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— SPLIT —

DIGITAL STEADY-STATE FLOW DISTRIBUTION
CODE FOR VARIOUS PRIMARY SYSTEM PUMP
COMBINATIONS

by

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SPLIT — Digital Steady-State Flow Distribution Code for
Various Primary System Pump Combinations

V. J. Galan, C. K. Miller

Key Words: SPLIT, Flow Distribution, Digital
Computer, Primary System

ABSTRACT

SPLIT is a digital computer code that resolves the steady-state flow distribution in the primary coolant system of a PWR plant with various pump combinations. The program includes the option to determine the flow split for two- and three-loop systems. SPLIT is characterized by low running times and compact printout. Multiple-use runs are an option.

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1. INTRODUCTION

In order to analyze multiple pump and loop operation in PWR plants, B&W has developed a quick, convenient, and accurate method for determining flow splits in the primary coolant system with any combination of operable pumps. The SPLIT digital code determines the flow distribution for systems having one to three loops.

For a plant with L primary loops, $3L+1$ simultaneous equations describe the pressure drop and flow in the loops. Flow paths for a two-loop plant are shown in Figure 1. The Newton-Raphson numerical method is employed to solve the simultaneous nonlinear equations. Using an initial first guess flow for each path, N iterations to solutions for the individual flow paths are performed to obtain the desired accuracy for total flow. For each value of flow during the iteration, the corresponding value of the head produced by the pump in the appropriate flow path is found by linear interpolation from a pump head curve input to the program. The convergence criterion is determined by the number of iteration steps used. The minimum convergence for reactor flow has been set at 1000 lb/h. This means that the difference between the final two iterations will be less than 1000 lb/h. The iteration may be tightened at the expense of additional running time. As set, however, this limit is within 0.001% of the true value.

SPLIT is characterized by low running times and compact printout. Each case is summarized on a single page of computer output. Multiple-use runs can be run as an option input to the program. Input and output are in mass units and/or volumetric units. The conversion to volumetric dimensions is made by multiplying the mass equations by the suitable conversion constant. The solution is valid, but the output is valid only for isothermal loop conditions.

The SPLIT program is sufficiently flexible to accept individual pump head capacity and efficiency curves (either test data or calculated) and/or differences in component pressure drop; i.e., the piping and steam generator pressure drops may be different.

Figure 1. Flow Paths for Two-Loop Plant

2. MATHEMATICAL MODEL

2.1. System Simulation

The system to be simulated is shown in Figure 1, except that the number of loops is allowed to vary between one and three, and the number of pumps per loop is allowed to be either one or two. The energy equation can be used to relate the pressure drops around the system to the pump head. For an incompressible fluid and steady-state flow conditions, the one-dimensional energy equation is

$$\frac{P_1}{V} + \frac{V_1^2}{2g} + Z_1 + \text{pump head} = \frac{P_2}{V} + \frac{V_2^2}{2g} + Z_2 + \text{losses}_{1-2}. \quad (1)$$

Taking points 1 and 2 to be coincident in order to be able to sum around the loop for each pump, equation 1 becomes

$$h_{ij} = \Delta P_r + \Delta P_i + \Delta P_{ij} \quad (2)$$

where

$$\begin{aligned} h_{ij} &= \text{pump head rise in } i\text{th loop for } j\text{th pump,} \\ \Delta P_r &= \text{reactor pressure drop,} \\ \Delta P_i &= \text{hot leg pressure drop in } i\text{th loop,} \\ \Delta P_{ij} &= \text{cold leg pressure drop in } i\text{th loop with } j\text{th pump.} \end{aligned}$$

Equation 2 can be rewritten

$$h_{ij} = \sum_{i=1}^L \sum_{j=0}^P \Delta P_{ij} + \Delta P_r \quad (3)$$

where

$$\begin{aligned} L &= \text{number of loops,} \\ P &= \text{number of pumps per loop,} \\ \Delta P_{i0} &= \text{hot leg pressure drop,} \\ \Delta P_{ij, j \neq 0} &= \text{cold leg pressure drop.} \end{aligned}$$

Conservation of mass is used to relate the flow through the various components in the loops to the pump flows:

$$W_{io} = \sum_{j=1}^P W_{ij} \quad i = 1, \dots, L \quad (4)$$

where i, j, P, L are as defined previously.

The reactor flow is given by

$$W_r = \sum_{i=1}^L W_{io}. \quad (5)$$

For a plant with L loops and P pumps per loop, equation 3 gives LP equations, and equation 4 gives L equations. Along with equation 5, this will yield $(LP + L + 1)$ equation with an equal amount of unknowns.

The pressure drop in the components of a loop of the system as a function of flow is given by

$$\Delta P = KW^2 \quad (6)$$

where

ΔP = pressure drop in the component,

K = resistance factor in the component,

W = flow through the component.

Writing equation 3 in terms of the expression in equation 6, equations 4 and 5 are used to eliminate $(L+1)$ of the unknowns leaving LP unknowns and LP equations. Note that the set of equations is nonlinear in the unknowns, and since the head is not given as an explicit function of the flow, the flow unknowns cannot be solved for explicitly but must be solved by a trial-and-error solution.

For example, the equations that describe the system as shown in Figure 1 are as follows:

From equation 5 —

$$W_T = W_1 + W_2 \quad (7)$$

From equation 4 —

$$W_1 = W_4 + W_5 \quad (8)$$

$$W_2 = W_6 + W_7 \quad (9)$$

From equations 3 and 6 —

$$\Delta P_4 = K_1 W_1^2 + K_4 W_4^2 + K_T W_T^2 = h_4 \quad (10)$$

$$\Delta P_5 = K_1 W_1^2 + K_5 W_5^2 + K_T W_T^2 = h_5 \quad (11)$$

$$\Delta P_6 = K_2 W_2^2 + K_6 W_6^2 + K_T W_T^2 = h_6 \quad (12)$$

$$\Delta P_7 = K_2 W_2^2 + K_7 W_7^2 + K_T W_T^2 = h_7 \quad (13)$$

where

W_T = total reactor flow,

W_1, W_2 = flows in hot legs and steam generators,

W_4, W_7 = flows in respective cold legs,

K_T = flow resistance in reactor,

K_1, K_7 = resistances in paths 1-7,

$\Delta P_4, \Delta P_7$ = loop pressure drops through the respective paths.

The seven equations and corresponding seven unknowns are grouped according to those which contain similar flow terms. The result is two groups of two equations plus the unifying equation (7).

2.2. Solution of System Equations

The Newton-Raphson method is used to solve the nonlinear equations to determine the pump flows. This method involves expanding the equations about the values of the independent variables, which gives a zero for the equations in a Taylor series and includes only lower order terms.

3. INPUT CARD DESCRIPTION

3.1. Preparation of Data Card Input

A sample data form is shown in section 3.2. The first card is input only once for each run. It contains such information as the number of cases to be run, the number of points input on each pump head curve, input and output form (whether mass or volumetric units), and specific volume information if required.

The next series of cards is for the pump head curves. All flow values are entered first and are shown on the sample data form as F01 and F02 cards. Pump head values are entered beginning on the card following the last flow entry. There must be the same number of each of these values as are input on the first data card. Five values are input on each card shown in the sample. Up to 99 points may be used for the pump head curve. These are denoted as H01 and H02 cards in the example shown.

If tables of pump efficiency versus flow rates are desired as input in order to determine pump horsepower, these values are entered on the card following the last pump head values. This series of cards is labeled E01 and E02 on the sample data form.

The next card is a case description card, which provides a record of the number of pumps operating in the loops, fluid temperature, date, and the like.

Card GEN01 is for general flow information: initial guess for reactor flow, K factor for reactor inlet to reactor outlet, number of pumps per loop, number of loops, number of paths per loop, and normal reactor flow. The number of paths per loop is the sum of the hot legs per loop and the number of cold legs per loop.

Cards PATH1 through PATH9 contain flow information pertaining to the named path. Note that the sequence of flow paths is 1, 4, 5, 2, 6, 7, 3, 8, 9. Paths 1, 2, and 3 are hot leg paths, and paths 4 through 9

are cold leg paths. This sequence keeps the correct cold legs with their associated hot legs. Flow guesses are input for each path. For backflow (pump out of service), a negative value should be input. The same holds for the K factors. The hot leg K factor includes the steam generator. The reverse-flow K factors are of different magnitude because of the locked rotor in the pump during reverse flow.

3.2. Sample Data Form

Sample data forms are shown on pages 8 and 9.

PROGRAM: <u>SPLIT</u>										CASE NUMBER:										CHARGE NUMBER:										NAME:										DATE:																																																											
NUMBER OF CASES										NO OF POINTS IN H-Q-E										FORM OF INPUT TO										FORM OF OUTPUT										FORM OF GUESSES										EFFICIENCY CURVE										SP. VOLUME										H-Q ID ARRAY										NO OF H																			
										TABLE										H-Q-E TABLE																																																																															
CARD No. 1																																																																																																			
INPUT ALL FLOW POINTS ON H-Q CURVE AND E-Q CURVE (NO. MUST CORRESPOND TO THAT GIVEN ON FIRST CARD); FOLLOW WITH ALL HEAD POINTS STARTING ON CARD AFTER LAST FLOW VALUE AND THEN ALL EFFICIENCY POINTS IF BHP DESIRED. H-QE POINTS MUST CORRESPOND TO Q-POINTS. FORMAT FOR ALL CARDS IS 5E15.7. MAY HAVE UP TO 99 POINTS FOR EACH.																																																																																																			
CARDS FOR FLOW																																																																																																			
CARDS FOR HEAD																																																																																																			
CARDS FOR EFFICIENCY																																																																																																			
THE FOLLOWING CARDS MUST BE SUPPLIED FOR EACH CASE RUN.																																																																																																			
TITLE AND/OR DATE CARD WITH AN 8A10 FORMAT																																																																																																			
Run Title Card																																																																																																			
Run Path Description Cards																																																																																																			
NEXT, RUN TITLE CARD																																																																																																			
NEXT, RUN PATH DESCRIPTION CARDS																																																																																																			

DATA FORM

PROGRAM: SPLIT	CASE NUMBER:		CHARGE NUMBER:	NAME:	DATE:
	1	2			
5	1	1	1	0	0.02086
1.0.0.4	1.0.0.4	1.0.0.4	1.0.0.4	1.0.0.4	1.2.3.4
1.2.2.5	1.3.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.2.5	3.8.2.7	3.5.5.1	3.2.1.0	2.7.8.0	1.0
2.2.9.1	1.7.5.3	1.1.3.6	1.0.0.4	1.0.0.4	1.0.1.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.2.7	1.6.6.0	1.0.3.7	1.0.0.4	1.0.0.4	1.1.1.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.6.2	1.7.1.4	1.0.9.2	1.0.0.4	1.0.0.4	1.1.1.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.5.7	1.7.0.4	1.0.8.2	1.0.0.4	1.0.0.4	1.1.1.5
0.0.0.0	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.5.7	1.7.0.4	1.0.8.2	1.0.0.4	1.0.0.4	1.1.1.5
0.0.0.0	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.5.7	1.7.0.4	1.0.8.2	1.0.0.4	1.0.0.4	1.1.1.5
0.0.0.0	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.5.7	1.7.0.4	1.0.8.2	1.0.0.4	1.0.0.4	1.1.1.5
0.0.0.0	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.5.7	1.7.0.4	1.0.8.2	1.0.0.4	1.0.0.4	1.1.1.5
0.0.0.0	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.5.7	1.7.0.4	1.0.8.2	1.0.0.4	1.0.0.4	1.1.1.5
0.0.0.0	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.5.7	1.7.0.4	1.0.8.2	1.0.0.4	1.0.0.4	1.1.1.5
0.0.0.0	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.5.7	1.7.0.4	1.0.8.2	1.0.0.4	1.0.0.4	1.1.1.5
0.0.0.0	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5
4.0.0.0	3.8.0.2	3.5.1.1	3.1.6.0	2.7.2.6	1.0
2.2.5.7	1.7.0.4	1.0.8.2	1.0.0.4	1.0.0.4	1.1.1.5
0.0.0.0	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5	0.9.5.5
1.0.0.4	1.1.3.5	1.4.4.5	1.5.5.5	1.6.6.5	1.1.1.5

4. OUTPUT DESCRIPTION

8 1 1 0 .0208600 1 2 3 4 4

#1 PUMP PERFORMANCE CURVE

FLOW GPM	HEAD FT.
7.0000000E+04	4.0250000E+02
8.0000000E+04	3.8270000E+02
9.0000000E+04	3.5510000E+02
1.0000000E+05	3.2100000E+02
1.1000000E+05	2.7800000E+02
1.2000000E+05	2.2910000E+02
1.3000000E+05	1.7530000E+02
1.4000000E+05	1.1360000E+02

#3 PUMP PERFORMANCE CURVE

FLOW GPM	HEAD FT.
7.0000000E+04	4.0000000E+02
8.0000000E+04	3.8020000E+02
9.0000000E+04	3.5110000E+02
1.0000000E+05	3.1600000E+02
1.1000000E+05	2.7360000E+02
1.2000000E+05	2.2620000E+02
1.3000000E+05	1.7140000E+02
1.4000000E+05	1.0920000E+02

#2 PUMP PERFORMANCE CURVE

FLOW GPM	HEAD FT.
7.0000000E+04	4.0000000E+02
8.0000000E+04	3.8020000E+02
9.0000000E+04	3.5110000E+02
1.0000000E+05	3.1600000E+02
1.1000000E+05	2.7260000E+02
1.2000000E+05	2.2270000E+02
1.3000000E+05	1.6690000E+02
1.4000000E+05	1.0370000E+02

#4 PUMP PERFORMANCE CURVE

FLOW GPM	HEAD FT.
7.0000000E+04	4.0000000E+02
8.0000000E+04	3.8020000E+02
9.0000000E+04	3.5110000E+02
1.0000000E+05	3.1600000E+02
1.1000000E+05	2.7360000E+02
1.2000000E+05	2.2570000E+02
1.3000000E+05	1.7040000E+02
1.4000000E+05	1.0820000E+02

OGONEE I RC PUMP SHUTDOWNS WITH CIRCLE W PUMPS AT 532 F 2/1

7/10/73

CASE NUMBER 2

INPUT

REACTOR FLOW (GUESS) = 2.8500000E+05 (GPM)

K (REACTOR) = 9.5580000E-10

NUMBER OF PRIMARY LOOPS = 2

NUMBER OF PUMPS PER LOOP = 2

NUMBER OF PATHS PER LOOP = 3

FLOW PATH
NUMBER

FLOW GUESS
(GPM)

K

THIS DATA IS FOR LOOP NUMBER 1

1	1.0000000E+05	3.7360000E-09
4	-4.0000000E+04	-6.7360000E-08
5	0.5000000E+04	7.9720000E-09

THIS DATA IS FOR LOOP NUMBER 2

2	1.0000000E+05	3.7360000E-09
6	0.5000000E+04	7.9720000E-09
7	9.5000000E+04	7.9720000E-09

OUTPUT

CASE NUMBER 2

OCONEE I PC PUMP SHUTDOWNS WITH CIRCLE W PUMPS AT 532 F 2/1 - 7/10/73

TOTAL REACTOR FLOW = 2.8403214E+05 (GPM)

FRACTION NORMAL REACTOR FLOW = .7534009

TOTAL REACTOR VESSEL PRESSURE DROP = 77.1084546 (FT.)

FLOW PATH NUMBER	FLOW (GPM)	FRACTION NORMAL FLOW	PRESSURE DROP (FT.)	PUMP HEAD (FT.)	PUMP BRAKE HORSEPOWER
THIS DATA IS FOR LOOP NUMBER 1					
1	8.1832581E+04	.4341251	25.0183906		
4	-3.8937625E+04	-.4131313	-102.1270990	0.00	*0000.00
5	1.2077021E+05	1.2813815	116.2751495	218.40	*0000.00
THIS DATA IS FOR LOOP NUMBER 2					
2	2.0219956E+05	1.0726767	152.7450959		
6	1.0109978E+05	1.0726767	81.4831307	311.34	*0000.00
7	1.0109978E+05	1.0726767	81.4831307	311.34	*0000.00

OUTPUT

CASE NUMBER 2

OCONEE I RC PUMP SHUTDOWNS WITH CIRCLE W PUMPS AT 532 F. 2/1

7/10/73

TOTAL REACTOR FLOW = 1.0921281E+08(LB/HR)

FRACTION NORMAL REACTOR FLOW = .7534009

TOTAL REACTOR VESSEL PRESSURE DROP = 25.6699606(PSI)

FLOW PATH - NUMBER - - -	FLOW (LB/HR)	FRACTION NORMAL FLOW	PRESSURE DROP (PSI)	PUMP HEAD (PSI)	PUMP BRAKE HORSEPOWER
THIS DATA IS FOR LOOP NUMBER 1					
1	3.1465334E+07	.4341251	8.3288027		
4	-1.4971851E+07	-.4131313	-33.9988478	0.00	*0000.00
5	4.6437186E+07	1.2813815	38.7088359	72.71	*0000.00
THIS DATA IS FOR LOOP NUMBER 2					
2	7.7747475E+07	1.0726767	50.8499440		
6	3.8873739E+07	1.0726767	27.1263219	103.65	*0000.00
7	3.8873738E+07	1.0726767	27.1263219	103.65	*0000.00

5. RESULTS

Steady-state data from Oconee 1 are compared with data predicted by the SPLIT code; the data are shown in Table 1. The test data reflect isothermal conditions during hot functional testing with the reactor core in place.

Table 1. SPLIT Data Vs Measured Oconee 1 Flows

<u>Pumps</u>	<u>Q_p, gpm</u>	<u>Flow (W), 10⁶ lb/h</u>		
		<u>Loop A</u>	<u>Loop B</u>	<u>Total core</u>
<u>SPLIT Output for 532F</u>				
2/2	94,640	72.4	72.2	144.7
2/1	101,100	77.7	31.4	109.2
2/0	107,000	82.0	-14.6	67.4
1/1	126,400	36.4	36.0	72.4
1/0	129,200	39.7	- 7.0	32.7
<u>Oconee 1 Measured at 532F</u>				
2/2	94,400	72.3	72.8	145.1
2/1	98,400	77.2	32.2	109.4
2/0	104,700	81.8	~11.0	~71.0
1/1	129,200	36.8	36.6	73.4
1/0	132,700	40.8	--	--

6. DISCUSSION

The results calculated using SPLIT agree well with the test values obtained from Ocone 1. The greatest difference between the two is less than 3% of pump flow for all cases and less than 2% of core flow for all cases except the 2/0 case. The 2/0 case shows 5% difference between the calculated and measured flows. This is within the range of the change in accuracy of the flow instrumentation with reverse flow through the B loop.