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THE PWR STEADY-STATE CAPABILITY
OF WRAP-A WATER REACTOR ANALYSIS PACKAGE

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ABSTRACT

This report describes the computational procedure employed in the Water Reactor Analysis Package (WRAP) to determine the steady-state operating conditions of a pressurized water reactor (PWR). The WRAP modular computational system, developed at the Savannah River Laboratory, is a reprogrammed version of the RELAP4 computer code with an extensively restructured input format, a dynamic dimensioning capability and additional computational capabilities such as this procedure.

This procedure can be used to compute the equilibrium volume states, core flow rates, and pump and steam generator characteristics corresponding to a particular PWR system nodalization. With this procedure, PWR transients may be computed by the WRAP system without extensive manual calculations of the initial conditions.

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1. INTRODUCTION

In April 1976, the Savannah River Laboratory (SRL) undertook a project to redesign and reprogram the then-most-recent version of the RELAP4 computer code.¹ The objective of the project was to produce a user-oriented code for routine production use that is more efficient and more readily modifiable than is RELAP4. A major task undertaken to accomplish this objective was the development of a computational procedure for determination of the operating conditions at steady-state in a pressurized water reactor (PWR).

This project resulted in the development of the Water Reactor Analysis Package (WRAP). WRAP is a reprogrammed version of RELAP4 with an extensively restructured input format, a dynamic dimensioning capability and additional computational capabilities such as the PWR steady-state capability described in this document. Companion documents^{2,3} present an overview of WRAP and provide detailed instructions for its use.

The PWR steady-state procedure in WRAP furnishes a capability for initialization of a PWR transient calculation that is not available to the user of RELAP4. The RELAP4 user must generate his own steady-state solution, usually by iteratively estimating the solution and executing short calculations to see if his estimate is reasonable. Each solution estimate made by the user must specify explicitly the pressure, temperature, quality or relative humidity and the mixture level of every volume in the system, with the mass flow rate of every junction. By contrast the WRAP user can obtain a steady-state solution automatically, by a single, short calculation. This solution is obtained from user specifications of thermodynamic states for only a few key control volumes in the system, along with the flow rate within each major coolant loop.

The following sections of this document summarize the WRAP PWR steady-state capability and system model, and present details of the computational procedure used to obtain the steady-state solution.

2. SUMMARY

The WRAP PWR steady-state procedure is totally automatic and requires minimal user input. The nodalization of the system must specify one or more loops connected by a common flow path containing the reactor core. Instead of specifying the volume variables and junction flows required by the RELAP4 pressure residual procedure, the user specifies the following quantities:

- o Specific enthalpies in the loop control volumes at the inlet to the common flow path
- o The pressurizer pressure and the elevation of the water in the pressurizer
- o The loop flow rates
- o Specific enthalpies and pressures on the secondary side of the heat exchangers (steam generators).

The procedure then computes the following quantities:

- o Thermodynamic states of all control volumes
- o Flow splits within the common flow path containing the core
- o Pump speeds
- o Certain heat exchanger (steam generator) characteristics, including variable secondary side wall heat transfer areas (simulating fouling factors) and flows that satisfy conservation of energy for the total system (primary and secondary side).

The user can optionally specify a desired stored energy within the reactor core, and the steady-state procedure will accordingly scale gap conductances.

3. SYSTEM MODEL

3.1 Geometry

The reactor system modeled by the steady-state procedure consists of at least one, but no more than eight coolant loops, connected through a common flow path containing the reactor core. A typical two-loop system nodalization of this type is shown for illustrative purposes in Figure 1. Each of the loops contains one pump (volumes 10 and 22) and one steam generator. Each steam generator contains several contiguous primary side volumes (volumes 3 through 6 and 15 through 18) and one secondary side volume (volumes 27 and 28). There is a pressurizer (volume 30) in one of the loops. Each loop volume contains no more than one inlet and one outlet junction having non-zero flow at steady-state operating conditions.

The loops are connected by a common flow path that contains the reactor core. The common path shown in Figure 1 is bounded on the upstream side by volume 46 and on the downstream side by volume 54. An arbitrary division of flow is permitted within these bounds.

Certain types of other volumes, such as accumulator or containment volumes (volumes 31, 32, and 33) can be connected to the loops by junctions having zero flow. However, the steady-state characteristics of these volumes will not be computed by the procedure, and must be supplied by the user.

FIGURE 1. A Typical System Nodalization Used in the WRAP PWR Steady-State Procedure.

FIGURE 2. Heat Slab Configuration Used in the WRAP PWR Steady-State Procedure.

3.2 Hydraulics

The steady-state form of the momentum equation is solved repeatedly during the steady-state procedure to determine pressure drops across junctions with non-zero flow. Permissible forms of this equation are those employed in the RELAP4/MOD5 code with the exception that two-stream flow with momentum mixing is not allowed. The general form of the equation used in the procedure is presented later.

3.3 Heat Transfer

As in RELAP4, six different heat slab configurations are permitted. These are illustrated in Figure 2. Case 1 and 3 slabs have control volume fluid conditions on one side and no heat transfer on the other. Case 2 slabs have internal heat generation and heat transfer to a control volume on only one surface. Case 4, 5, and 6 slabs have heat transfer at both surfaces. Case 4 has a control volume at each surface, while case 5 and 6 have a control volume at the hot surface and a heat sink at the other surface.

Use of heat slabs in the steady-state procedure is subject to the following restrictions:

1. Case 2 slabs cannot be used outside of the common flow path containing the core.
2. Case 4 slabs cannot be used outside of the steam generators.

Furthermore, within each steam generator heat transfer to the secondary side must take place within heat slabs of a single type. This type may be either case 4, 5, or 6.

The RELAP4 option for use of non-conducting heat exchangers may be used instead of heat slabs to model steam generator heat transfer.

4. INPUT AND OUTPUT SPECIFICATIONS

Input to the steady-state procedure differs in several respects from the input required for the RELAP4 code. These differences are enumerated below.

1. The user should supply only the following thermodynamic state data:
 - a. specific enthalpies for the loop control volumes at the inlets to the common flow path containing the core (volumes 12 and 26 in Figure 1)
 - b. the pressurizer pressure

- c. initial conditions for accumulators, containment, and steam generator secondary side volumes, as well as their connecting junctions.
2. The user should supply flow only for the loops and not within the common flow path.
3. The user must supply the names of certain control volumes, *viz*,
 - a. the upper and lower bounds to the common flow path
 - b. the pressurizer
 - c. steam generator inlets and outlets
 - d. pumps
 - e. loop inlets to the common flow path.
4. The correct junction flow direction must be implicit in the user's specification of the system nodalization.
5. The user must observe the previously stated restrictions on specifications of heat slabs.
6. The user must supply form-loss coefficients for all junctions.
7. The user may supply a value of stored energy for the core.

The initialization procedure produces data sufficient to execute a transient calculation. Included in this data are:

1. Thermodynamic states of all control volumes within the system loops and the common flow path.
2. Flow splits within the common flow path.
3. Pump speeds that produce heads sufficient to balance the pressure drop in each loop.
4. Steam generator characteristics to balance heat removal requirements for each loop, *viz*,
 - a. the secondary side wall heat transfer area (for case 4 slabs), or
 - b. the sink temperature (for case 5 and 6 slabs), or
 - c. the effective heat transfer coefficient (for non-conducting heat exchangers).
5. Core slab gap conductances and internal temperatures consistent with user-supplied stored energy specifications.

These data are computed by the procedure in about 2 minutes of IBM 360/195 CPU time for a test problem with the nodalization illustrated in Figure 1.

5. COMPUTATIONAL DETAILS

5.1 Solution Strategy

Calculations of a system such as that shown in Figure 1 are performed in two steps, *viz*,

1. Computation of thermodynamic states and flow splits for all control volumes downstream of the pumps, and upstream of the steam generators.
2. Computation of steam generator and pump characteristics, and states of the intermediate volumes.

Step 1 in the steady-state procedure starts with the computation of specific enthalpies for all control volumes between the inlets to the common flow path, and the loop volume connected to the pressurizer. The steady-state form of the energy balance equation is used. Initial estimates of core flow rates are supplied automatically by the procedure.

Next the thermodynamic states are determined for all volumes between the volume adjacent to the pressurizer and the inlets to the common flow path. This is done by iterating the steady-state momentum equation and the equation of state starting with the pressure of the volume adjacent to the pressurizer. The volume state is determined using the pressure and specific enthalpies as independent variables.

Then initial estimates of the flow splits within the common flow path containing the core are refined. Within this flow path, there will be, generally, a complex network of series and parallel hydraulic circuits. The number of independent junction flows within the path and the minimum set of momentum and mass balance equations necessary to uniquely specify these flows are determined automatically by the procedure. The resultant set of equations is solved using the Hardy-Cross technique. These new core flows are then used to recompute volume specific enthalpies between the core inlets and the pressurizer.

The preceding procedure is iterated until the volume enthalpies converge. Following convergence, enthalpies, pressures, and thermodynamic states are determined for all loop control volumes lying between the core inlets and the pump outlets, and between the core outlets and the inlets to the upstream sides of the steam generators.

Step 2 in the steady-state procedure starts with an estimate of the pump energy input to the system, based on the rated pump speed. The steady-state energy balance equation is then solved for volumes between the pump inlets and the steam generator outlets, to determine volume enthalpies. Next, the heat transfer properties of each steam generator heat slab are computed, along with the states of steam generator primary side control volumes. These calculations utilize both the steam generator inlet and outlet enthalpies, and the requirement for a steady-state system energy balance. Specific steam generator properties computed by the procedure depend on the slab types selected as previously discussed.

After the steam generator solution, the momentum equation is solved to compute volume pressures from the steam generator inlets downstream to the pumps. These pressures are then used with previously determined loop pressures to determine up-dated values of pump speeds to balance the pressure drops in each loop. The up-dated speeds are used to determine new pump energy inputs, and the calculation is iterated. Iteration continues until the pump speeds converge.

After completion of steps 1 and 2, the stored energy within core heat slabs is adjusted to optional input specifications. If this option is chosen, the initialization procedure will adjust the thermal gap conductivities to match the specifications and to maintain a constant heat flux across each slab.

5.2 Thermodynamic State Calculation

Brief descriptions are given below of the techniques used to compute thermodynamic state variables in the steady-state procedure.

5.2.1 Pressure Calculation. The steady-state form of the momentum equation is evaluated for the pressure difference between adjacent volumes. The form for flow from volume k to volume ℓ across junction i is

$$(P_k - P_\ell) = \text{Fanning Friction} - \Delta P_{\text{gravity}} + \text{junction form loss} + \text{momentum flux} \quad (1)$$

where

$$\text{Fanning Friction} = \left[w_k |w_k| \left(\frac{f_k L_k}{\rho_k D_k A_k^2} \right) + w_\ell |w_\ell| \left(\frac{f_\ell L_\ell}{\rho_\ell D_\ell A_\ell^2} \right) \right] \quad (2)$$

$$\Delta P_{\text{gravity}} = (\rho \Delta Z)_k - (\rho \Delta Z)_\ell \quad (3)$$

$$\text{junction form loss} = \frac{w_i |w_i|}{2\rho_i A_i^2} \left(\text{form loss} + \text{pump loss coefficients} \right) \quad (4)$$

$$\text{momentum flux} = w_\ell^2 \left(\frac{1}{\rho_\ell A_\ell^2} \right) - w_k^2 \left(\frac{1}{\rho_k A_k^2} \right) + w_i^2 \left[\frac{1}{2\rho_i} \left(\frac{1}{A_k^2} - \frac{1}{A_\ell^2} \right) \right] \quad (5)$$

and where

- w = flow rate
- f = fanning friction factor
- L = volume length
- ρ = fluid density
- D = hydraulic flow diameter
- A = flow area
- ΔZ = height above reference elevation.

5.2.2 Enthalpy Calculation. To compute volume and junction specific enthalpies, the steady-state energy balance equation is solved. For a volume i having k inlet and k' outlet junctions, this equation is

$$\sum_{k'} w_{k'} \left(h_{k'} + \frac{V_{k'}^2}{2} + \Delta Z_{k'} \right) = Q_i + \sum_k w_k \left(h_k + \frac{V_k^2}{2} + \Delta Z_k \right) \quad (6)$$

where h , $V^2/2$, and ΔZ are enthalpy, kinetic, and potential energy, respectively, and Q_i is the heat transfer rate in the volume.

Equation (6) is solved in one of two different ways:

1. Given k inlet junctions at known conditions, Equation (6) is solved for constant outlet junction enthalpies, h ; i.e.

$$h_{\text{out}} w_{\text{out}} = Q_i + \sum_k w_k \left(h_k + \frac{V_k^2}{2} + \Delta Z_k \right) - \sum_{k'} w_{k'} \left(\frac{V_{k'}^2}{2} + \Delta Z_{k'} \right) \quad (7)$$

is solved for h_{out} .

2. Given k'outlet junctions with known conditions, (6) is solved for a single inlet junction enthalpy; i.e.

$$\sum_{k'} w_{k'} (h_{k'} + V_{k'}^2 / 2 + \Delta Z_{k'}) - Q_i = w_{in} (h_{in} + V_{in}^2 / 2 + \Delta Z_{in}) \quad (8)$$

is solved for a single value h_{in} .

In either case, having computed junction enthalpies, the volume enthalpy is defined by the average

$$h_i = \frac{\sum_{k'} w_{k'} h_{k'} + \sum_k w_k h_k}{\sum_{k'} w_{k'} + \sum_k w_k} \quad (9)$$

5.2.3 Volume State Calculation. Volume state descriptions are determined by interpolation in the standard RELAP4 steam tables using the pressure and enthalpy as independent variables.

5.3 The Core Flow Calculations

Core flow calculations are performed by solving a system of mass balance and pressure equations for the steady-state junction flows within the general multiple channel flow path containing the reactor core. Important variables in this solution procedure are defined in Table 1.

TABLE 1
Definition of Quantities
Used in the Steady-State Solution for the Core Flows

Mixing Volume	A control volume having more than one inlet or more than one outlet junction.
MNOX	The total number of mixing volumes within the common flow path containing the core.
VMIX(m)	Volume number of the m^{th} mixing volume, $m = 1, 2, \dots, MNOX$.
KNOX(m)	The number of inlet junctions to the m^{th} mixing volume.
WP(j)	Flow (lbm/sec) through the j^{th} junction.
IW1(j)	Index of the volume immediately upstream of the j^{th} junction.
IW2(j)	Index of the j^{th} junction.
$\bar{W}(m)$	Average mass flow rate in the m^{th} volume.

For a system with MNOX mixing volumes, there will be

$$K_1 = \text{MNOX}$$

mass balance equations and

$$K_2 = \sum_{m=1}^{\text{MNOX}} (\text{KNOX}(m) - 1)$$

pressure equations to be solved for a total of

$$K_T = K_1 + K_2$$

independent values of flow $WP(j)$. The general form of the mass balance equation for the m^{th} mixing volume is

$$\sum_{j=1}^{J_m} WP(j) = \sum_{j=1}^{J_{m'}} WP(j), \quad (10)$$

For J_m inlet junctions into m and $J_{m'}$ outlet junctions from m .

The general form of the pressure balance equation is

$$\sum_{JJ} \Delta P(j) = 0 \quad (11)$$

where JJ is a sequence of junctions that starts and terminates at different inlet junctions to a mixing volume. This sequence defines one of the K_2 closed flow loops within the common flow path. $\Delta P(j)$ is an expression defining the pressure drop caused by flow through the j^{th} junction. Generally, ΔP is composed of a sum of as many as seven products of junction dependent coefficients, C_i , and functions of junction flow, f_i , i.e.,

$$P(j) = \sum_{i=1}^7 C_i(j) f_i(j)$$

The C_i 's and f_i 's are listed in Table 2.

TABLE 2
Definition of Terms
in ΔP Expression for the j th Junction

i	$C_i(j)$	$f_i(j)$
1	HEAD2(j)-HEAD1(j)	1.0
2	PFANG1(j)	$\bar{W}(IW1(j)) \bar{W}(IW1(j)) $
3	PFANG2(j)	$\bar{W}(IW2(j)) \bar{W}(IW2(j)) $
4	PFLOSS(j)	$WP(j) WP(j) $
5	MFLOS2(j)	$\bar{W}^2(IW2(j))$
6	MFLOS1(j)	$-\bar{W}^2(IW1(j))$
7	MFLOSS(j)	$WP^2(j)$

The Hardy-Cross⁴ method of solution is used to solve Equations (10) and (11). This method requires the iterative solution of a set of K_2 linear equations in incremental flow corrections. The procedure is to:²

1. Make an initial guess of the K_T flows, consistent with the mass balance equations.
2. Solve an equation that is based on a Taylor series expansion of the first of the K_2 flow equations for an increment δ , by substituting the initial guesses of flows from (1), then update these initial guesses by δ .
3. Repeat (2) for each of the K_2 flow loops.
4. Iterate steps 2 and 3 until $\delta_i = 0$, $i = 1, 2, \dots, K_2$.

The general expression for δ for the JJ th flow loop is

$$\delta_{JJ} = - \frac{\sum_{j=JJ} \left(\sum_{i=1}^7 C_i(j) f_i(j) \right)}{\sum_{j=JJ} \left(\sum_{i=1}^7 |C_i(j) g_i(j)| \right)}, \quad (12)$$

where the C_i and f_i are as defined in Table 2, and the g_i are in Table 3.

TABLE 3
Definitions of Some Terms
in the Hardy-Cross Solution for Flow Corrections

<u>i</u>	<u>$g_i(j)$</u>
1	1.0
2	$2 \bar{W}(IW1(j))$
3	$2 \bar{W}(IW2(j))$
4	$2 WP(j)$
5	$2 \bar{W}(IW2(j))$
6	$- 2 \bar{W}(IW1(j))$
7	$2 WP(j)$

5.4 Steam Generator Calculations

Three different heat conductor types are permitted for representation of steam generators within the steady-state procedure. These correspond to RELAP heat slab cases 4, 5, and 6 in Figure 2. Treatments of each of these conductors by the procedure are presented below.

5.4.1 Conductor Type #1. In this case the slab is a RELAP case 4 slab (bounded by two control volumes). Heat slab properties (geometry, nominal heat transfer areas and coefficients, and thermal conductivity) are supplied by the user, as is the secondary side fluid temperature. Given these quantities, the steady-state procedure will solve for

1. The temperatures of the control volumes on the steam generator primary side,
2. The slab power removal fractions,
3. The secondary side wall heat transfer area required to satisfy the equations of state and conservation of energy.

The solution procedure assumes the heat transfer rate for the i th slab can be expressed as

$$q_i = K_i(T_i - T_s) = \frac{T_i - T_s}{\frac{1}{h_{s_i} (S A_{s_i})} + b_i} \quad (13)$$

where

q_i = the heat transferred to the secondary side fluid

h_{s_i} = the secondary side heat transfer coefficient

A_{s_i} = a nominal secondary side heat transfer area

S = a scale factor to be applied to A_{s_i}

T_i = the primary side control volume temperature

T_s = the secondary side temperature

b_i = the lumped effect of primary side convection and slab conduction

K_i = the effective "conductance" of the i^{th} slab.

With the above assumptions, the procedure is to:

1. Estimate initial values of the above parameters.
2. Iteratively solve for the temperatures of each primary side control volume, using the enthalpy transport equation

$$H_i = H_{i-1} - \frac{K_i(T_i - T_s) + K_{i-1}(T_{i-1} - T_s)}{2W} \quad (14)$$

and the equation of state $T_i = f(P_i, H_i)$

where

W = primary side flow rate.

3. Determine the q_i and the h_{s_i} from the RELAP slab initialization procedure using the T_i from (2), and the initial values of h_{s_i} .
4. Use the q_i to solve equation (13) for the b_i .
5. Scale the secondary side heat transfer by solving

$$\sum_{i=1}^{I_{\max}} q_i = \sum_{i=1}^{I_{\max}} \frac{(T_i - T_s)}{\frac{1}{S_i h_{s_i} A_{s_i}} + b_i} \quad (15)$$

for S_i .

6. Compute new values of K_i from

$$K_i = 1/(1/h_{s_i} (S_1 A_{s_i} + b_i)) . \quad (16)$$

7. Iterate steps (2) through 6 until

$$S_{n+1} = S_n . \quad (17)$$

and then redefine the A_{s_i} accordingly for use in the transient calculation.

5.4.2 Conductor Type #2. This type models a RELAP case 5 or case 6 slab. It consists of a slab with one surface adjacent to the primary side control volume, and the other surface adjacent to a special sink with a constant, unknown, temperature T_2 . The heat slab geometry, secondary side heat transfer coefficient, and fractional power removal, $f_i = q_i/q_{total}$ are supplied by the user. The procedure will

1. Compute the primary side volume temperatures, following the procedure outlined in step (2) for conductors of type #4, with the enthalpy transport expressed as:

$$H_i = H_{i-1} - \frac{q_{total}}{2W} (f_i + f_{i-1}) . \quad (18)$$

2. Compute T_2 , using the RELAP4 initialization procedure for a case 5 or 6 conductor.

5.4.3 Conductor Type #3. This is the RELAP non-conduction heat exchanger model. For this type, steam generator slabs have no explicit heat transfer properties given or required. Instead, a constant T_s and values of f_i are supplied by the user. The steady-state procedure then determines an effective heat transfer coefficient C_i such that, for each primary side volume,

$$f_i q_{total} = C_i W (T_i - T_s) , \quad (19)$$

The procedure will

1. Compute the T_i , using equation (18) as the basis for enthalpy transport.
2. Compute the C_i from equation (19).

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