suction Head Curve

To represent the net positive suction head (NPSH) curve, we again use Y_p defined by equation (2.3a) but $\triangle p$ is the pressure difference between the pressure at the suction nozzle and the fluid vapor pressure. $Y_{p'}$ again is only a function of one varible -x- defined by equation (2.3b).

The relationship between $Y_{p'}$ and x is:

$$Y_{p'} = h(x) \tag{2.5a}$$

where h(x) is defined by the given NPSH curve.

2.6. Mechanical Seals

The purpose of the mechanical seals is to limit the leakage of reactor coolant along the impeller shaft to the surroundings. Each seal consists of two highly polished surfaces, positioned in parallel, one surface attached to the rotating shaft and the other surface attached to a stationary portion of the pump. Surrounding the seals is a heat exchanger which cools the seals, an auxillary impeller, a throttle bushing, and piping that sends to and removes from the seals water that acts as a coolant and lubricant for the surfaces.

There are many varieties, Karassik(8), of seal configurations. One arrangement that is used in Maine Yankee pumps(7) is now discussed for illustrative purposes. There are four mechanical face seals in each Maine Yankee pump. Three of the seals are mounted in a cartridge and they are used to contain the reactor coolant pressure. The fourth seal is mounted on top of the cartridge.

Roughly 2.84 liters per second (L/s) from the component cooling water system (CCWS) and 0.38 L/s from the chemical and control volume system (CVCS) enter the mechanical seal area. 2.84 L/s goes to the heat exchanger and 0.32 L/s is pushed through the throttle bushing by the auxillary impeller and goes to the reactor coolant. 0.06 L/s is sent to the seals.

The 0.06 L/s sent to the seals passes through labryinth flow restrictions which bypass each of the three mechanical seals in the cartridge. The labryinth flow restrictions are designed to divide the total pressure drop across the first three seals so that each seal has the same pressure differential. The flow past the third seal region is piped back to the CVCS. Any leakage past the fourth seal is sent to the quench tank. The seals region and the flow through the region are shown in figures 2.6.1 and 2.6.2.

There are sensors that measure the pressure of the seal water after passing through the three seals in the cartridge. There is also a sensor that measures the pressure difference across the throttle bushing. If for example one of the seals fails, this will cause an increase in the seal water return flow to the CVCS. An increase in the return flow will cause a decrease in flow rate and pressure drop across the throttle bushing. An operator seeing the decrease in pressure drop across the throttle bushing will increase the flow from the

CVCS into the seal area to restore the pressure drop and flow rate across the throttle bushing back to normal.

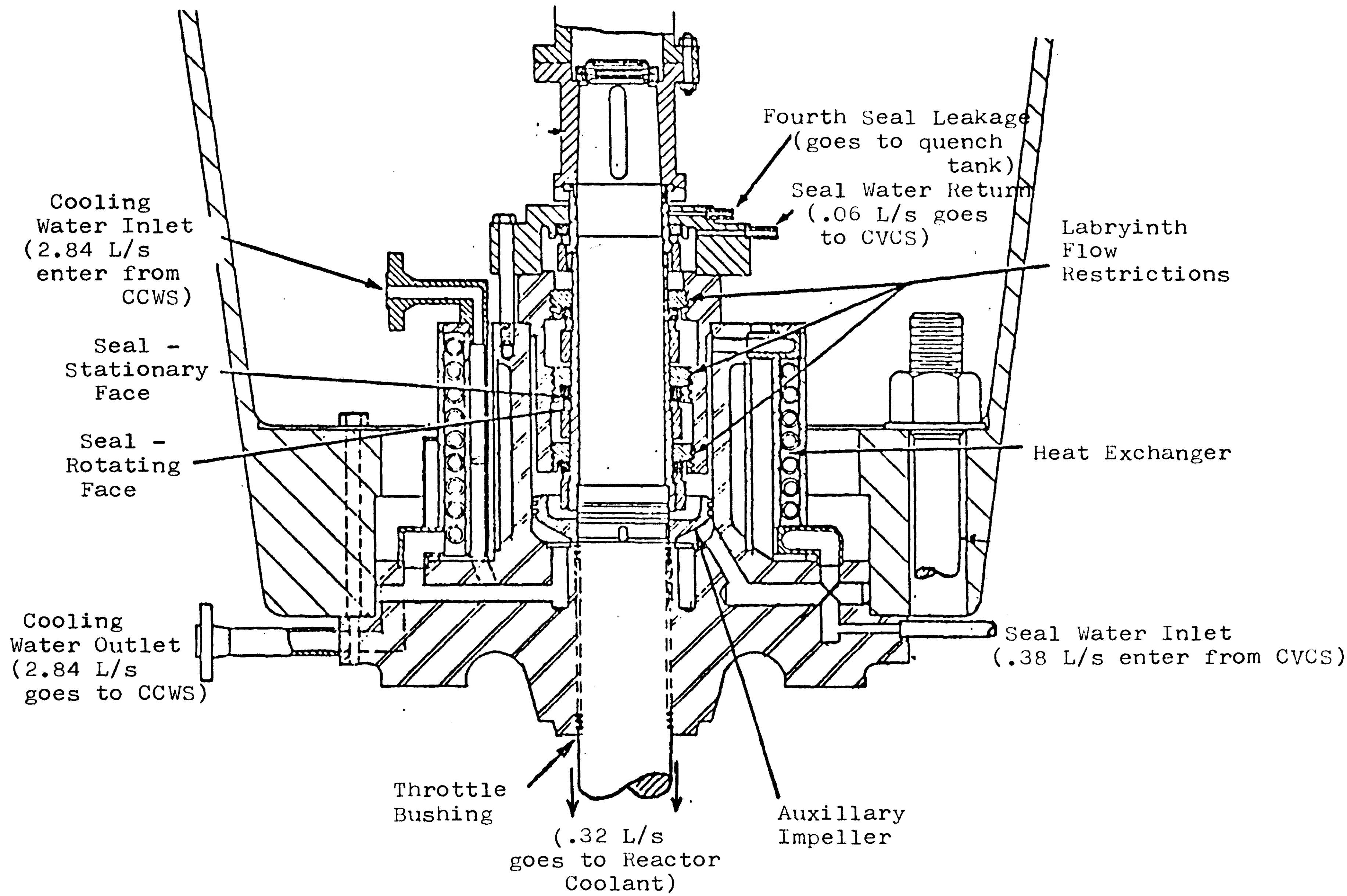


Figure 2.6.1 Mechanical Seals Region
(ref-Maine Yankee(7))

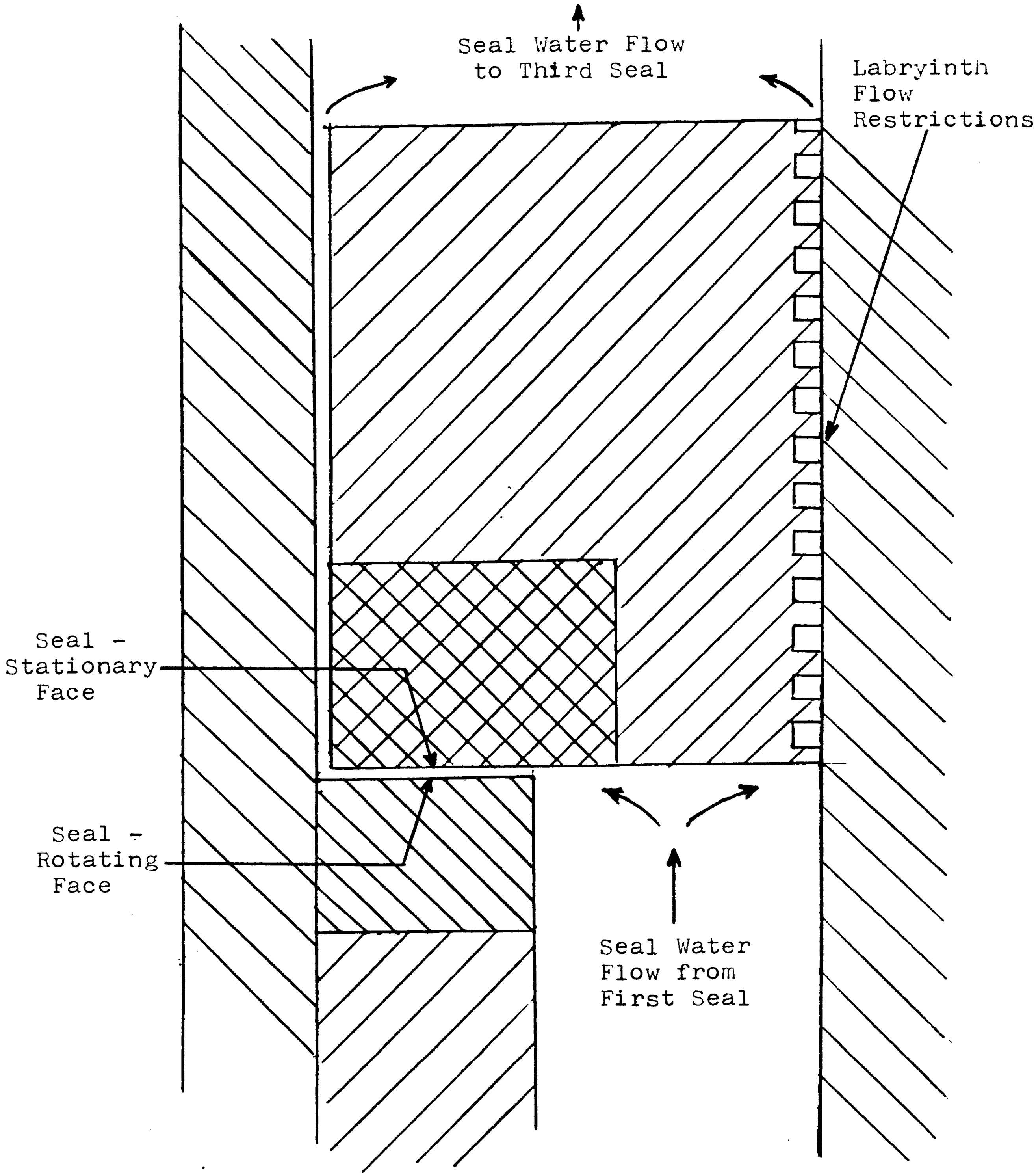


Figure 2.6.2 General Diagram of
Second Mechanical Seal
(ref.-Maine Yankee(7))

3.LOOP FLOW BEHAVIOR

The pump is only a part of the operating description for the reactor coolant system(RCS). We must also describe the resistances to flow when the coolant moves through the various RCS components.

To describe the loop flow, two equations are used. The first equation deals with how the pump impeller speed changes with the torques applied within the pump, equation (2.4h). This equation is important because the performance of one of the RCS components - pump - is dependent on the pump speed.

The second equation relates changes in loop mass flow to pressure losses across each RCS components. In this equation we have assumed the fluid density remains constant even during transients. Therefore, for the case of flow coastdown, the result will be no occurence of natural circulation.

During some loop flow transients, the flow many reverse in a loop and the mass flow equation takes this into consideration. When the flow does reverse in a loop, the pump impeller in that loop does not reverse its rotation. The pump has an anti-reverse rotation device to prevent impeller reverse rotation. In this situation, the pump does not deliver a pressure rise to the fluid but acts as a resistance to flow and causes a pressure loss.

3.1.Mass Flow Equation and Resistances

The mass flow equation for a closed loop of several components is:

$$\sum_{i} \frac{(L_i)}{(A_i)} \frac{dW_i}{dt} = \Delta p_p - \sum_{i \neq p} \Delta p_i \qquad (3.1a)$$

where

L_i = ith component length (m)

A_i = ith component cross sectional area (m^2)

W_i = mass flow through ith component (kg/s)

t = time (s)

Δp_i = friction and shock pressure drop across the ith component (Pa)

Δp_p = pressure rise across the pump (Pa)

The formulas for friction and shock pressure drop are:

$$(\Delta p)_{fr} = \frac{L(f|W|W)}{2A^2 D_h \rho} \qquad (3.1b)$$

and

$$(\Delta p)_{sh} = \frac{K|W|W}{2A^2 \rho} \qquad (3.1c)$$

where

L = length of flow (m)

A = cross sectional area of flow (m^2)

D_h = hydraulic diameter (m)

f = friction pressure drop constant

ρ = fluid density (kg/m^3)

W = mass flow (kg/s)

Also, the reactor vessel has another pressure drop term. This is due to the spacers holding the fuel rods in the core. The spacer pressure drop formula is:

$$(\Delta p)_{sp} = \frac{C_v \epsilon^2 |W| W}{2A^2 \rho} \qquad (3.1d)$$

C_v = modified drag coefficient

= ratio of projected grid cross section to undisturbed flow cross section

Δp_{ρ} is equal to the head capacity curve described in section(2.3). When the flow reverses in the loop the head-capacity curve is replaced with equation (3.1c). No information defining the value of K was found. It was arbitrarily set equal to -5 in all the examples in Chapter 6.

The different types of RCS components are the reactor vessel(composed of many hydraulic sub-components), the piping connecting the components, the reactor coolant pump, the stop valves, and the steam generator. There is a bypass stop valve directly connecting the two stop valves in the loop. This valve is also a RCS component but we have asssumed that it is closed during all situations and the loop flow is through the other components.

The mass flow through the piping, the reactor coolant pump, the stop valves, and the steam generator is the same. Therefore, equation (3.1a) is:

$$\frac{(L_{RV})}{(A_{RV})}\frac{dW_{RV}}{dt} + \sum_{i \neq RV} \frac{(L_i)}{(A_i)}\frac{dW_L}{dt} = \Delta p_p - \sum_{i \neq p} \Delta p_i \qquad (3.1e)$$

where

W_{RV} = reactor vessel flow (kg/s)

W_L = loop flow (kg/s) .

the first summation is taken over all components in the loop under consideration(but not the reactor vessel); and the second summation is taken over the same components and the reactor vessel.

The reactor vessel flow (W_{RV}) is equal to the sum of the flows in all of the loop. Therefore, the flow in each loop is coupled to the flow in the other loops. If pump failure occurs in one loop, this will cause a smaller reactor vessel mass flow and a smaller pressure drop. A smaller reactor vessel pressure drop causes a smaller pressure rise delivered by the nonfailed pumps. Therefore, the flow in the loops with the nonfailed pumps will increase.

4. COMPUTATIONAL METHOD

4.1. Finite Difference Equations

Equations (2.4h) and (3.1a) can be cast into finite difference equations:

$$\Delta w^j = \frac{\Delta t}{I_p} \left(T_e^{j-1} - T_b^{j-1} - T_w^{j-1}\right) \tag{4.1a}$$

$$\Delta W_L^j = \frac{1}{\left[\sum\limits_{i \neq RV} \frac{(L_i)}{(A_i)}\right]} \left[- \frac{(L_{RV})}{(A_{RV})} \Delta W_{RV}^{j-1} - \Delta t \sum_{i \neq p} \Delta p_i^{j-1} + \Delta t \Delta p_p^{j-1} \right] \tag{4.1b}$$

where

j = jth time value

$j - 1$ = $j - 1$ th time value

Δt = time increment (s)

To calculate the present value or jth value of the change in pump impeller speed and the change in loop mass flow, we use the previous values or j-1 th values of the loop mass flow, the reactor vessel mass flow, and the torques.

There is a limitation imposed on these equations. The value of the time increment (Δt) must not be too large or else the results become inaccurate. For the examples shown in Chapter 6, a Δt no greater than 0.1 second is used. Work was done on values of 0.2 and 0.5 seconds for Δt. The results from this work were very inaccurate compared to the true values.

5.SENSOR FAILURE DETECTION AND IDENTIFICATION

5.1.Idealized Cases

The pump model can be used to validate flow sensors. The simplest situation from Hopps(9), is shown in figure 5.1.1.

The inputs to the pump model are sensors supplying a pump speed, a suction pressure, and a discharge pressure. In the pump model, the pressure head delivered by the pump is a function of the pump impeller speed and the mass flow through the pump. The difference between the discharge pressure and the suction pressure is equal to the pressure head. Once the pressure head and the pump speed are known, the mass flow can be determined. Two flow sensors are necessary in order to determine which flow value is correct if there is a discrepancy in flow values between one of the flow sensors and the pump model.

A more elaborate scheme, from Hopps(9), can be devised to test the other sensors besides the flow sensors. This design is shown in figure 5.1.2.

In this case, there are two pump models and redundancy in suction and discharge pressure sensors. Both the suction and discharge pressure sensors can be checked if either of the pump models gives a wrong value for the flow. The pump speed sensor can be checked if both pump models give wrong flow values.

5.2. Actual Cases

The way this pump model can be applied in any given actual case (without changing existing sensor complement) depends strongly on the strengths and weaknesses of the given sensor complement and redundancy. For example, in the Maine Yankee plant associated sensors are temperature sensors that measure the coolant temperature at various points along the loop and pressure sensors that measure the pressure drop across the steam generator and this pressure drop value in turn is used to determine the mass flow through the loop. These do not fit in the patterns of section 5.1. The optimum way of using the pump model has not yet been established.

5.3. Supplementary Information

Certain items of information that lie outside of the main pump model are important for reliable plant operation. They should be made available to the operator for information and possible alarm. They are NPSH, interseal pressures, and pressure drop across the throttle bushing.

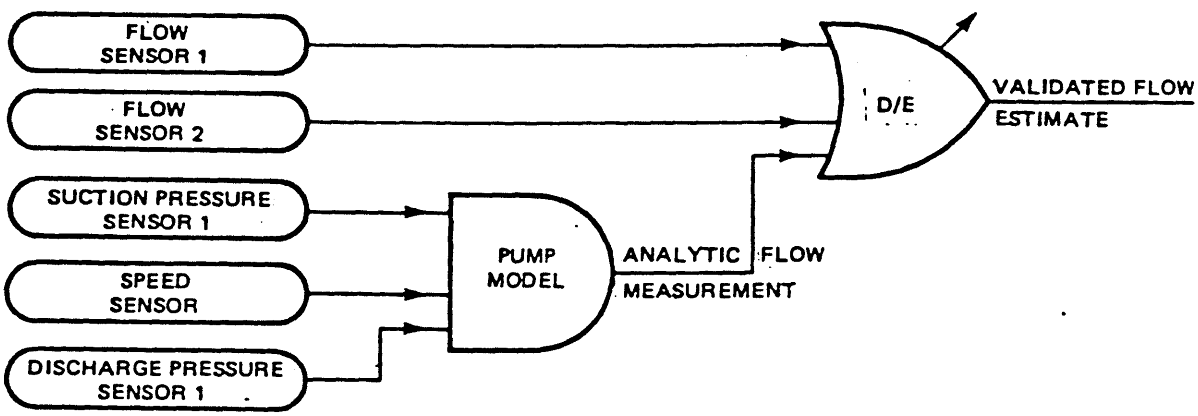


Figure 5.1.1.Design used to validate flow sensors (ref.-Hopps(9)).

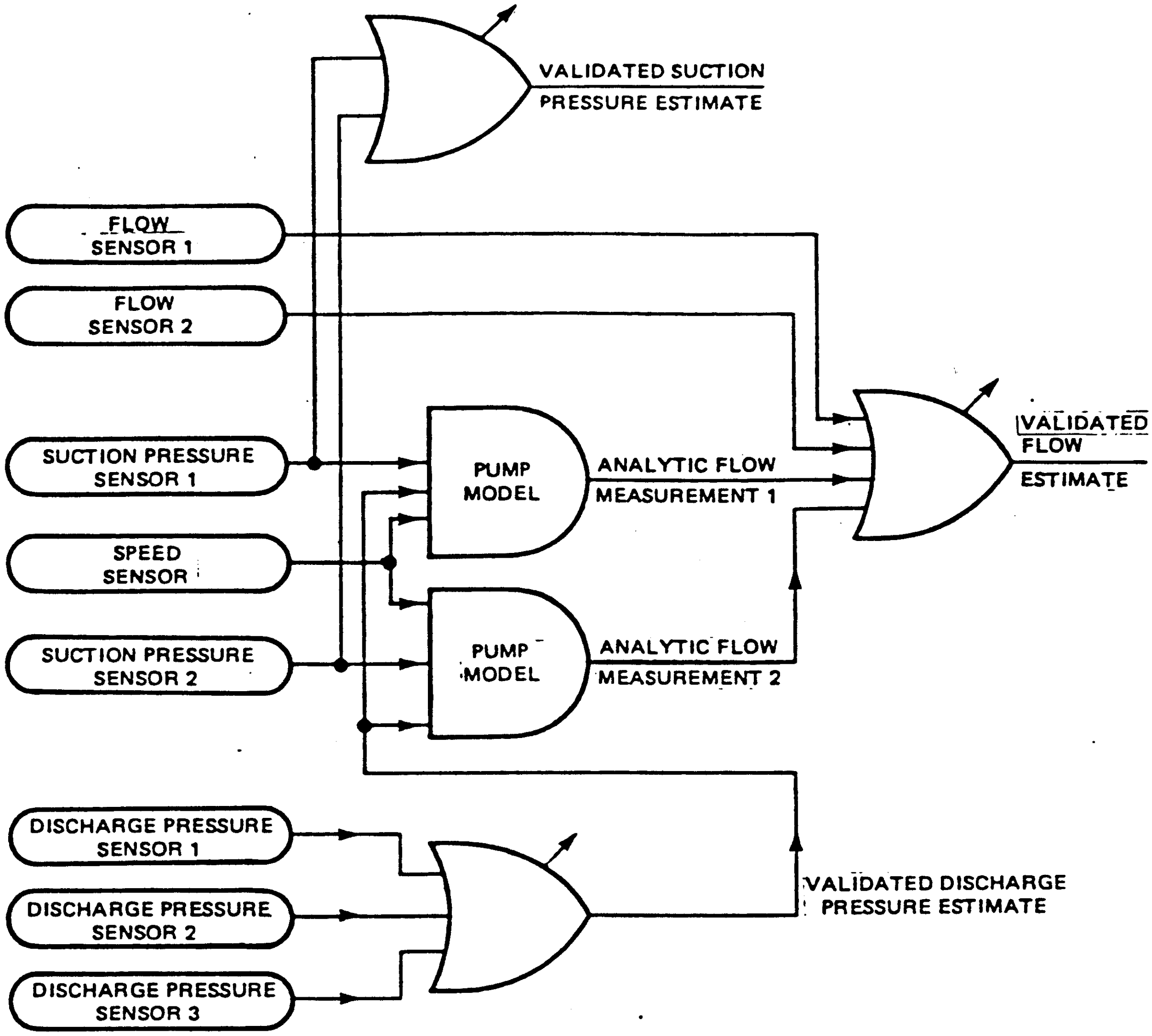


Figure 5.1.2.Design used to validate flow, pressure, and speed sensors. (ref.-Hopps(9)).

6.APPLICATIONS

6.1.Example from Fuls' Report

In this application from Fuls(2), the reactor is a four loop reactor (similar to Shippingport) with one pump and one steam generator in each loop. All the pumps are identical but two different types of steam generators are used. The transient occurring is the failure of one of the pumps. The objective of the problem is to determine the mass flow in each loop during the transient. During the transient, there will be be three different loop flow values: one value for the loop with the failed pump and steam generator of type a; another value for the loop with a nonfailed pump and steam generator of type a; and a value for the loops with a nonfailed pump and steam generator of type b. The solutions by Fuls is performed by an independent technique so that this case provides a mathematical verification.

6.1.1.Rated Conditions

W_{LO} = normal loop flow

= 793 kg/s (loops 1 or 2)

= 810 kg/s (loops 3 or 4)

w_R = rated pump speed

= 188.5 rad/s

ρ_R = rated density

= 759 kg/m^3

Δp_0 = normal operation pump pressure rise

= 827 kPa (loops 1 or 2)

= 813 kPa (loops 3 or 4)

6.1.2. Flow Geometries

Reactor Vessel

i) A_{RV} = area = .97 m^2

ii) L_{RV} = length = 18.29 m

Steam Generator

i) A_{SG} = .18 m^2 (loops 1 or 2)

L_{SG} = 15.24 m

ii) A_{SG} = .18 m^2 (loops 3 or 4)

L_{SG} = 9.45 m

Piping

i) A_p = .11 m^2

ii) L_p = 33.53 m (loops 1 or 2)

= 45.72 m (loops 3 or 4)

6.1.3. Head-Capacity Curve

The functional relationship between Y_p and x is taken to be quadratic:

$$Y_p = C_1 x^2 + C_2 \quad . \tag{6.1.3a}$$

Two points on the head-capacity curve for the given pump are provided:

W(kg/s)	Δp(kPa)
1053	590
527	999

Fuls does not give rated values for the pump. The rated values of the pump mass flow and the pump pressure rise were set equal to the average of the normal operation mass flow in the loops and the average of the normal operation pump pressure rise in the loops.

W_{pR} = rated pump mass flow

= (793+810)/2 kg/s

= 802 kg/s

Δp_{pR} = rated pump pressure rise

= (827+813)/2 kPa

= 820 kPa

Using the given points and the rated values and substituting them into equations (2.3a) and (2.3b) we have for Y and x (setting $\rho = \rho_R$ and $w = w_R$):

x	Y_p
1.31	.72
.66	1.22

Therfore the values of C_1 and C_2 in equation (6.1.3a) are:

$C_1 = -.39$

$C_2 = 1.39$

Now we have an equation for Y_p. Knowing Y_p and using equation (2.3a) the values of Δp(pressure rise through the pump) can be determined.

When the pump impeller stops rotating and the mass flow through the pump reverses, the impeller acts as a resistance to the flow. To represent the pump when the flow reverses, equation (3.1c) is used in place of the head-capacity curve.

$$(\Delta p)_{sh} = \frac{K|W_L|W_L}{2A^2\rho} \qquad (6.1.3b)$$

$$\rho = 759 \text{ kg/m}^3$$

$$A = .11 \text{ m}^2$$

Fuls does not give a value for K, therfore it has been arbitrarily set equal to -5.

6.1.4.Brake Horsepower Torque

A BHP curve is not given but it's equivalent is. In order to represent the BHP curve two terms are used. One term represents the torque imparted to the fluid and the other term represents the hydraulic losses incurred in the impeller.

The first term is:

$$T_f = \frac{W\Delta p}{\rho w} \qquad (6.1.4a)$$

where Δp is the pressure head delivered by the pump to the fluid.

The second term is:

$$T_h = T_{h0}\,\frac{\left(rw - \dfrac{W}{\rho A}\right)^2}{\left(rw_R - \dfrac{W_0}{\rho_R A}\right)^2} \qquad (6.1.4b)$$

where

T_{h0} = normal operation hydraulic loss torque

= 796 N·m

r = pump impeller radius

= .19 m

W_0 = 876 kg/s (mass flow for T_{h0} determination)

Therefore the hydraulic loss torque is:

$$T_h = 1.16((.19)w - (1.198x10^{-2})W)^2 \quad . \qquad (6.1.4c)$$

6.1.5.Mass Flow Equation

The mass flow equation is:

$$\left[\sum_{i \neq RV} \frac{(L_i)}{(A_i)}\right] \frac{dW_L}{dt} + \frac{(L_{RV})}{(A_{RV})} \frac{dW_{RV}}{dt} = -\Delta p_{RV} - \Delta p_{SGj} - \Delta p_{pj} + \Delta p$$

where

W_L = loop mass flow

W_{RV} = reactor vessel mass flow

Δp_{RV} = pressure drop across the reactor vessel

Δp_{SGj} = pressure drop across loop j steam generator

Δp_{pj} = pressure drop across loop j piping

Δp = pressure head delivered by loop j pump

j = loop number

= a means loops 1 or 2

= b means loops 3 or 4

All pressure losses used for this example have the form:

$$\Delta p = \Delta p_0 \frac{(W)^2}{(W_0)^2}$$

where Δp and Wo equal the normal operation pressure drop across and the mass flow through the component.

Reactor Vessel

The reactor vessel's normal operation values are:

$\Delta p_{RVO} = 650$ kPa

$W_{RVO} = 3205$ kg/s.

Therefore the pressure drop across the reactor vessel is:

$$\Delta p_{RV} = 0.062(W_{RV})^2. \qquad (6.1.5a)$$

Steam Generator

For the steam generators the normal operation values are:

$\Delta p_{SGaO} = 104$ kPa (loops 1 or 2)

$W_{SGaO} = 793$ kg/s

$\Delta p_{SGbO} = 79$ kPa (loops 3 or 4)

$W_{SGbO} = 810$ kg/s

The pressure drop formulas for the steam generators are:

$$\Delta p_{SGa} = 0.165(W_L)^2 \text{ (loops 1 or 2)}$$
$$\Delta p_{SGb} = 0.121(W_L)^2 \text{ (loops 3 or 4)} \qquad (6.1.5b)$$

Piping

The normal operation values of the piping are:

$\Delta p_{pa0} = 73$ kPa (loops 1 or 2)

$W_{pa0} = 793$ kg/s

$\Delta p_{pb0} = 85$ kPa (loops 3 or 4)

$W_{pb0} = 810$ kg/s

The pressure drop formulas for the piping are:

$$\Delta p_{pa} = 0.116(W_L)^2 \quad \text{(loops 1 or 2)}$$
$$\Delta p_{pb} = 0.129(W_L)^2 \quad \text{(loops 3 or 4)} \qquad (6.1.5c)$$

6.1.6.Pump Speed Equation

The pump speed equation is:

$$I_p \frac{dw}{dt} = T_e - T_b - T_w \quad . \qquad (6.1.6a)$$

The moment of inertia (I_p) for the rotating parts of the pump is:

$$I_p = 16.86 \text{ kg m}^2 .$$

During normal operation (nonfailure of a pump) the sum of the torques is equal to zero. This equation is only used for the pump that is incurring a transient because the nonfailed pump's speed changes only slightly during the transient. For the nonfailed pump during the transient, there is an increase in flow through the pump. An increase in flow causes the brake horsepower torque to decrease. This decrease in brake horsepower torque causes a slight increase in pump speed. An increase in pump speed causes the electric torque to decrease. Therefore the result is the sum of the torques is equal to zero again with a slight increase in pump speed.

The electric torque (T_e) is assumed to instantaneously go to zero during loss of power transient.

The BHP torque (T_b) has been already calculated in section 6.1.4.

The windage and bearing torque (T_w) is calculated using these formulas:

$$T_w = T_{wR}(w/w_R)^2 \qquad w>.19w_R \qquad (6.1.6b)$$
$$= .035T_{wR} \qquad 0<w<.19w_R$$
$$= .1T_{wR} \qquad w=0$$

T_{wR} and w_R are the normal operation values of the windage and bearing torque and pump speed. They are:

$$T_{wR} = 663 \text{ N}\cdot\text{m}$$
$$w_R = 188.5 \text{ rad/s}$$

6.1.7.Calculations

Program Input

tau = electric torque time decay constant

= 10^{-7} s

dt = time increment

= .05 s (to agree with Fuls' value)

limit = number of time increments

= 30

n = total number of pumps

= 4

np = total number of failed pumps

= 1

d = pump resistance constant

= -5

Program Output

See table 6.1.1 for an output comparison.

6.1.8.Conclusions

The results given in table 6.1.1 for core flow differ no more than 0.6% from those of Fuls. This seems adequately close to give one verification point for the computer program.

The derivation demonstrates an alternate way of specifying the BHP curve (by supplying the hydraulic power and impeller losses).

Table 6.1.1.Results for the Example from Fuls' Report

Initial Flow Values

Loops 1&2 initial flow = 793 kg/s

Loops 3&4 initial flow = 810 kg/s

Core initial flow = 3206 kg/s

	Core Flow Fraction		Loop 1 Flow Fraction	
Time(s)	Fuls' Results	This Report's Results	Fuls' Results	This Report's Results
0.10	.988	.984	.943	.927
0.20	.968	.962	.834	.810
0.30	.948	.942	.713	.685
0.40	.930	.924	.592	.563
0.50	.914	.908	.474	.446
0.60	.898	.894	.361	.336
0.70	.884	.880	.251	.231
0.80	.872	.867	.145	.131
0.90	.856	.855	.040	.034
1.00	.842	.842	-.064	-.060
1.10	.827	.830	-.167	-.153

	Loop 2 Flow Fraction		Loop 3&4 Flow Fraction	
Time(s)	Fuls' Results	This Report's Results	Fuls' Results	This Report's Results
0.10	1.003	1.010	1.003	1.008
0.20	1.014	1.021	1.012	1.018
0.30	1.028	1.036	1.024	1.031
0.40	1.045	1.053	1.039	1.047
0.50	1.063	1.071	1.056	1.064
0.60	1.081	1.088	1.072	1.081
0.70	1.098	1.105	1.089	1.097
0.80	1.114	1.121	1.105	1.112
0.90	1.130	1.136	1.121	1.127
1.00	1.146	1.150	1.136	1.142
1.10	1.161	1.163	1.151	1.155

6.2. Maine Yankee Reactor

The pump model and computational model has been applied to the analysis of the Maine Yankee reactor. In this example, there are two situations; one is that only one pump fails; and the second is that all the pumps fail. Information on the reactor was found in the Maine Yankee Reactor FSAR(10) and also from information provided by the Yankee Atomic Electric Company(11).

6.2.1. Maine Yankee Head-Capacity Curve

The Maine Yankee head-capacity is given in figure 6.2.1 and in table 6.2.1 .

The functional relationship between Y_p and x is chosen to be quadratic:

$$Y_p = C_1 x^2 + C_2 .$$

We solve for C_1 and C_2 by choosing two points on the given Y_p , x curve.

Therefore the values for C_1 and C_2 are:

$$C_1 = \frac{Y_{p1} - Y_{p2}}{x_1^2 - x_2^2}$$

and

$$C_2 = \frac{Y_{p2}x_1^2 - Y_{p1}x_2^2}{x_1^2 - x_2^2}$$

To improve the accuracy of the head-capacity curve we divided the curve into three regions.

For x greater than or equal to 0.7397

$$C_1 = -1.06 \qquad (x \geq 0.7397)$$
$$C_2 = 2.06.$$

For x between 0.308 and 0.7397

$$C_1 = -.53 \qquad (0.308 \leq x < 0.7397)$$
$$C_2 = 1.77.$$

For x between 0.000 an 0.308

$$C_1 = -.53 \qquad (0.000 \leq x < 0.308)$$
$$C_2 = 1.77$$

but for this range we add a correction term to the Y equation. This term is:

$$\delta Y_p = \delta Y_{pO}(1 - \frac{x}{x_O})^n$$

where

$$\delta Y_{pO} = Y_p \text{ (true at } x=0) - C_2$$
$$= 0.04$$
$$x_O = 0.308$$
$$n = 0.71$$

Table 6.2.1. Maine Yankee Head-Capacity Curve

Rated Values

W_R = rated loop flow = 6061 kg/s

Δp_R = rated pump pressure rise = 510 kPa

ρ_R = normal operation fluid density = 739 kg/m^3

w_R = rated pump speed = 125.7 rad/s (60 Hz)

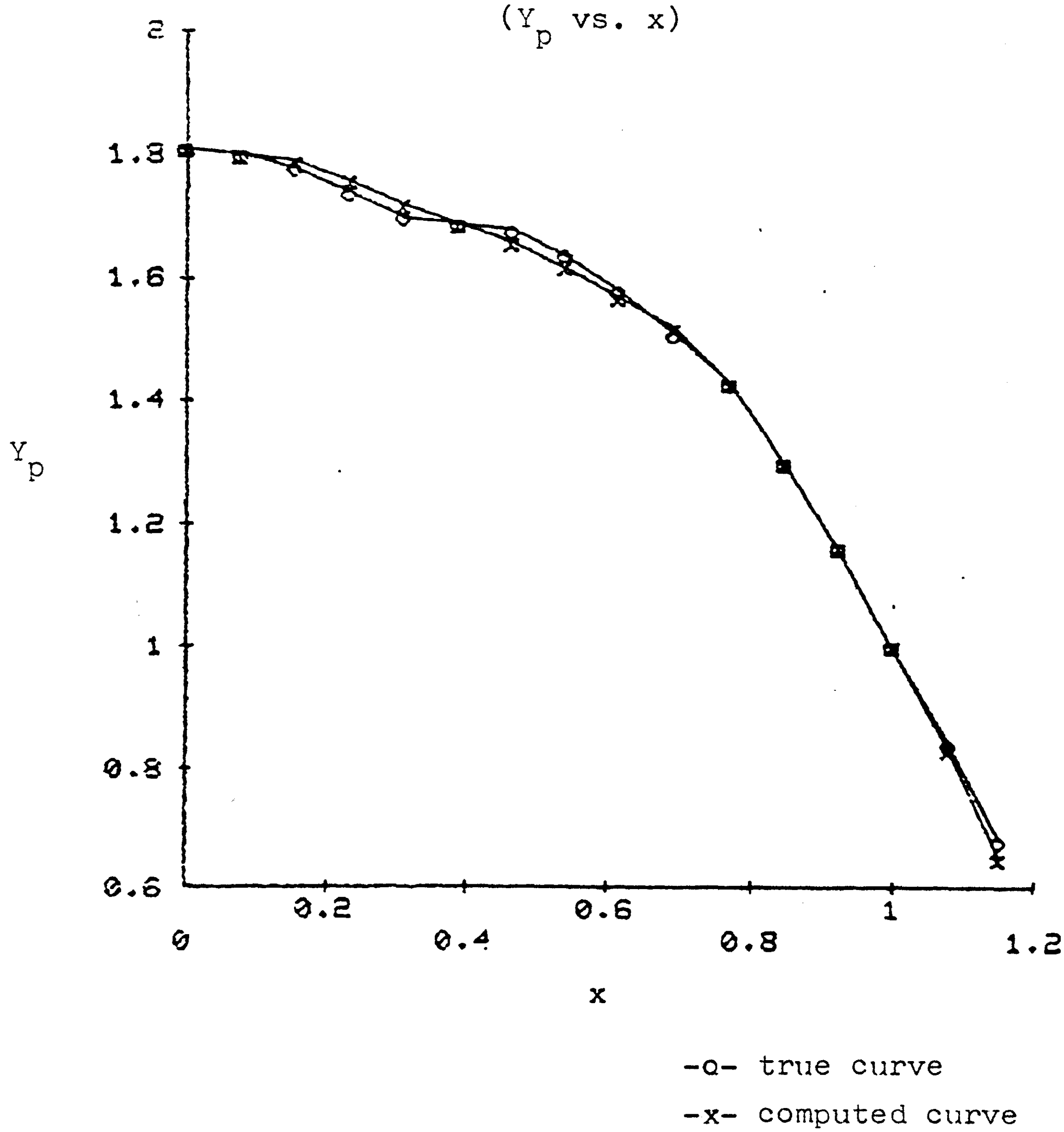
(Table given at ρ = 739 kg/m^3 and w = 125.7 rad/s)

x	True Values Yp	Computed Values Yp
0.000	1.81	1.81
0.077	1.80	1.80
0.154	1.78	1.79
0.231	1.74	1.76
0.308	1.70	1.72
0.385	1.69	1.69
0.462	1.68	1.66
0.539	1.64	1.62
0.615	1.58	1.57
0.692	1.51	1.52
0.769	1.43	1.43
0.846	1.30	1.30
0.923	1.16	1.16
1.000	1.00	1.00
1.080	0.84	0.83
1.150	0.68	0.65

(True values taken from curve provided in Maine Yankee(7))

Figure 6.2.1. MAINE YANKEE HEAD CAPACITY CURVE

(Y_p vs. x)



6.2.2.Maine Yankee Brake Horsepower Curve

The Maine Yankee BHP curve is given in figure 6.2.2 and in table 6.2.2 .

Two straight lines fit between the following coordinate points (x, Y_T) = (0.000,1.4), (0.367,1.0), and (1.000,1.0).

Therefore, the functional relationship between Y_T and x in this range is:

$$Y_T = C_3 x + C_4 \ .$$

For x equal to 0.00 to 0.367

$$C_3 = -1.09 \qquad (0.000 \leq x \leq 0.367)$$
$$C_4 = 1.4 \ .$$

For x between 0.367 and 1.00

$$C_3 = 0.00 \qquad (0.367 < x \leq 1.000)$$
$$C_4 = 1.00 \ .$$

For x greater than 1.00, information was provided by Yankee Atomic Electric Co.(as prepared for a large break LOCA RELAP case). The functional relationship between Y_T and x for x greater than 1.00 is:

$$Y_T = C_5 x + C_6 x^2 \ .$$

For x greater than 1.00 but less than 2.00

$$C_5 = 2.00 \qquad (1.00 < x < 2.00)$$
$$C_6 = -1.00 \ .$$

For x greater than or equal to 2.00

$$C = 2.54$$

$$C = -1.40 \quad (2.00 \le x)$$

From the information provided, there is a discontinuity occurring at x = 2.00. Work was not done on this discontinuity to determine its cause(s).

Table 6.2.2.Maine Yankee BHP Curve

Rated Values

W_R = rated loop flow = 6061 kg/s

T_{bR} = rated BHP torque

$$= \frac{P_{bR}}{w_R} = \frac{4.94 \times 10^6 \text{ watt}}{125.7 \text{ rad/s}}$$

$= 39.3$ kN·m

ρ_R = normal operation fluid density = 739 kg/m^3

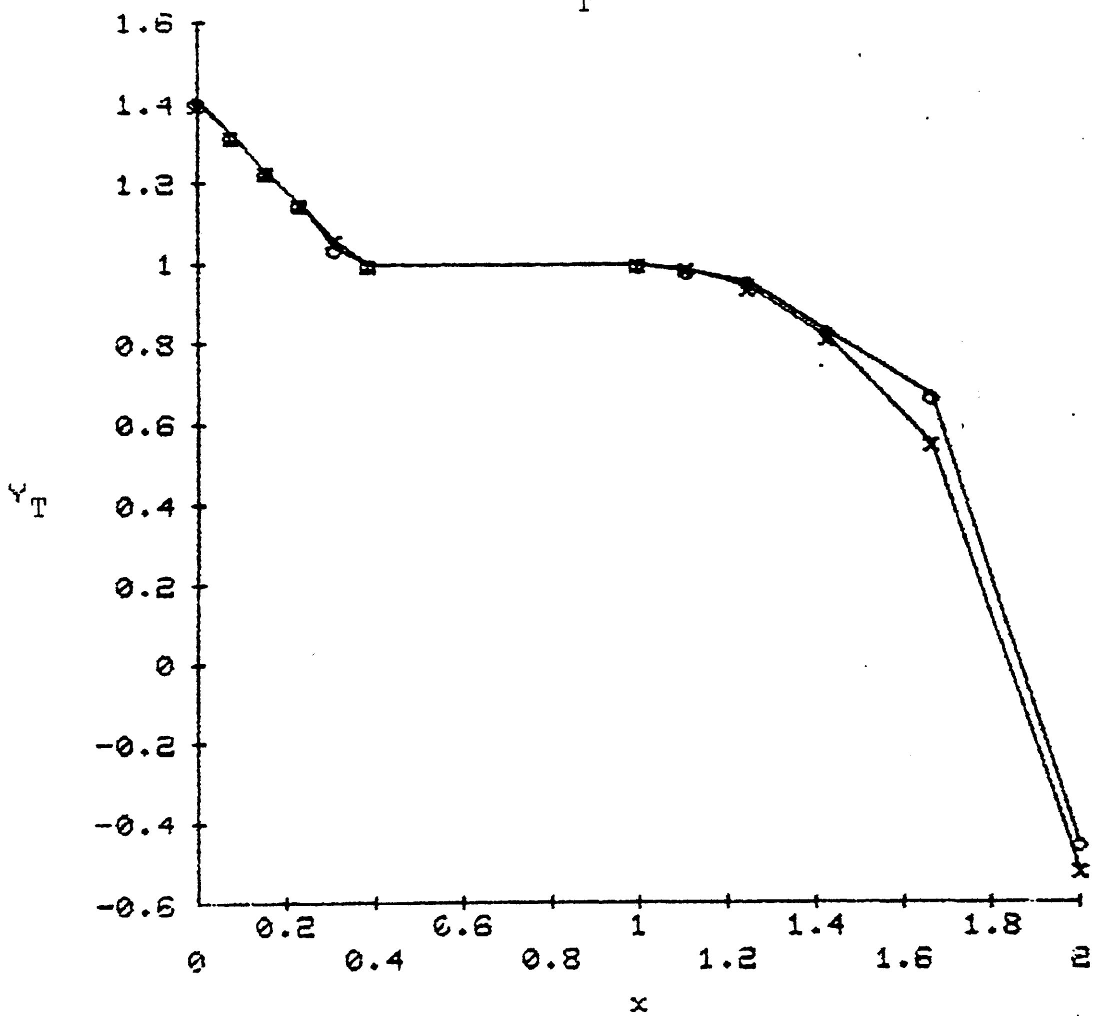
w_R = rated pump speed = 125.7 rad/s

(Table given at ρ = 739 kg/m^3 and w = 125.7 rad/s)

x	True Values Y_T	Computed Values Y_T
0.000	1.410	1.400
0.077	1.320	1.320
0.154	1.230	1.230
0.231	1.150	1.150
0.308	1.040	1.060
0.385	1.000	1.000
1.000	1.000	1.000
1.110	0.984	0.988
1.250	0.953	0.938
1.430	0.829	0.815
1.670	0.669	0.551
2.000	-0.452	-0.520
2.500	-2.690	-2.400
3.333	-7.110	-7.070
5.000	-21.300	-22.300
10.000	-110.000	-115.000
∞	$-\infty$	$-\infty$

(True data taken from curve provided in Maine Yankee(7) and from curve provided by Yankee Atomic Electric Co.'s RETRAN program)

Figure 6.2.2.MAINE YANKEE BHP CURVE
(Y_T vs. x)



-o- true curve

-x- computed curve

6.2.3. Maine Yankee Net Positive Suction Head Curve

The Maine Yankee NPSH curve is given in figure 6.2.3 and table 6.2.3.

The functional relationship between $Y_{p'}$ and x is chosen to be quadratic:

$$Y_{p'} = C_7 x^2 + C_8 .$$

Solving for C_7 and C_8 from the graph(figure 6.2.3) the values of the constants are:

$$C_7 = 1.15$$
$$C_8 = -0.149 .$$

Table 6.2.3. Maine Yankee NPSH Curve

Rated Values

W_R = rated loop flow = 6061 kg/s

ρ_R = normal operation fluid density = 739 kg/m^3

w_R = rated pump speed = 125.7 rad/s

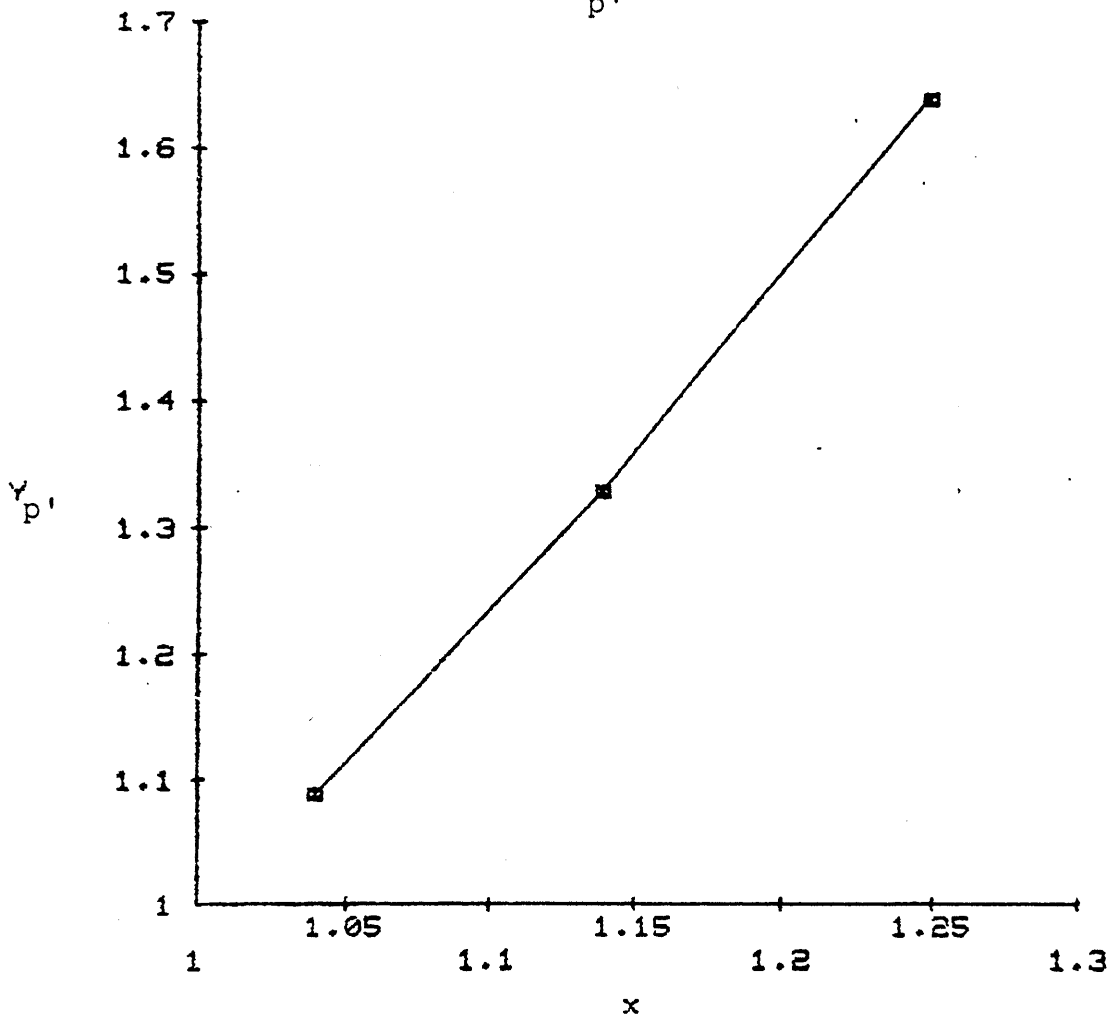
$\Delta p'_R$ = rated NPSH = 438 kPa

(Table given at ρ = 739 kg/m^3 and w = 125.7 rad/s)

x	True Values Yp'	Computed Values Yp'
1.040	1.09	1.09
1.140	1.33	1.33
1.25	1.64	1.64

(True values taken from curve provided in Maine Yankee(7))

Figure 6.2.3.MAINE YANKEE NPSH CURVE
($Y_{p'}$ vs. x)



-O- true curve

-x- computed curve

6.2.4.Mass Flow Equation

The general mass flow equation (equation(3.1e)) is:

$$\frac{(L_{RV})}{(A_{RV})}\frac{dW_{RV}}{dt} + \sum_{i \neq RV}\frac{(L_i)}{(A_i)}\frac{dW_L}{dt} = \Delta p_p - \sum_{i \neq p}\Delta p_i$$

The pressure drop across each component in the loop can be due to friction and to shock.

<u>friction pressure loss</u>

The general equation for friction pressure drop (equation(3.1b)) is:

$$(\Delta p)_{fr} = \frac{L(f|W|W)}{2A^2 D_h \rho}$$

The friction factor f is determined from a Moody plot from Rust(29),figure4.1. First, the value of ϵ/D is determined for the component considered. Then the values of the friction factor f is plotted versus the Reynolds number on log-log paper. From this graph, a formula for the friction factor can be determined as a function of mass flow.

<u>shock pressure loss</u>

The general formula for shock pressure drop (equation(3.1c)) is:

$$(\Delta p)_{sh} = \frac{K|W|W}{2A^2 \rho}$$

To determine K, the pressure drop formula is set equal to its normal operation value.

All K values are considered constant (i.e. they do not change when flow changes).

Listed in table 6.2.4 are the normal operation values of

Table 6.2.4. Maine Yankee Reactor Pressure Losses (kPa)
Full Flow, Zero Power, Average Temp. = 288 C
(ref. - Maine Yankee (10))

component	friction	shock	total
two stop valves		20.6	20.6
piping	15.4	48.7	64.1
steam generator			255.1
tubes	210.5	15.3	
plenums		29.3	
reactor vessel			170.2
inlet & 90° turn		39.3	
thermal shield	5.0	3.2	
lower plenum		40.7	
core	31.8	2.6	
core spacer		12.3	
outlet & nozzles		35.3	
	262.7	247.3	510.0
pump pressure head			510.0

each component in the loop.

stop valves

$$(\Delta p)_{sh} = \frac{K|W_L|W_L}{2A^2\rho}(\#\text{ of valves})$$

$\rho = 739\ kg/m^3$

$A = .569\ m^2$

$K = .135$

no. of stop valves/loop = 2

$$(\Delta p)_{sh} = (5.63\times10^{-4})|W_L|W_L$$

piping friction loss

$$(\Delta p)_{fr} = \frac{L(f|W_L|W_L)}{2A^2D_h\rho}$$

$\rho = 739\ kg/m^3$

$A = .569\ m^2$

$L = 13.4\ m$

$D_h = .851\ m$

$\epsilon/D = 5.37\times10^{-5}$

$f = f_3 = (3.931\times10^{-2})|W_L|^{-0.129}$

$$(\Delta p)_{fr} = (3.287\times10^{-2})f_3|W_L|W_L$$

piping shock loss - this loss is due to the two 90° turns the coolant does in going from the steam generator to the pump.

$$(\Delta p)_{sh} = \frac{K|W_L|W_L}{2A^2\rho}(\#\text{ of 90 turns})$$

$\rho = 739\ kg/m^3$

$A = .569\ m^2$

$K = .32$

$$(\Delta p)_{sh} = (1.326x10^{-3})|W_L|W_L$$

<u>steam generator tube friction loss</u>

$$(\Delta p)_{fr} = \frac{L(f|W_L|W_L)}{2A^2 D_h \rho}$$

$\rho = 739\ kg/m^3$

$A = 1.104\ m^2$

$L = 15.91\ m$

$D_h = .0168\ m$

ϵ/D = smooth tubing

$f = f_4 = (4.277x10^{-2})|W_L|^{-0.157}$

$$(\Delta p)_{fr} = (.526)f_4|W_L|W_L$$

<u>steam generator tube shock loss</u> - this shock loss is due to entering and exiting the tubes. To determine the K's (one for entering and one for exiting) σ (ratio of tube area to area at tube entrance or exit) is determined first. Then the values of the K's are determined from Rust(12), figure 4.5.

$$(\Delta p)_{sh} = \frac{(K_e + K_c)|W_L|W_L}{2A^2 \rho}$$

$\rho = 739\ kg/m^3$

$A = 1.104\ m^2$

$\sigma = .33$

K_e = exit loss constant = .475

K_c = entrance loss constant = .275

$$(\Delta p)_{sh} = (4.165\times10^{-4})|W_L|W_L$$

steam generator inlet and outlet plenum shock loss - this loss is due to the flow going from the inlet pipe to the inlet plenum and from the outlet plenum to the outlet pipe.

$$(\Delta p)_{sh} = \frac{K|W_L|W_L}{2A^2\rho}$$

ρ = 739 kg/m^3

A = .569 m^2

K = .38

$$(\Delta p)_{sh} = (7.969\times10^{-4})|W_L|W_L$$

reactor vessel (RV) inlet nozzle and 90 turn shock loss

$$(\Delta p)_{sh} = \frac{K|W_L|W_L}{2A^2\rho}$$

ρ = 739 kg/m^3

A = .569 m^2

K = .51

$$(\Delta p)_{sh} = (1.07\times10^{-3})|W_L|W_L$$

RV thermal shield shock loss - this loss is due to the coolant entering and exiting the thermal shield area. A pressure drop calculation was done indicating how the flow divides between the outer passage (reactor vessel & thermal shield) and the inner passage (thermal shield core core support barrel). Seventy-eighty percent of the total reactor vessel flow goes through the outer passage. Also in order to determine the K's, σ was calculated and the K's were determined from Rust(12),figure 4.5.

$$(\Delta p)_{sh} = \frac{(K_e + K_c)|W_{TS}|W_{TS}}{2A^2\rho}$$

$\rho = 739\ kg/m^3$

$A = 1.73\ m^2$

$\sigma = .78$

$K_e = .05$
$K_c = .1$ — Sum adjusted to 0.47 x 0.15 = .071

$W_{TS} = .78W_{RV}$

$$(\Delta p)_{sh} = (2.06x10^{-5})|W_{RV}|W_{RV}$$

(The value of the thermal shield shock pressure loss using this formula was higher than the normal operation value. Therefore, we multiplied the shock loss equation by .47 to equal the normal operation value)

$$(\Delta p)_{sh} = (9.767x10^{-6})|W_{RV}|W_{RV}$$

<u>RV thermal shield friction loss</u>

$$\Delta p)_{fr} = \frac{L(f|W_{TS}|W_{TS})}{2A^2D_h\rho}$$

$\rho = 739\ kg/m^3$

$A = 1.73\ m^2$

$L = 4.68\ m$

$D_h = .26\ m$

$\epsilon/D = .00017$

$f = f_1 = (1.204x10^{-2})|W_{TS}|^{-.069}$

$W_{TS} = .78W_{RV}$

$$(\Delta p)_{fr} = (2.476\times10^{-3})f_1 |W_{RV}|W_{RV}$$

RV lower plenum loss

$$(\Delta p) = p_0 \frac{|W_{RV}|W_{RV}}{(W_{RVO})^2}$$

$\Delta p_0 = 40.68$ kPa

$W_{RVO} = 18{,}200$ kg/s

$$(\Delta p) = (1.228\times10^{-4})|W_{RV}|W_{RV}$$

core friction loss

$$(\Delta p)_{fr} = \frac{L(f|W_{RV}|W_{RV})}{2A^2 D_h \rho}$$

$\rho = 739$ kg/m^3

$A = 4.95$ m^2

$L = 3.47$ m

$D_h = .0135$ m

$\epsilon/D = 3.7 \times 10^{-5}$

$f = f_2 = (.0479)|W_{RV}|^{-.129}$

$$(\Delta p)_{fr} = (7.1\times10^{-3})f_2|W_{RV}|W_{RV}$$

core shock loss

$$(\Delta p)_{sh} = \frac{(K_e + K_c)|W_{RV}|W_{RV}}{2A^2\rho}$$

$\rho = 739$ kg/m^3

$A = 4.95$ m^2

$\sigma = .63$

$K_e = .14$

$K_c = .15$

$$(\Delta p)_{sh} = (8.01\times10^{-6})|W_{RV}|W_{RV}$$

core spacer loss - there are pressure loss due to the spacers supporting the fuel rods in the core. This formula for spacer pressure drop loss is from Rust(33),eq. 4.2.57. The equation for C_v was determined in the same way as the friction factors were determined.

$$(\Delta p)_{sp} = \frac{C_v \in^2 |W_{RV}|W_{RV}}{2A^2 \rho}$$

$\rho = 739\ kg/m^3, A = 4.95\ m^2$

$\in$ = ratio of projected grid cross section to undisturbed flow cross section

$$= \frac{2Pt - t^2}{P^2 - \frac{\pi}{4}D^2}$$

P = pitch = .0148 m

t = thickness of spacer walls = .77 mm

D = .0112 m

$\in$ = .184

C_v = modified drag coefficient

$= 54.86|W_{RV}|^{-.0245}$

$$(\Delta p)_{sp} = (7.481\times10^{-6})cv|W_{RV}|W_{RV}$$

core outlet region and nozzle shock loss

$$(\Delta p)_{sh} = \frac{K|W_L|W_L}{2A^2\rho}$$

$\rho = 739\ kg/m^3$

$A = .569\ m^2$

K = .46

$$(\Delta p)_{sh} = (9.61 \times 10^{-4}) |W_L| W_L$$

pump - the pressure loss is equal to the pressure head delivered by the pump. This is equal to the head-capacity curve in section (6.2.1).

Inertance Values (Maine Yankee(10))

stop values

a) L = length $\cong$ 0.0 m

piping

a) L= 13.38 m

b) A = area = .569 m^2

steam generator

a) tube length = 15.91 m

tube area = 1.104 m^2

b) inlet and outlet plenum length = .83 m

inlet and outlet plenum area = .72 m^2

pump

a) L $\cong$ 0.0 m

reactor vessel

a) 90 turn L = .74 m

90 turn A = 3.42 m^2

b) thermal shield L = 4.68 m

thermal shield A = 1.73 m^2

c) lower plenum L = 3.38 m

lower plenum A = 6.16 m^2

d) core L = 3.47 m

core A = 4.95 m^2

e)core outlet L = 1.99 m

core outlet A = 4.95 m^2

6.2.5.Pump Speed Euation

The pump speed equation (equation (2.4h)) is:

$$I_p \frac{dw}{dt} = T_e - T_b - T_w$$

where

I_p = moment of inertia of rotating parts of pump

= 4214 kg·m^2

<u>windage and bearing torques</u> (T_w)

Equation (2.4g) is used for these torques. They are:

$$T_w = T_{wR}(w/w_R)^2 \qquad w>.19w_R$$
$$= .035T_{wR} \qquad 0<w<.19w_R$$
$$= .1T_{wR} \qquad w = 0$$

T_{wR} and w_R are the normal operation values of the windage and bearing torques and pump speed. They are (information not available, therefore arbitrarily set to 2%):

$$T_{wR} = .02(T_{bR})$$
$$= .02(39.3 \text{ kN m})$$
$$= 787 \text{ N m}$$
$$w_R = 125.7 \text{ rad/s}$$

<u>BHP torque</u> (T_b)

The BHP torque was calculated in section 6.2.2.

<u>electric torque</u> (T_{eR})

The electric torque equation (equation(2.4f)) is:

$$T_e = T_{eR} (e^{-t/tau})^2 (w/w_R)$$

where

T_{eR} = normal operation value of electric torque

= $T_{bR} + T_{wR}$

= 40.1 kN·m

tau = time decay of electric torque

= it is an input into the program

= 10^{-7} s.

6.2.6. One Pump Failure Transient

In this situation, one pump fails. The object of the problem is to determine how the reactor vessel flow changes with time and to compare these results with results obtained from the Maine Yankee FSAR(10).

The inputs to the program for this case is:

tau = electric torque time decay constant

= 10^{-7} s

dt = time increment

= .1 s (see section (4.1))

limit = no. of time increments

= 80

n = total no. of pumps

= 3

np = total no. of failed pumps

= 1

d = pump resistance constant

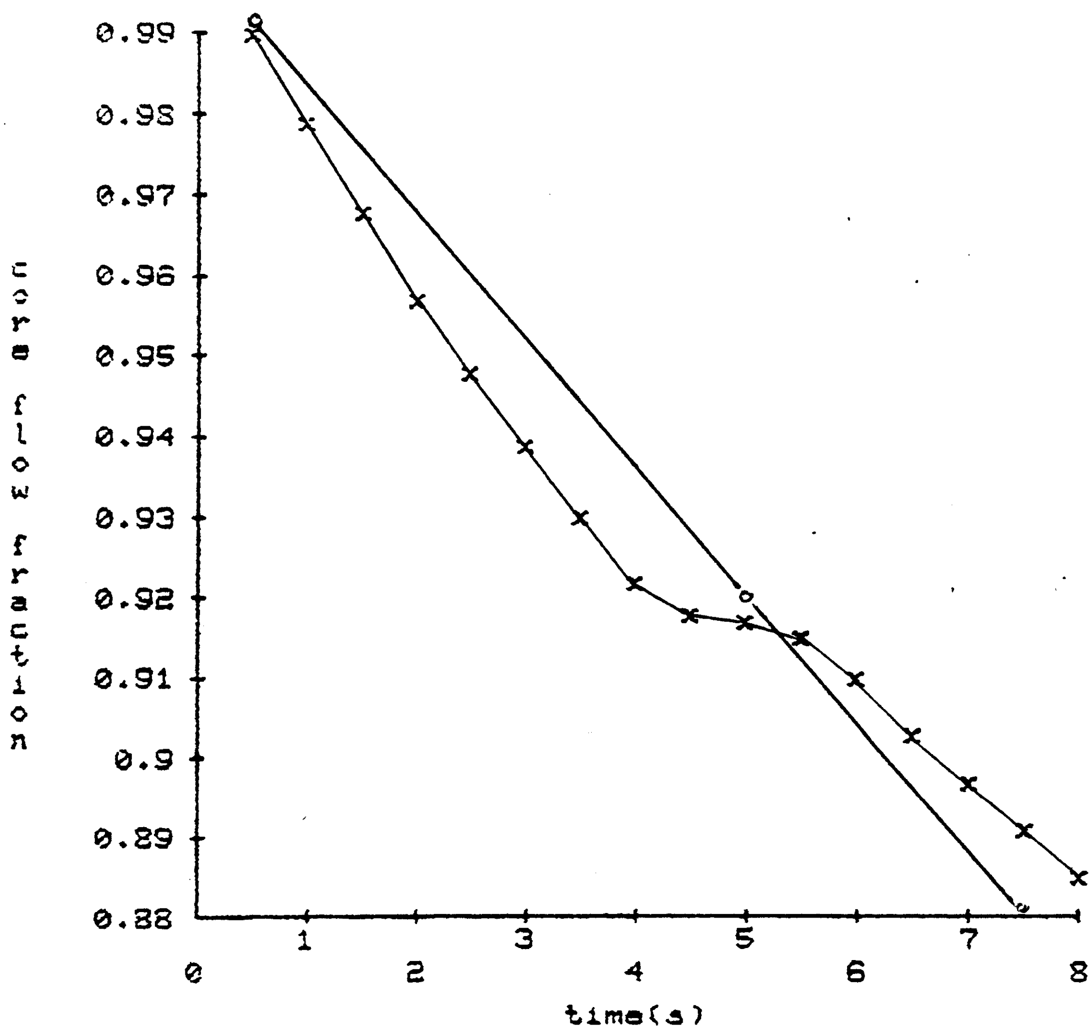
= -5

The results from this report and the true values are shown in table 6.2.5 and figure 6.2.4. There is a kink occurring at a core flow fraction of 0.915. The cause of this kink could be due to the dividing of the head-capacity curve into three regions. Work was not done to determine if this was the cause of the kink.

Table 6.2.5. Results for Maine Yankee One Pump Failure Transient

Time(s)	Maine Yankee FSAR(10) Core Flow Fraction	Computed Values Core Flow Fraction
0.5	0.990	0.990
1.0	0.985	0.979
1.5	0.980	0.968
2.0	0.975	0.957
2.5	0.963	0.948
3.0	0.950	0.939
3.5	0.943	0.930
4.0	0.935	0.922
4.5	0.933	0.918
5.0	0.920	0.917
5.5	0.915	0.915
6.0	0.910	0.910
6.5	0.903	0.903
7.0	0.895	0.897
7.5	0.880	0.891
8.0	0.875	0.885

Figure 6.2.4 MAINE YANKEE ONE PUMP FAILURE



-o- true curve

-x- computed curve

6.2.7. Complete Loss-of-Flow Accident

In this situation, all the pumps have failed. The object of the problem is to determine the reactor vessel flow versus time and to compare these results with those obtained from the Maine Yankee Start-Up report(11).

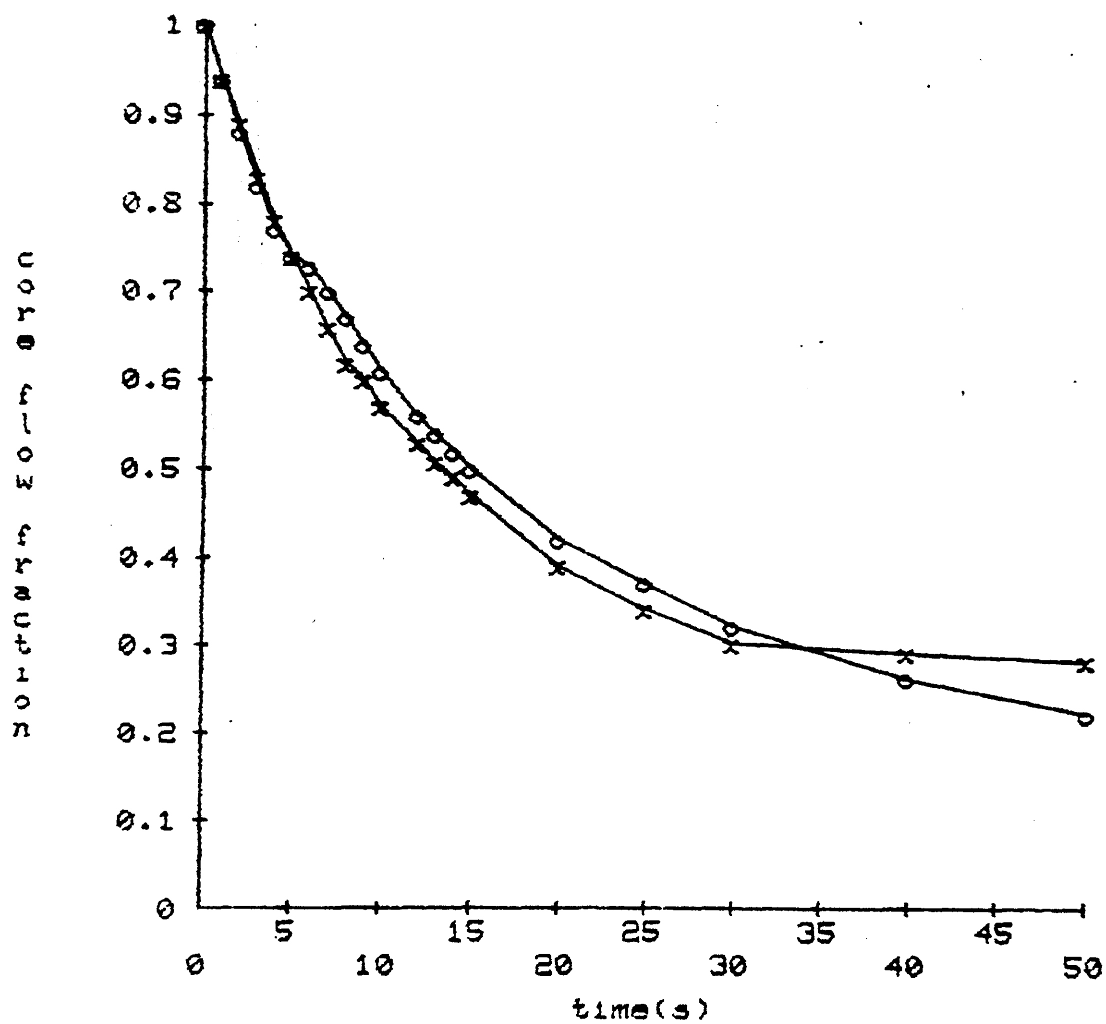
The inputs to the program are the same as in section 6.2.6 except that np equals 3.

The results from this report and the true values are shown in table 6.2.6 and figure 6.2.5. There is a kink occurring at a core flow fraction of 0.74. The cause of the kink could be due to the dividing of the head-capacity curve into three regions. Work was not done to determine if this was the cause of the kink.

Table 6.2.6. Results for Maine Yankee Complete Loss-of-Flow Accident

Time(s)	Maine Yankee Start-Up(11) Core Flow Fraction	Computed Values Core Flow Fraction
0.0	1.00	1.00
1.0	0.94	0.94
2.0	0.89	0.88
3.0	0.83	0.82
4.0	0.78	0.77
5.0	0.74	0.74
6.0	0.70	0.73
7.0	0.66	0.70
8.0	0.62	0.67
9.0	0.60	0.64
10.0	0.57	0.61
12.0	0.53	0.56
13.0	0.51	0.54
14.0	0.49	0.52
15.0	0.47	0.50
20.0	0.39	0.42
25.0	0.34	0.37
30.0	0.30	0.32
40.0	0.29	0.26
50.0	0.28	0.22

Figure 6.2.5.MAINE YANKEE COMPLETE LOSS-OF-FLOW ACCIDENT



6.2.8. Conclusions

For the one pump failure case the results in table 6.2.5 differ from the true values by no more than 2%. This seems adequately close for the pump model to be useful to model the Maine Yankee Reactor during this kind of transient.

For the complete loss-of-flow accident - the results from 0 seconds to 35 seconds are also very close (within 8%) to the true values. After 35 seconds the calculated values begin to fall under the true curve. There is no apparent explanation for this discrepancy. Natural convective processes are probably unimportant in this flow range. It does seem that the experimental curve changes slope in a manner not incorporated in the modeling.

7.CONCLUSIONS AND RECOMMENDATIONS

The performance of a reactor coolant pump has been adequately represented. By using dimensionless quantities, equations have been developed to represent each characteristic curve. The inertances and the pressure losses of the reactor loops have also been modeled. Using this loop model and the pump model, flow values have been predicted during plant transients.

Further work must be done on the pump model to handle cases of flow reversal in the loop. The pump resistance constant was arbitrarily set equal to -5 in all the examples in Chapter 6 and must be determined more precisely. The electric torque is generally assumed to go instantaneously to zero during pump failure. This assumption was made in all the examples but more information must be obtained to test the validity of this assumption. Thermal bouyancy features should be incorporated in the models. This will permit the calculation of portions of transients in which natural circulation becomes important. A final recommendation is to extend this single phase model to possible two phase situations. The work of Wilson(13) should be incorporated in the new pump model.

APPENDIX A COMPUTER PROGRAM USED FOR EXAMPLE FROM FULS' REPORT

A.1.Nomenclature

```
c
c   a1       mass flow through each loop-initial value
c   a2       (L/A) values for each loop
c   a3       coefficient used in change of mass flow equation
c
c   d        pump resistance constant - used when flow
c            reverses in pump
c   delm     change in mass flow at time tl
c   dml      mass flow through the loop at time tl
c   dwl      change in pump speed at time tl
c   dt       time increment
c
c   flowl    subroutine that determines the change in loop mass flow
c            and the change in pump speed in the failed pump
c   flowll   subroutine that determines the change in mass flow
c            in the loop that contains the nonfailed pump
c
c   hc       pressure rise delivered by pump
c
c   limit    number of time increments
c
c   n        total number of pumps
c   np       total number of failed pumps
c
c   t        absolute time after the first pump fails
c   tau      time decay constant of electric torque
c   tl       absolute time after the first pump fails
c   twb      windage and bearing torques
c
c   wl       pump speed at time tl
c   wr       rated pump speed
c   w4       mass flow through the reactor vessel
c
```

A.2.Program Listing

```
      dimension tl(4),wl(4),dml(4),dwl(4),delm(4)
      rewind 10
      rewind 11
      rewind 12
      rewind 13
      write(6,10)
10    format(1x,"enter tau,dt,limit,no. of pumps, no. of pump
     &failures, and pump resistance constant")
      read(5,11)tau,dt ,limit,n,np,d
11    format(v)

c     initialize all the pumps-mass flow in kg/s,pump speed in s-1

      do 40 l=1,n
      tl(l)=0.0
      wl(l)=188.5
      if(l.le.2)go to 20
      a1=813.7187
      go to 30
20    a1=797.5061
      go to 16
30    continue
      dml(l)=a1
      dwl(l)=0.0
      delm(l)=0.0
40    continue

c     write headings of all the failed pumps

      k=1
      if(np.lt.1)go to 50
      write(10,12)k,tl(k),wl(k),dml(k)
      if(np.lt.2) go to 60
      write(11,12) (k+1),tl(k+1),wl(k+1),dml(k+1)
      if (np.lt.3) go to 70
      write(12,12) (k+2),tl(k+2),wl(k+2),dml(k+2)
      if(np.lt.4)go to 80
      write(13,12) (k+3),tl(k+3),wl(k+3),dml(k+3)
22    format(///,30x,"pump number",2x,i2,///,20x,"failure
     & at time",1x,f10.4,10x,"s",//,10x,"Initial pump speed",1x
     &,f10.4,1x,"s-1",//,10x,"Initial mass flow",1x,f10.4,
     &1x,"kg/s",///,18x,"Time",1x,"(s)",27x,"Pump Speed"
     &,1x,"(s-1)",22x,"Mass Flow",1x,"(kg/s)")
      go to 90

c     write headings of all nonfailed pumps

50    write(10,14)k,wl(k),dml(k)
60    write(11,14) (k+1),wl(k+1),dml(k+1)
70    write(12,14) (k+2),wl(k+2),dml(k+2)
80    write(13,14) (k+3),wl(k+3),dml(k+3)
14    format(///,30x,"pump number",2x,i2,///,10x,"Initial
```

```
     & pump speed",1x,f10.4,1x,"s-1",//,10x,"Initial mass flow",
     &1x,f10.4,1x,"kg/s",///,18x,"Time",1x,"(s)",27x,
     &"Pump Speed",1x,"(s-1)",22x,"Mass Flow",1x,"(kg/s)")

90        continue
          t=0.0
          do 190 j=1,limit
          t=t+dt
          if(np.eq.0.0)go to 110

c         flowl determines mass flow through and pump speed
c         of the failed pump

          do 100 k=1,np
          call flowl(tau,dt,tl,wl,dml,dwl,delm,k,n,np,t,d)
100       continue
          if(n.eq.np)go to 130

c         flowll determines mass flow through the nonfailed pump

110       do 120 k=1,n-np
          call flowll(dt,tl,wl,dml,dwl,delm,k,n,np,t,d)
120       continue

130       do 170 k=1,n
          do 160 l=1,n
          if(k.le.2)go to 140
          a2=480.32
          go to 150
140       a2=429.64
          go to 150
150       continue
          if(k.ne.1)delm(k)=delm(k)-(18.86/a2)*delm(1)
160       continue
170       continue

c         update the mass flow through the failed and nonfailed pumps
          do 180 k=1,n
          dml(k)=dml(k)+delm(k)
          if(wl(k).le.0.0)wl(k)=0.0
180       continue

c         write the time, pump speed, and mass flow of all the pumps
          write(10,13)t,wl(1),dml(1)
          write(11,13)t,wl(2),dml(2)
          write(12,13)t,wl(3),dml(3)
          write(13,13)t,wl(4),dml(4)
13        format(15x,2(f10.4,30x),f10.4)
          write(15,15)dwl(1)
15        format(v)
30        continue
          stop
          end
```

```
c         flowl determines mass flow through and pump speed
c         of failed pump

          subroutine flowl(tau,dt,tl,wl,dml,dwl,delm,k,n,np,t,d)
          dimension tl(4),wl(4),dml(4),dwl(4),delm(4)
          wr=188.5

c         determine pressure head delivered by pump

          hc=31.94*wl(k)**2-4.916E-01*dml(k)**2
          if(dml(k).le.0.0)hc=-(d*(5.45E-02)*dml(k)*abs(dml(k)))

c         determine windage and bearing torques

          if(wl(k).ge.35.27) go to 20
          if(wl(k).lt.0.0) wl(k)=0.0
          if(wl(k).eq.0.0) go to 30
          twb=23.21
          go to 40
20        twb=1.866E-02*wl(k)**2
          go to 40
30        twb=66.315
40        continue

c         determine change in pump speed

          dwl(k)=(dt/16.94)*(-1.318E-03*dml(k)*hc*wl(k)/wl(k)**2
     &-1.24*((.19)*wl(k)-(1.198E-02)*dml(k))**2-twb)

c         determine mass flow through the reactor vessel

50        w4=0.0
          do 60 l=1,n
          w4=w4+dml(l)
60        continue

c         update pump speed
c         update pressure head delivered by pump

          wl(k)=wl(k)+dwl(k)
          hc=31.94*wl(k)**2-4.916E-01*dml(k)**2

c         determine change in mass flow

          if(k.le.2)go to 70
          a1=480.32
          a2=2.51E-01
          go to 80
70        a1=429.64
          a2=2.815E-01
          go to 80
80        continue
          delm(k)=(dt/a1)*((-6.194E-02)*w4*abs(w4)
     &-(a2)*dml(k)*abs(dml(k))+hc)
```

```
1         return
          end

c         flowll determines mass flow through nonfailed pump

          subroutine flowll(dt,tl,wl,dml,dwl,delm,k,n,np,t,d)
          dimension tl(4),wl(4),dml(4),dwl(4),delm(4)
          m=np+k

c         determine mass flow through the reactor vessel

          w4=0.0
          do 60 l=1,n
          w4=w4+dml(l)
60        continue

c         determine pressure head delivered by pump

          hc=31.94*wl(m)**2-4.916E-01*dml(m)**2
          if(dml(m).le.0.0)hc=-(d*(5.45E-02)*dml(m)*abs(dml(m)))

c         determine change in mass flow

          if(m.le.2)go to 70
          a1=480.32
          a2=2.51E-01
          go to 80
70        a1=429.64
          a2=2.815E-01
          go to 80
80        continue
          delm(m)=(dt/a1)*((-6.194E-02)*w4*abs(w4)
     &-(a2)*dml(m)*abs(dml(m))+hc)

1         return
          end
```

APPENDIX B COMPUTER PROGRAM USED FOR MAINE YANKEE REACTOR

B.1. Nomenclature

```
c
c   a       ratio of normalized flow divided by normalized speed
c a1-a4    coefficients used in pump speed equation
c a5-a13   coefficients used in mass flow equation
c
c   b1      brake horsepower torque divided by pump impeller
c           moment of inertia
c   b2      correction to head capacity curve when mass flow
c           is below 1864.8 kg/s
c
c   c3      coefficient used in brake horsepower torque equation
c   c4      coefficient used in brake horsepower torque equation
c   cv      modified drag coefficient used in spacer pressure
c           drop formula
c
c   d       pump resistance constant - used when flow reverses in pump
c   delm    change in mass flow in loop at time tl
c   dml     mass flow through the loop at time tl
c   dmr     rated mass flow through the loop
c   dwl     change in pump speed at time tl
c   dt      increment in time
c
c   f1      friction factor for thermal shield
c   f2      friction factor for core
c   f3      friction factor for piping
c   f4      friction factor for steam generator
c   flowl   subroutine that determines the change in loop mass flow
c           and the change in pump speed of the failed pump
c   flowll  subroutine that determines the change in mass flow through
c           the loop with the nonfailed pump
c
c   hc      pressure rise delivered by the pump
c
c   limit   the number of time increments
c
c   n       the total number of pumps in the reactor
c   np      the total number of failed pumps
c
c   tau     time decay constant of electric torque
c   t       absolute time after the first pump fails
c   tl      absolute time after the first pump fails
c   tp      time after each pump fails
c   tr      rated BHP torque
c   twb     windage and bearing torques
c
c   wl      pump speed
c   wr      rated pump speed
c   w4      mass flow through the reactor vessel
c   w5      normalized mass flow through the reactor vessel
c
```

B.2.Program Listing

```
          dimension tl(3),wl(3),dml(3),dwl(3),delm(3)
          rewind 10
          rewind 11
          rewind 12
          rewind 16
          write(6,10)
10        format(1x,"enter tau,dt,limit,no. of pumps, no. of pump
     &failures, and pump resistance constant")
          read(5,11)tau,dt ,limit,n,np,d
11        format(v)

c         initialize all the pumps-mass flow in kg/s,pump speed in s-1

          do 20 l=1,n
          tl(l)=0.0
          wl(l)=125.66
          dml(l)=6060.600
          dwl(l)=0.0
          delm(l)=0.0
20        continue

c         write headings of all the pumps that failed

          k=1
          if(np.lt.1)go to 30
          write(10,12)k,tl(k),wl(k),dml(k)
          if(np.lt.2) go to 40
          write(11,12) (k+1),tl(k+1),wl(k+1),dml(k+1)
          if (np.lt.3) go to 50
          write(12,12) (k+2),tl(k+2),wl(k+2),dml(k+2)
12        format(///,30x,"pump number",2x,i2,///,10x,"failure at time",
     &1x,f10.4,1x,"s",//,10x,"Initial pump speed",1x f10.4,1x,
     &"s-1",//,10x,"Initial mass flow",1x,f10.4,1x,"kg/s",///,
     &18x,"Time",1x,"(s)",27x,"Pump Speed",1x"(s-1)",22x,
     &"Mass Flow",1x,"(kg/s)")
          go to 60

c         write headings of all the pumps that do not fail

30        write(10,14)k,wl(k),dml(k)
40        write(11,14) (k+1),wl(k+1),dml(k+1)
50        write(12,14) (k+2),wl(k+2),dml(k+2)
14        format(///,30x,"pump number",2x,i2,///,10x,"Initial
     & pump speed",1x,f10.4,1x,"s-1",//,10x,"Initial mass flow",
     &1x,f10.4,1x,"kg/s",///,18x,"Time",1x,"(s)",
     &27x,"Pump Speed",1x,"(sec-1)",22x,"Mass Flow",1x,"(kg/s)")

60        continue
          t=0.0
          do 150 j=1,limit
          t=t+dt
          if(np.eq.0.0)go to 80
```

```
c         flowl  determines mass flow through and pump speed
c         of the failed pump

          do 70 k=1,np
          call flowl(tau,dt,tl,wl,dml,dwl,delm,k,n,np,t,d)
70        continue
          if(n.eq.np)go to 100

c         flowll determines mass flow through the nonfailed pump

80        do 90 k=1,n-np
          call flowll(dt,tl,wl,dml,dwl,delm,k,n,np,t,d)
90        continue

100       do 120 k=1,n
          do 110 l=1,n
          if(k.ne.l)delm(k)=delm(k)-(4.36/43.65)*delm(l)
110       continue
120       continue

c         update mass flow through and pump speed of the failed pumps
c         update the mass flow through the nonfailed pumps

          do 130 k=1,n
          wl(k)=wl(k)+dwl(k)
          dml(k)=dml(k)+delm(k)
          if(wl(k).le.0.0)wl(k)=0.0
130       continue

          w4=0.0

          do 140 jj=1,n
          w4=w4+dml(jj)
140       continue


c         write the time, pump speed, and mass flow of all the pumps

          write(10,13)t,wl(1),dml(1)
          write(11,13)t,wl(2),dml(2)
          write(12,13)t,wl(3),dml(3)
13        format(15x,2(f10.4,30x),f10.4)

c         print time and normalized reactor vessel flow

          w5=w4/1.82E+04
          write(16,17)t,w5
17        format(f10.4,",",f10.4)
150       continue
          stop
          end

c         flowl determines mass flow through and pump speed
```

```
c         of failed pump

          subroutine flowl(tau,dt,tl,wl,dml,dwl,delm,k,n,np,t,d)
          dimension tl(3),wl(3),dml(3),dwl(3),delm(3)
          data a1,a2,a3,a4/7.69E-02,7.469E-02,2.69E-02,1.4E+03/
          data a5,a6,a7,a8,a9,a10,a11,a12,a13/5.133E-03,3.287E-02,
     &5.26E-01,1.406E-04,2.476E-03,7.1E-03,7.481E-06,4.36,43.65/
          tr=3.93E+04
          dmr=6060.6
          wr=125.66
          tp=t-tl(k)
          if(tp.lt.0.0) go to 140

c         determining windage and bearing torques

          if(wl(k).ge.23.51) go to 20
          if(wl(k).lt.0.0) wl(k)=0.0
          if(wl(k).eq.0.0) go to 30
          twb=6.533E-03
          go to 40
20        twb=1.183E-05*wl(k)**2
          go to 40
30        twb=1.867E-02
40        continue

c         determining BHP torque

          a=(dml(k)/dmr)/(wl(k)/wr)
          if(a.gt.2)go to 50
          if(a.gt.1)go to 60
          if(a.gt.3.5E-01)go to 70
          c3=-1.09
          c4=1.4
          x=wl(k)
          xr=wr
          go to 80
50        c3=2.54
          c4=-1.4
          x=dml(k)
          xr=dmr
          go to 80
60        c3=2.00
          c4=-1.0
          x=dml(k)
          xr=dmr
          go to 80
70        c3=0.0
          c4=1.00
          x=wl(k)
          xr=wr
80        continue
          b1=(1/4213.99)*(tr*(wl(k)/wr)*c3*(dml(k)/dmr)
     &+c4*tr*(x/xr)**2)
```

```
c         determining change in pump speed

          y=-2*tp/tau
          if(y.lt.-50.0)dwl(k)=dt*(-b1-twb)
          if(y.ge.-50.0)dwl(k)=dt*(a1*wl(k)*exp(y)-b1-twb)

          b2=0.0
          if(dml(k).le.1.8648E+03)b2=(1.40*wl(k)**2)*(1-(dml(k)
     &/1.8648E+03))**(.7143)

c         determining mass flow through the reactor vessel

          w4=0.0
          do 90 l=1,n
          w4=w4+dml(l)
90        continue

c         determining friction factors and drag coefficient

          f1=1.204E-02*(abs(w4))**(-6.86E-02)
          f2=4.785E-02*(abs(w4))**(-1.29E-01)
          f3=3.931E-02*(abs(dml(k)))**(-1.29E-01)
          f4=4.277E-02*(abs(dml(k)))**(-1.57E-01)
          cv=54.86*(abs(w4))**(-2.45E-01)

c         determining pressure rise delivered by pump

          if(dml(k).le.0.0)go to 120
          if(dml(k).gt.4499.75)go to 100
          if(dml(k).le.4499.75)go to 110
100       hc=64.15*wl(k)**2-1.37E-02*dml(k)**2
          go to 130
110       hc=57.11*wl(k)**2-7.364E-03*dml(k)**2+b2
          go to 130
120       hc=-(d*(4.181E-03)*dml(k)*abs(dml(k)))
130       continue

c         determining change in mass flow

          delm(k)=(dt/a13)*((-a5-f3*a6-f4*a7)*dml(k)*abs(dml(k))
     &+(-a8-f1*a9-f2*a10-cv*a11)*w4*abs(w4)+hc)

140       return
          end

c         flowll determines mass flow through the nonfailed pump

          subroutine flowll(dt,tl,wl,dml,dwl,delm,k,n,np,t,d)
          dimension tl(3),wl(3),dml(3),dwl(3),delm(3)
          data a5,a6,a7,a8,a9,a10,a11,a12,a13/5.133E-03,3.287E-02,
     &5.26E-01,1.406E-04,2.476E-03,7.1E-03,7.481E-06,4.36,43.65/
          b2=0.0
          m=np+k
          if(dml(m).le.1.8648E+03)b2=(1.40*wl(m)**2)*(1-(dml(m)
```

```
     &/1.8648E+03))**(.7143)

c          determining mass flow through the reactor vessel

           w4=0.0
           do 20 l=1,n
           w4=w4+dml(l)
20         continue

c          determining friction factors and drag coefficient

           f1=1.204E-02*(abs(w4))**(-6.86E-02)
           f2=4.785E-02*(abs(w4))**(-1.29E-01)
           f3=3.931E-02*(abs(dml(m)))**(-1.29E-01)
           f4=4.277E-02*(abs(dml(m)))**(-1.57E-01)
           cv=54.86*abs(w4)**(-2.45E-01)

c          determining pressure rise delivered by the pump

           if(dml(m).le.0.0)go to 50
           if(dml(m).gt.4499.75)go to 30
           if(dml(m).le.4499.75)go to 40
30         hc=64.15*wl(m)**2-(1.37E-02)*dml(m)**2
           go to 60
40         hc=57.11*wl(m)**2-7.364E-03*dml(m)**2+b2
           go to 60
50         hc=-(d*(4.181E-03)*dml(m)*abs(dml(m)))
60         continue

c          determining change in mass flow

           delm(m)=(dt/a13)*((-a5-f3*a6-f4*a7)*dml(m)*abs(dml(m))
     &+(-a8-f1*a9-f2*a10-cv*a11)*w4*abs(w4)+hc)

70         return
           end
```

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