ESTIMATE OF LOCA-FI PLENUM PRESSURE UNCERTAINTY FOR A FIVE-RING RELAP5 PRODUCTION REACTOR MODEL (U)

by
D. P. Griggs
Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

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SRTC SAVANNAH RIVER TECHNOLOGY CENTER, AIKEN, SC 29808
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1. INTRODUCTION

The RELAP5/MOD2.5 code (RELAP5)[1] is used to perform best-estimate analyses of certain postulated Design Basis Accidents (DBAs) in SRS production reactors. Currently, the most limiting DBA in terms of reactor power level is an instantaneous double-ended guillotine break (DEGB) loss of coolant accident (LOCA). A six-loop RELAP5 K Reactor model is used to analyze the reactor system behavior during the Flow Instability (FI) phase of the LOCA, which comprises only the first 5 seconds following the DEGB.[2] The RELAP5 K Reactor model includes tank and plenum nodalizations having five radial rings and six azimuthal sectors.[3] The reactor system analysis provides time-dependent plenum and tank bottom pressures for use as boundary conditions in the FLOWTRAN code[4], which models a single fuel assembly in detail. RELAP5 also performs the system analysis for the latter phase of the LOCA, denoted the Emergency Cooling System (ECS) phase.[5] Results from the RELAP analysis are used to provide boundary conditions to the FLOWTRAN-TF code[6], which is an advanced two-phase version of FLOWTRAN.

The RELAP5 K Reactor model has been tested for LOCA-FI[7] and Loss-of-Pumping Accident[8] analyses and the results compared with equivalent analyses performed with the TRAC-PF1/MOD1 code[9] (TRAC). An equivalent RELAP5 six-loop, five-ring, six-sector L Reactor model has been benchmarked[3,10-12] against qualified single-phase system data from the 1989 L-Area In-Reactor Test Program[13,14]. The RELAP5 K and L Reactor models have also been subjected to an independent Quality Assurance verification.[15]

The quantification of uncertainty is an important element of determining safe operating power levels for SRS reactors. A detailed methodology for the determination of uncertainty for the FI phase of a DEGB LOCA has been developed.[16] In this methodology, uncertainties in the transient plenum and tank bottom pressures calculated by the reactor system code are two among many accounted for in determining the overall uncertainty in the nominal ("best estimate") power limits. Consequently, these system code uncertainties are quantified as part of the limits methodology. A methodology for estimating the uncertainty in the predicted time-dependent plenum pressures for the DEGB LOCA was developed and applied originally to the TRAC code[17] In this methodology, the plenum pressure uncertainty is estimated by comparing steady-state plenum pressure data measured in L Reactor with TRAC benchmarks of the L Reactor tests, and confirmed by comparisons with RELAP5 LOCA results calculated by an independent group. A preliminary application of the plenum pressure uncertainty methodology to RELAP5 has also been performed[18]. This report describes the application of a modified version of this methodology to the estimation of RELAP5 plenum pressure uncertainties for the FI phase of the LOCA.

2.0 1989 L REACTOR TEST SERIES AC4M

As part of the effort to restart P, K, and L Reactors following their shutdown in 1988, a series of tests were performed in L Reactor to provide integral hydraulic data pertinent to various modes of reactor operation. The tests were performed with a fresh Mark 22 charge at zero power. The reactor was operated with no helium cover gas and the blanket gas space vented to atmosphere. Many of these tests focused on the low tank level conditions characteristic of the

ECS phase of a DEGB LOCA. In the these test series referred to as "AC4M," either 5 or 6 alternating current (AC) pump motors were used to drive the reactor coolant pumps during the tests. The tank level was varied from overflow conditions to about 10" in successive hold points or "steps". Several of the steps conducted with the tank at overflow were selected for benchmarking the RELAP5 model and for estimating plenum pressure uncertainty. One of the selected test steps was performed with all six process pumps under both AC and direct current (DC) power as in normal operation. Three of the test steps were conducted with five process pumps under AC and DC power and the sixth pump inoperative. These three test steps resulted in backflow through the loop containing the inoperative pump, thereby simulating some of the thermal-hydraulic conditions expected in the LOCA. The remaining test steps were conducted with five process pumps under AC and DC power and the sixth pump inoperative with the loop rotovalves closed. This configuration produces a "no-flow" condition in one loop. Table 1 presents the basic configuration of the selected test steps.

One of the goals of the 1989 Tests was to measure the plenum pressure distribution in some detail. Special pressure tap plenum plugs were used to measure pressures inside the permanent sleeve and universal sleeve housing (USH) at approximately 30 plenum locations. The location of these pressure measurements on a reactor facemap is shown in Figure 1. As Figure 1 shows, each RELAP5 plenum cell encompasses all or part of a number (15-41) of permanent sleeve positions. For the 1989 L Reactor tests, the 24 plenum cells comprising rings 1 through 4 (1 being the center ring) represent the region providing boundary conditions for the fuel assemblies. The positions associated with ring 5 are occupied by blanket assemblies, gas port sleeves, confinement heat removal instrument plugs, or long plenum plugs.

Figure 1 also shows that the pressure measurements were concentrated in the interior of the plenum. At seven of these locations, flow down the assembly was blocked by additional instrumentation packages. For these "no-flow" positions, the measured pressure is considered to be equal to the plenum pressure (i.e., the pressure outside the USH and permanent sleeve). For the remaining positions shown in Figure 1, the assembly was not blocked, so the measured pressure is less than the exterior plenum pressure because of the pressure drop associated with the flow through the slots in the permanent sleeve and the holes in the USH. The QUAL89 program[19] converts the pressure measurement made inside the permanent sleeve and USH to an average plenum pressure outside the permanent sleeve using data on pressure drop and flow rate measured in "A" tank. The methodology for this conversion was subjected to a technical review as part of the qualification effort for the 1985 L Reactor hydraulics data[20,21]; the implementation of this methodology in QUAL89 has also been reviewed[22]. These converted plenum pressure measurements (referred to hereafter as "plenum data") have been used in the development and benchmarking of L Reactor models for RELAP5[3,10-12] and are used in the current work as well.

3. UNCERTAINTY ESTIMATION METHODOLOGY

The details of the methodology and its prior application to the TRAC code are discussed in WSRC-TR-90-263[17]. The methodology for estimating the transient plenum pressure uncertainty was developed to be consistent with the uncertainty methodology itself. The uncertainty required for the limits analysis is for the time interval 0.5 to 2.0 seconds during the LOCA. It is given as one standard deviation of a normal distribution in terms of absolute pressure in pounds per square inch (psi). The plenum pressure uncertainty to be estimated is an average over the portion of the plenum that provides boundary conditions to flowzones 1-4, since only these flowzones are considered in satisfying the core-wide probability of not exceeding the limits criterion.

The plenum pressure uncertainty is estimated by comparing plenum pressure measurements from selected hold points, or "steps", from the AC4M test series run in L Reactor in 1989 to RELAP5 analyses of the tests. The RELAP5 code and a five-ring, six-sector 1989 L Reactor Test model were benchmarked against the seven AC4M steps by Gill[12]. The RELAP5 plenum pressure results from the benchmark analyses of the seven selected test steps are compared to the data using an approach consistent with the uncertainty methodology. The RELAP5 cell-averaged pressures are interpolated spatially to give calculated values at the location of each measured plenum pressure. The interpolation scheme, which uses a linear method in the azimuthal direction and a spline fit in the radial direction, is taken from the overall limits uncertainty methodology. As part of the preliminary estimation of RELAP5 plenum pressure uncertainty[18], the INTERP1 program[17] used in the TRAC uncertainty analysis was modified to accept RELAP5 plenum pressure results in Pascals rather than psia and assembly azimuthal position in degrees rather than radians; some minor formatting changes were made as well. The resulting program, called INTERP2, is used to perform the comparison of calculated and measured plenum pressures. Appendix A contains a listing of INTERP2.

For a given test step, INTERP2 performs the interpolation of RELAP5 plenum pressures to the permanent sleeve locations where measurements were made and calculates the differences between the plenum pressure data and the interpolated RELAP5 pressures. Both absolute and relative pressure differences are calculated, as well as the sum and sum of the squares of the differences. The absolute differences are calculated as interpolated RELAP5 pressure minus measured pressure. The relative differences are the absolute differences divided by the data.

The INTERP2 program is run for each test step in turn. Two input files are required for each run. The first file, "interp.in", contains the RELAP5 plenum pressures for the given test, the radii of the plenum rings, and the number of assembly positions to be compared. The 24 pressures for rings 1 through 4 are given in Pascals absolute (Pa) and the radii in inches. The calculated plenum pressures are ordered according to the TRAC plenum cell numbering convention shown in Figure 2. The second input file, "olcp.in", contains the On-Line Computer (OLC) number and "r,θ" location of each assembly position to be included and the corresponding measured plenum pressure, in psia. In this case, the 25 plenum pressure measurements corresponding to assembly positions in K-14.1[23] flowzones 1 through 4 are included. The radial positions are given in inches and the azimuthal positions given in degrees, with the azimuthal origin taken to be the radius between TRAC sectors 1 and 6 and increasing angles in the counterclockwise direction. The output of the INTERP2 program is written to a file called "interp.out". This file contains the RELAP5 plenum cell pressures, the plenum radii, and the total number of assembly positions considered. It also shows the interpolated RELAP5 pressures, the pressure measurements, and the absolute and relative differences between them for each position considered. Finally, the sum and sum of the squares of the differences (both absolute and relative) is given.

The sums and sums of squares of the pressure differences from INTERP2 are used to calculate the mean and standard deviation of all the differences for a number of tests. The mean and standard deviation of the distribution of the differences are calculated according to the following expressions:

$$\mu = (\Sigma\delta)/N \qquad (1)$$

$$\sigma = \{[N\Sigma(\delta)^2 - (\Sigma\delta)^2]/[N(N-1)]\}^{0.5} \qquad (2)$$

where,

μ = the mean of the distribution of differences;

σ = the standard deviation of the distribution of differences;

δ = the difference (absolute or relative) between the interpolated RELAP5 plenum pressure and the measured plenum pressure at a particular location; and
N = the total number of pressure differences in the distribution.

This calculation is not done in INTERP2; rather it is done separately using the results from several INTERP2 runs. The derivation of Equation 2 is given in Ref. 17.

Once the mean and standard deviation of the sample distribution of differences are determined, they are used to estimate the plenum pressure uncertainty. The sample mean is an indication of any systematic difference, or bias, between the data and the interpolated RELAP5 pressures. The sample standard deviation is a measure of the variability of the differences about the mean. The sample standard deviation obtained with Equation 2 can be used to make a conservative estimate of the transient uncertainty (given that any bias implied by the sample mean is also taken into account).

4.0 UNCERTAINTY ESTIMATE RESULTS

The INTERP2 program was run for the seven selected AC4M steps (i.e., 19, 16, 27, 46, 14, 29, and 44). Appendix B contains the "interp.out" files for the 7 steps (note that all the information from the "olcp.in" and "interp.in" files is also in the "interp.out" files).

Table 2 presents a summary of the INTERP2 results for the 7 steps. Each test had 25 measurements in positions corresponding to K-14.1 flowzones 1-4, for a total of 175 comparisons. As discussed before, the values in Table 2 can be used to determine absolute and relative means and standard deviations for selected tests or groups of tests. In the previous uncertainty analyses[17,18], the approach was to combine all the available tests to determine the plenum pressure error mean and standard deviation. For TRAC, the selected benchmark tests were either of the 6 AC full flow or the 5 AC with 1 backflow (BF) type. Though the "5 AC, 1 BF" tests provide flow and pressure distributions that are the most representative of a plenum inlet break LOCA, these tests alone were not considered to provide a complete basis for estimating plenum pressure uncertainty. The measurement positions in the 1985 L Reactor tests were concentrated in a 120° sector, and in each case the backflow loops received flow from that sector. This distribution of measurement locations meant that plenum pressure behavior in regions receiving flow from loops with operating AC pumps was "under-represented" in the "5 AC, 1 BF" type of test. Consequently, three "6 AC" tests were combined with three "5 AC, 1 BF" tests to provide a better representation of the plenum-wide pressure uncertainty.

In the preliminary estimate of RELAP5 plenum pressure uncertainty, the approach was to replicate the earlier TRAC methodology as much as possible. As Table 1 shows, the available qualified benchmark cases included three "5 AC, 1 BF" but only one unique "6 AC" case. The three tests of the 5 AC with 1 no-flow (NF) type were included to increase the total number of tests (and data points) to be comparable to that used for TRAC.

As Figure 1 shows, the distribution of plenum pressure measurements in the 1989 L Reactor tests was not concentrated in any sector. There is therefore no apparent need to combine different types of tests as done previously. The three "5 AC, 1 NF" tests provide information on the model's ability to predict another distinct type of plenum pressure distribution, but the applicability of these results to LOCA plenum pressure prediction uncertainty is somewhat indirect. The three "5 AC, 1 BF" tests alone may provide an appropriate and sufficient basis for the estimation of uncertainty. In order to decide the question of test selection, the three flow configurations represented in the tests are examined individually and then with all seven tests combined as before.

Table 3 shows the results of determining the means and standard deviations of the distributions of absolute plenum pressure prediction "errors" for the "6 AC" case, the three "5 AC, 1 NF" cases, the three "5 AC, 1 BF" cases, and all seven cases combined. The mean errors range from 0.35 psi for the "5 AC, 1 NF" cases to 0.99 psi for the "5 AC, 1 BF" cases. For all combinations, the mean is positive, indicating a positive plenum pressure "bias" in the RELAP5 model. The standard deviation ranges from 1.85 psi for the "5 AC, 1 NF" cases to 2.34 psi for the "6 AC" case. Overall, the best benchmark results are for the "5 AC, 1 NF" cases and the worst are for the "5 AC, 1 BF" case. Note that the average plenum pressure is highest for the "6 AC" case and lowest for the "5 AC, 1 BF" case. Thus, the amount of "error" in the prediction does not appear to be proportional to the average plenum pressure, but depends primarily on the configuration of the tests. In light of these results, it seems appropriate to base the uncertainty estimate upon the "5 AC, 1 BF" cases because they are the most "LOCA-like" and provide the most conservative estimate.

A second issue in arriving at a plenum pressure uncertainty estimate for the LOCA is the use of the absolute or relative mean and standard deviation from the data. One approach is to use the standard deviation in the absolute pressure differences as the basis for the uncertainty. Another approach is to use the standard deviation of relative differences as the measure of uncertainty and assume that the absolute uncertainty is proportional to the plenum pressure. This approach yields a lower uncertainty estimate for the LOCA because the pressure level during the LOCA is significantly lower than in the L Reactor tests.

The two approaches yield the following results:

Absolute pressure differences (interpolated RELAP5 minus data) -

mean:	0.99 psi
standard deviation:	2.05 psi

Relative pressure differences (absolute differences divided by data) -

mean:	0.018
standard deviation:	0.033

The average calculated LOCA plenum pressure in rings 1-3 over the time period of interest is about 44 psia. Table 4 shows the RELAP5 plenum pressures in rings 1-3 at 0.5s, 1.0s, 1.5s, and 2.0s during the LOCA[7]. The average of these pressures at each time is also shown. Applying the relative mean of 0.018 and the relative standard deviation of 0.033 to the average plenum pressures (rings 1-3) at these times gives the following results:

time: 0.5s	mean: 0.80 psi	standard deviation:	1.49 psi
time: 1.0s	mean: 0.79 psi	standard deviation:	1.47 psi
time: 1.5s	mean: 0.78 psi	standard deviation:	1.44 psi
time: 2.0s	mean: 0.77 psi	standard deviation:	1.44 psi

Using this approach, the LOCA mean plenum pressure error and standard deviation over the time period of interest are approximately 0.8 psi and 1.5 psi, respectively, as compared to approximately 1.0 psi and 2.1 psi, respectively, taken directly from the data. Since there is no basis in the data supporting the "scaling" of the uncertainty to the average plenum pressure, the higher values should be used. Historically, a transient plenum pressure uncertainty of ±2.5 psi with no bias correction has been used in determining the LOCA-FI effluent temperature limits.[16] Based upon the results given above, the LOCA-FI limits for K-15.1 should account for a +1.0 psi bias in the predicted transient plenum pressures and retain the ±2.5 psi uncertainty used previously.

5.0 CONCLUSIONS

The transient plenum pressure uncertainty methodology used previously in the LOCA-FI limits methodology has been applied to the five-ring, six sector RELAP5 model that is the basis for the K-15.1 LOCA system analysis. Seven hold points from the 1989 L Reactor AC4M Test Series were evaluated as a basis for estimating the plenum pressure uncertainty. It was concluded that the uncertainty should be based upon the three data sets from simulated LOCA (5 loops under AC pumping with 1 loop in backflow) hold points. Measured plenum pressures from these tests were compared to calculated plenum pressures from RELAP5 benchmarks of the tests. The RELAP5 pressures, which represent averages over relatively large plenum control volumes, were interpolated to give pressures at the locations where measurements were taken and a distribution of differences between measured and calculated pressures was obtained. The resulting distribution of differences have an absolute mean and standard deviation of 0.99 and 2.05 psi, respectively. The mean value of approximately 1.0 psi represents a "bias" in the RELAP5 prediction of plenum pressures that must be accounted for in the determination of effluent temperature limits. Therefore, it is recommended that the K-15.1 LOCA-FI limits account for a +1.0 psi bias and a ± 2.5 psi transient plenum pressure uncertainty.

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Table 1

Configurations of Selected AC4M Test Steps

Step	Tank Level (in)	Pumps	Process Water Systems 1	2	3	4	5	6
19	229.9	6 AC	AC	AC	AC	AC	AC	AC
16	228.7	5 AC	AC	BF	AC	AC	AC	AC
27	228.5	5 AC	AC	AC	BF	AC	AC	AC
46	228.8	5 AC	AC	AC	AC	BF	AC	AC
14	229.6	5 AC	AC	NF	AC	AC	AC	AC
29	229.5	5 AC	AC	AC	NF	AC	AC	AC
44	229.6	5 AC	AC	AC	AC	NF	AC	AC

Key: AC - pumps operated with AC and DC motors, normal full flow in system;
BF - pump off, backflow in system;
NF - pump off, rotovalves closed, no flow in system.

TABLE 2

SUMMARY OF INTERP2 RESULTS FOR 7 AC4M TEST STEPS

Step	N	Absolute Differences		Relative Differences	
		$\Sigma\delta$	$\Sigma(\delta^2)$	$\Sigma\delta$	$\Sigma(\delta^2)$
19	25	15.65	141.38	0.209	0.021
16	25	31.10	132.99	0.551	0.037
27	25	28.35	146.47	0.517	0.042
46	25	14.76	104.12	0.277	0.027
14	25	18.46	94.03	0.296	0.021
29	25	5.37	85.88	0.101	0.019
44	25	2.21	81.63	0.052	0.017
Total	175	115.90	786.50	2.003	0.184

TABLE 3

SUMMARY OF ABSOLUTE UNCERTAINTY RESULTS FOR 7 AC4M TEST STEPS

Step	N	Absolute Differences		mean	sigma
		$\Sigma\delta$	$\Sigma(\delta^2)$	psi	psi
6 AC	25	15.65	141.38	0.63	2.34
5 AC, 1 NF	75	26.04	261.54	0.35	1.85
5 AC, 1 BF	75	74.21	383.58	0.99	2.05
All seven	175	115.90	786.50	0.66	2.02

TABLE 4

RELAP5 LOCA PLENUM PRESSURES

RELAP5 Plenum Cell	Plenum Pressure (kPa) at:			
	0.5s	1.0s	1.5s	2.0s
Ring 1, Sector 1 (3)	299.27	294.38	286.87	286.87
Ring 1, Sector 2	299.84	294.96	287.44	287.44
Ring 1, Sector 5	286.06	281.44	274.25	274.25
Ring 1, Sector 6 (4)	294.36	289.53	282.13	282.13
Ring 2, Sector 1 (3)	319.27	314.62	306.98	306.98
Ring 2, Sector 2	320.60	315.98	309.93	308.33
Ring 2, Sector 5	275.19	271.35	266.06	264.70
Ring 2, Sector 6 (4)	307.26	302.61	296.73	295.17
Ring 3, Sector 1 (3)	340.44	336.18	330.11	328.44
Ring 3, Sector 2	342.28	338.05	331.98	330.31
Ring 3, Sector 5	270.35	266.99	261.97	260.66
Ring 3, Sector 6 (4)	323.65	319.26	313.36	311.74
Average, kPa	308.94	304.55	298.68	297.13
Average, psia	44.81	44.17	43.32	43.10

Figure 1
1989 L Reactor Test Plenum Pressure Measurement Locations

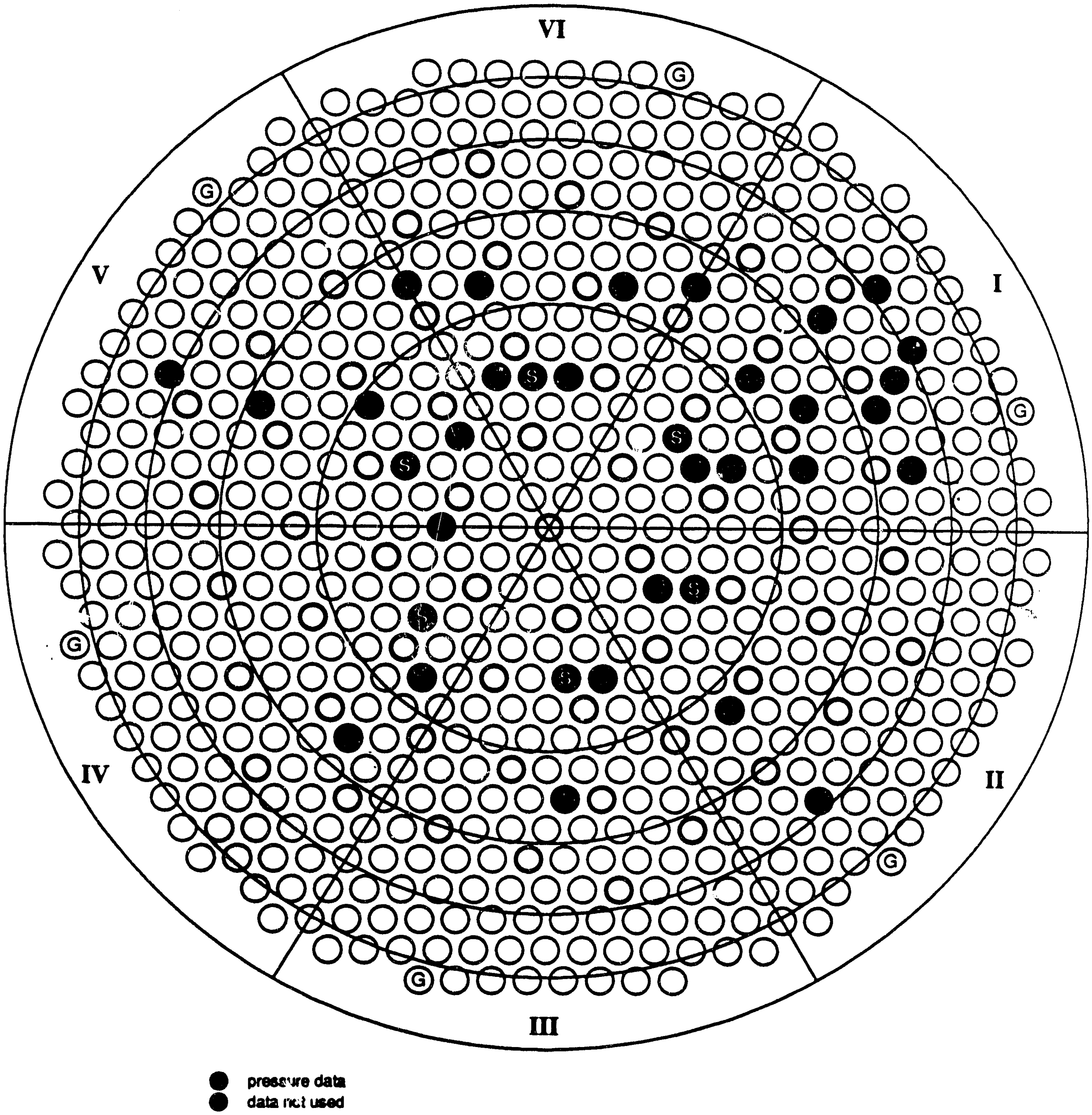
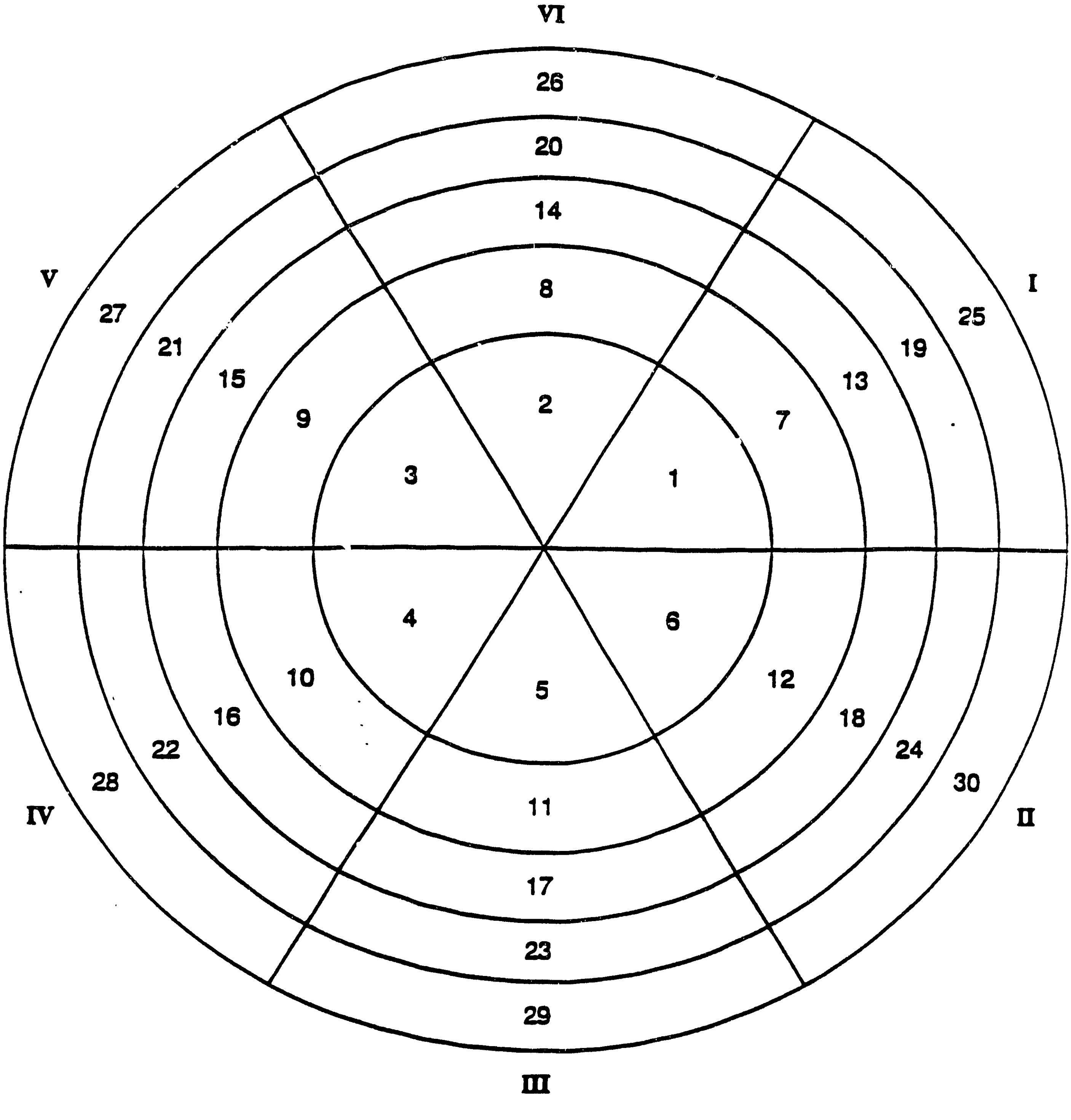


Figure 2
Five-Ring Plenum Grid with TRAC Cell Numbering Convention

Roman Numerals Indicate SRS Process Water System Numbers



APPENDIX A

INTERP2 Program Listing

```
c       this program interpolates among RELAP5 cell pressures
c       (using a cubic spline interpolation scheme
c       to create three curves along each of the sector lines
c       followed by a linear weighting of the values on the
c       lines by the angle from each line ) to determine
c       calculated plenum pressures that can be compared
c       directly with measured plenum pressures
      dimension nolc(90),nolc2(90),ttot(90),press(90)
      dimension p(24),ppa(24),xll(8),yl(8,3),fdp(8,3)
      dimension r(90),theta(90),diff(90),rdiff(90)
      open(unit=11,file='interp.in',status='old')
      open(unit=12,file='olcp.in',status='old')
      open(unit=6,file='interp.out',status='new')
      nin=11
      read(nin,107) (p(i),i=1,24)
  107 format(f10.2)
      pconv=6894.7573
      do 90 i=1,24
      ppa(i)=p(i)
      p(i)=p(i)/pconv
   90 continue
      write(6,108) ((i,ppa(i),p(i)),i=1,24)
  108 format(' The RELAP5 pressures for the different cells are:',
     1/6x,'N',5x,'Pa',13x,'psia',/24(4x,i3,1x,f10.2,4x,f10.2/))
      read(nin,100) r1,r2,r3,r4
  100 format(1x,f7.2,1x,f7.2,1x,f7.2,1x,f7.2)
      write(6,101) r1,r2,r3,r4
  101 format(1x,'the inner and outer radii are',4(1x,f10.2))
c
c      this code is taken from Numerical Methods in
c      Engineering by Ferziger, p.17,18
c
      nd=8
      xll(1)=-(r4+r3)/2.
      xll(2)=-(r3+r2)/2.
      xll(3)=-(r2+r1)/2.
      xll(4)=-(r1/2.)
      xll(5)=r1/2.
      xll(6)=(r1+r2)/2.
      xll(7)=(r2+r3)/2.
      xll(8)=(r3+r4)/2.
      do 200 kki=1,3
      yl(1,kki)=p(21+kki)
      yl(2,kki)=p(15+kki)
      yl(3,kki)=p(9+kki)
      yl(4,kki)=p(3+kki)
      yl(5,kki)=p(kki)
      yl(6,kki)=p(6+kki)
      yl(7,kki)=p(12+kki)
      yl(8,kki)=p(18+kki)
c
c      the next step sets up the spline function
c
      call spline(nd,xll,yl(1,kki),fdp(1,kki))
  200 continue
c
c       we now set up a loop that interpolates among the press.
c
      read(nin,102) nass
  102 format(1x,i3)
      write(6,103) nass
  103 format(1x,' The number of assemblies considered is ',i3)
      write(6,109)
```

```
  109 format(/3x,'n',5x,'olc',4x,'radius',6x,'theta',4x,
     1'p, interp',2x,'p, L data',3x,'(I - L)',2x,'(I - L)/L')
      do 1 i = 1,nass
      read(12,104) nolc(i),r(i),theta(i),press(i)
  104 format(5x,i3,3(5x,f6.2))
    1 continue
c
c     loop over all assemblies to find the two lines it is between
c
      var=0.0
      rvar=0.0
      do 205 i=1,nass
      if(theta(i).lt.30.or.theta(i).ge.330.)then
c
c      interpolate between line 1+ and line 3-
c
      call speval(nd,x11,y1(1,1),fdp(1,1),r(i),tt1)
      r2=-r(i)
      call speval(nd,x11,y1(1,3),fdp(1,3),r2,tt2)
      the=theta(i)
      if(the.lt.31.)the=the+360.
      ttot(i)=tt2*(390.-the)/60.+tt1*(the-330.)/60.
      go to 204
      end if
      if(theta(i).lt.90.and.theta(i).ge.30.)then
c
c      interpolate between line 1+ and 2+
c
      call speval(nd,x11,y1(1,1),fdp(1,1),r(i),tt1)
      call speval(nd,x11,y1(1,2),fdp(1,2),r(i),tt2)
      the=theta(i)
      ttot(i)=tt2*(the-30.)/60.+tt1*(90.-the)/60.
      go to 204
      end if
      if(theta(i).lt.150.and.theta(i).ge.90.) then
c
c      interpolate between lines 2+ and 3+
c
      call speval(nd,x11,y1(1,2),fdp(1,2),r(i),tt1)
      call speval(nd,x11,y1(1,3),fdp(1,3),r(i),tt2)
      the=theta(i)
      ttot(i)=tt2*(the-90.)/60.+tt1*(150.-the)/60.
      go to 204
      end if
      if(theta(i).lt.210.and.theta(i).ge.150.) then
c
c      interpolate between lines 3+ and 1-
c
      call speval(nd,x11,y1(1,3),fdp(1,3),r(i),tt1)
      r2=-r(i)
      call speval(nd,x11,y1(1,1),fdp(1,1),r2,tt2)
      the=theta(i)
      ttot(i)=tt2*(the-150.)/60.+tt1*(210.-the)/60.
      go to 204
      end if
      if(theta(i).lt.270.and.theta(i).ge.210.) then
c
c      interpolate between lines 1- and 2-
c
      r2=-r(i)
      call speval(nd,x11,y1(1,1),fdp(1,1),r2,tt1)
      call speval(nd,x11,y1(1,2),fdp(1,2),r2,tt2)
      the=theta(i)
```

```
      ttot(i)=tt2*(the-210.)/60.+tt1*(270.-the)/60.
      go to 204
      end if
c
c      interpolate between lines 2- and 3-
c
      r2=-r(i)
      call speval(nd,x11,y1(1,2),fdp(1,2),r2,tt1)
      call speval(nd,x11,y1(1,3),fdp(1,3),r2,tt2)
      the=theta(i)
      ttot(i)=tt2*(the-270.)/60.+tt1*(330.-the)/60.
 204  diff(i)=ttot(i)-press(i)
      rdiff(i)=diff(i)/press(i)
      sum=sum + diff(i)
      rsum=rsum + rdiff(i)
      var=var + (abs(diff(i)))**2
      rvar=rvar + (abs(rdiff(i)))**2
      write(6,150) i,nolc(i),r(i),theta(i),ttot(i),press(i),
     1diff(i),rdiff(i)
 150  format(1x,2(i4,2x),2(f9.3,2x),3(f9.2,2x),f7.3)
 205  continue
      write(6,152) sum,var
      write(6,151) rsum,rvar
 151  format(/1x,'Sum of relative errors:',4x,f7.3/
     11x,'Sum squared relative errors:',f7.3)
 152  format(/1x,'Sum of pressure errors:',4x,f9.2,3x,'psia'/
     11x,'Sum squared pressure errors:',f9.2,3x,'psia')
      stop
      end
      subroutine spline(n,x,y,fdp)
      dimension x(8),y(8),a(8),b(8),c(8),r(8),fdp(8)
      alamda=1.
      nm2=n-2
      nm1=n-1
      c(1)=x(2)-x(1)
      do 1 i=2,nm1
      c(i)=x(i+1)-x(i)
      a(i)=c(i-1)
      b(i)=2.*(a(i)+c(i))
      r(i)=6.*((y(i+1)-y(i))/c(i)-(y(i)-y(i-1))/c(i-1))
    1 continue
      b(2)=b(2)+alamda*c(1)
      b(nm1)=b(nm1)+alamda*c(nm1)
      do 2 i=3,nm1
      t=a(i)/b(i-1)
      b(i)=b(i)-t*c(i-1)
      r(i)=r(i)-t*r(i-1)
    2 continue
      fdp(nm1)=r(nm1)/b(nm1)
      do 3 i=2,nm2
      nmi=n-i
      fdp(nmi)=(r(nmi)-c(nmi)*fdp(nmi+1))/b(nmi)
    3 continue
      fdp(1)=alamda*fdp(2)
      fdp(n)=alamda*fdp(nm1)
      return
      end
      subroutine speval(n,x,y,fdp,xx,f)
      dimension x(8),y(8),fdp(8)
      nm1=n-1
      do 1 i=1,nm1
      if(xx.le.x(i+1)) go to 10
    1 continue
```

```
10 dxm=xx-x(i)
   dxp=x(i+1)-xx
   del=x(i+1)-x(i)
   f=fdp(i)*dxp*(dxp**2/del-del)/6.+fdp(i+1)*dxm*(dxm**2/del-
  1del)/6.+y(i)*dxp/del+y(i+1)*dxm/del
   return
   end
```

APPENDIX B

"Interp.out" Files for AC4M Steps 19, 16, 27, 46, 14, 29, and 44

"Interp.out" File for AC4M Step 19

The RELAP5 pressures for the different cells are:

N	Pa	psia
1	550911.50	79.90
2	550956.50	79.91
3	550969.00	79.91
4	550846.50	79.89
5	550799.00	79.89
6	550799.00	79.89
7	567017.00	82.24
8	567034.50	82.24
9	567003.00	82.24
10	566747.00	82.20
11	566719.50	82.20
12	566750.00	82.20
13	588629.50	85.37
14	588498.50	85.35
15	588458.50	85.35
16	588358.00	85.33
17	588351.00	85.33
18	588389.00	85.34
19	651800.00	94.54
20	651839.00	94.54
21	652021.00	94.57
22	651830.50	94.54
23	651791.00	94.53
24	651785.50	94.53

the inner and outer radii are 44.88 63.47 77.73 90.39
The number of assemblies considered is 25

n	olc	radius	theta	p, interp	p, L data	(I - L)	(I - L)/L
1	198	61.020	156.590	82.91	87.73	-4.82	-0.055
2	201	42.580	145.280	81.29	81.12	0.17	0.002
3	100	25.240	133.900	80.06	80.59	-0.53	-0.007
4	54	37.040	19.110	80.84	80.73	0.11	0.001
5	127	54.670	26.330	82.28	82.91	-0.63	-0.008
6	242	73.080	24.500	86.51	89.15	-2.64	-0.030
7	59	30.510	23.410	80.38	80.71	-0.33	-0.004
8	115	56.000	60.000	82.39	85.02	-2.63	-0.031
9	124	49.000	38.210	81.81	79.36	2.45	0.031
10	129	50.480	13.900	81.92	79.17	2.75	0.035
11	238	67.510	38.950	84.28	83.13	1.15	0.014
12	243	67.510	21.050	84.28	80.36	3.92	0.049
13	248	71.040	9.830	85.55	79.67	5.88	0.074
14	15	24.250	330.000	79.98	80.74	-0.76	-0.009
15	148	50.480	313.900	81.89	81.31	0.58	0.007
16	71	32.080	289.110	80.46	79.93	0.53	0.007
17	161	54.670	273.670	82.24	82.05	0.19	0.002
18	83	38.970	231.050	80.97	79.75	1.22	0.015
19	177	57.300	227.780	82.46	78.97	3.49	0.044
20	34	21.000	180.000	79.83	80.96	-1.13	-0.014
21	47	30.510	83.410	80.39	80.62	-0.23	-0.003
22	106	32.080	109.110	80.50	79.22	1.28	0.016
23	110	50.480	73.900	81.94	82.37	-0.43	-0.005
24	210	56.000	120.000	82.39	78.29	4.10	0.052
25	214	50.480	106.100	81.94	80.01	1.93	0.024

Sum of pressure errors: 15.65 psia
Sum squared pressure errors: 141.38 psia

Sum of relative errors: 0.209
Sum squared relative errors: 0.021

"Interp.out" File for AC4M Step 16

The RELAP5 pressures for the different cells are:

N	Pa	psia
1	407725.00	59.14
2	409119.50	59.34
3	409279.00	59.36
4	408750.69	59.28
5	407083.19	59.04
6	405682.69	58.84
7	419563.00	60.85
8	425375.00	61.70
9	425925.31	61.78
10	424625.00	61.59
11	418264.50	60.66
12	406261.69	58.92
13	435977.31	63.23
14	445366.81	64.59
15	446473.31	64.76
16	444945.81	64.53
17	434721.00	63.05
18	407716.31	59.13
19	484893.19	70.33
20	503131.81	72.97
21	505621.00	73.33
22	503216.50	72.99
23	485044.50	70.35
24	412363.00	59.81

the inner and outer radii are 44.88 63.47 77.73 90.39
The number of assemblies considered is 25

n	olc	radius	theta	p, interp	p, L data	(I - L)	(I - L)/L
1	198	61.020	156.590	62.43	67.91	-5.48	-0.081
2	201	42.580	145.280	60.79	60.88	-0.09	-0.001
3	100	25.240	133.900	59.51	58.86	0.65	0.011
4	54	37.040	19.110	59.66	58.76	0.90	0.015
5	127	54.670	26.330	60.76	61.11	-0.35	-0.006
6	242	73.080	24.500	63.66	63.25	0.41	0.007
7	59	30.510	23.410	59.42	57.07	2.35	0.041
8	115	56.000	60.000	61.40	63.04	-1.64	-0.026
9	124	49.000	38.210	60.64	60.08	0.56	0.009
10	129	50.480	13.900	60.17	57.33	2.84	0.050
11	238	67.510	38.950	62.58	62.16	0.42	0.007
12	243	67.510	21.050	61.90	60.04	1.86	0.031
13	248	71.040	9.830	61.95	59.00	2.95	0.050
14	15	24.250	330.000	58.85	58.43	0.42	0.007
15	148	50.480	313.900	59.33	58.32	1.01	0.017
16	71	32.080	289.110	59.26	58.10	1.16	0.020
17	161	54.670	273.670	60.58	57.17	3.41	0.060
18	83	38.970	231.050	60.17	58.47	1.70	0.029
19	177	57.300	227.780	61.55	58.65	2.90	0.050
20	34	21.000	180.000	59.25	59.08	0.17	0.003
21	47	30.510	83.410	59.80	57.08	2.72	0.048
22	106	32.080	109.110	59.95	57.40	2.55	0.044
23	110	50.480	73.900	61.19	59.08	2.11	0.036
24	210	56.000	120.000	61.88	58.08	3.80	0.066
25	214	50.480	106.100	61.42	57.66	3.76	0.065

Sum of pressure errors: 31.10 psia
Sum squared pressure errors: 132.99 psia

Sum of relative errors: 0.551
Sum squared relative errors: 0.037

"Interp.out" File for AC4M Step 27

The RELAP5 pressures for the different cells are:

N	Pa	psia
1	407045.50	59.04
2	407375.69	59.08
3	407284.00	59.07
4	405346.19	58.79
5	403498.31	58.52
6	405040.50	58.75
7	423584.50	61.44
8	424329.50	61.54
9	423568.50	61.43
10	416423.50	60.40
11	403953.00	58.59
12	416222.50	60.37
13	443974.00	64.39
14	444802.69	64.51
15	443706.50	64.35
16	432637.81	62.75
17	405305.31	58.78
18	432405.50	62.72
19	501335.50	72.71
20	503320.00	73.00
21	501913.00	72.80
22	482188.81	69.94
23	409746.69	59.43
24	481706.81	69.87

the inner and outer radii are 44.88 63.47 77.73 90.39
The number of assemblies considered is 25

n	olc	radius	theta	p, interp	p, L data	(I - L)	(I - L)/L
1	198	61.020	156.590	61.96	65.21	-3.25	-0.050
2	201	42.580	145.280	60.49	58.97	1.52	0.026
3	100	25.240	133.900	59.23	58.12	1.11	0.019
4	54	37.040	19.110	59.90	59.59	0.31	0.005
5	127	54.670	26.330	61.41	62.79	-1.38	-0.022
6	242	73.080	24.500	65.27	68.18	-2.91	-0.043
7	59	30.510	23.410	59.48	58.50	0.98	0.017
8	115	56.000	60.000	61.64	64.99	-3.35	-0.051
9	124	49.000	38.210	61.01	60.03	0.98	0.016
10	129	50.480	13.900	60.86	58.74	2.12	0.036
11	238	67.510	38.950	63.41	63.74	-0.33	-0.005
12	243	67.510	21.050	63.17	61.69	1.48	0.024
13	248	71.040	9.830	63.99	60.05	3.94	0.066
14	15	24.250	330.000	58.81	56.78	2.03	0.036
15	148	50.480	313.900	59.73	55.02	4.71	0.086
16	71	32.080	289.110	58.74	57.55	1.19	0.021
17	161	54.670	273.670	58.70	57.30	1.40	0.024
18	83	38.970	231.050	59.20	55.95	3.25	0.058
19	177	57.300	227.780	60.00	57.39	2.61	0.045
20	34	21.000	180.000	58.87	56.85	2.02	0.036
21	47	30.510	83.410	59.58	58.69	0.89	0.015
22	106	32.080	109.110	59.69	56.62	3.07	0.054
23	110	50.480	73.900	61.20	62.09	-0.89	-0.014
24	210	56.000	120.000	61.64	57.56	4.08	0.071
25	214	50.480	106.100	61.20	58.45	2.75	0.047

Sum of pressure errors: 28.35 psia
Sum squared pressure errors: 146.47 psia

Sum of relative errors: 0.517
Sum squared relative errors: 0.042

"Interp.out" File for AC4M Step 46

The RELAP5 pressures for the different cells are:

N	Pa	psia
1	408768.00	59.29
2	408744.19	59.28
3	407836.19	59.15
4	405770.19	58.85
5	406888.00	59.01
6	408237.50	59.21
7	425688.50	61.74
8	425119.31	61.66
9	419354.00	60.82
10	406284.19	58.93
11	418071.50	60.64
12	424307.69	61.54
13	446480.00	64.76
14	445133.19	64.56
15	435498.69	63.16
16	407704.19	59.13
17	434506.00	63.02
18	444639.00	64.49
19	504755.50	73.21
20	502774.50	72.92
21	485294.50	70.39
22	412310.50	59.80
23	484749.00	70.31
24	502626.69	72.90

the inner and outer radii are 44.88 63.47 77.73 90.39
The number of assemblies considered is 25

n	olc	radius	theta	p, interp	p, L data	(I - L)	(I - L)/L
1	198	61.020	156.590	61.05	60.81	0.24	0.004
2	201	42.580	145.280	60.20	58.84	1.36	0.023
3	100	25.240	133.900	59.31	58.83	0.48	0.008
4	54	37.040	19.110	60.24	60.10	0.14	0.002
5	127	54.670	26.330	61.77	63.58	-1.81	-0.028
6	242	73.080	24.500	65.79	70.39	-4.60	-0.065
7	59	30.510	22.410	59.76	58.94	0.82	0.014
8	115	56.000	60.000	61.85	66.08	-4.23	-0.064
9	124	49.000	38.210	61.28	59.77	1.51	0.025
10	129	50.480	13.900	61.37	59.35	2.02	0.034
11	238	67.510	38.950	63.71	64.38	-0.67	-0.010
12	243	67.510	21.050	63.70	62.47	1.23	0.020
13	248	71.040	9.830	64.84	61.83	3.01	0.049
14	15	24.250	330.000	59.30	57.99	1.31	0.023
15	148	50.480	313.900	61.02	58.73	2.29	0.039
16	71	32.080	289.110	59.54	56.16	3.38	0.060
17	161	54.670	273.670	60.72	59.64	1.08	0.018
18	83	38.970	231.050	59.21	58.26	0.95	0.016
19	177	57.300	227.780	59.50	58.20	1.30	0.022
20	34	21.000	180.000	58.97	58.51	0.46	0.008
21	47	30.510	83.410	59.78	59.68	0.10	0.002
22	106	32.080	109.110	59.80	58.03	1.77	0.030
23	110	50.480	73.900	61.37	63.42	-2.05	-0.032
24	210	56.000	120.000	61.37	58.28	3.09	0.053
25	214	50.480	106.100	61.16	59.59	1.57	0.026

Sum of pressure errors: 14.76 psia
Sum squared pressure errors: 104.12 psia

Sum of relative errors: 0.277
Sum squared relative errors: 0.027

"Interp.out" File for AC4M Step 14

The RELAP5 pressures for the different cells are:

N	Pa	psia
1	449243.69	65.16
2	449630.31	65.21
3	449676.69	65.22
4	449392.19	65.18
5	448898.31	65.11
6	448729.50	65.08
7	461472.19	66.93
8	464421.69	67.36
9	464663.50	67.39
10	463768.00	67.26
11	460379.50	66.77
12	455455.50	66.06
13	478498.31	69.40
14	483890.50	70.18
15	484555.50	70.28
16	483527.69	70.13
17	477376.00	69.24
18	463307.19	67.20
19	529310.00	76.77
20	541645.50	78.56
21	543503.00	78.83
22	541748.00	78.57
23	529516.00	76.80
24	483777.69	70.17

the inner and outer radii are 44.88 63.47 77.73 90.39

The number of assemblies considered is 25

n	olc	radius	theta	p, interp	p, L data	(I - L)	(I - L)/L
1	198	61.020	156.590	68.01	73.16	-5.15	-0.070
2	201	42.580	145.280	66.50	66.52	-0.02	0.000
3	100	25.240	133.900	65.36	65.47	-0.11	-0.002
4	54	37.040	19.110	65.81	65.67	0.14	0.002
5	127	54.670	26.330	66.91	67.24	-0.33	-0.005
6	242	73.080	24.500	70.06	69.85	0.21	0.003
7	59	30.510	23.410	65.50	65.20	0.30	0.005
8	115	56.000	60.000	67.27	69.20	-1.93	-0.028
9	124	49.000	38.210	66.66	66.14	0.52	0.008
10	129	50.480	13.900	66.49	64.92	1.57	0.024
11	238	67.510	38.950	68.63	67.54	1.09	0.016
12	243	67.510	21.050	68.28	66.16	2.12	0.032
13	248	71.040	9.830	68.78	64.87	3.91	0.060
14	15	24.250	330.000	65.13	65.64	-0.51	-0.008
15	148	50.480	313.900	66.10	65.60	0.50	0.008
16	71	32.080	289.110	65.47	64.48	0.99	0.015
17	161	54.670	273.670	66.76	65.30	1.46	0.022
18	83	38.970	231.050	66.06	64.72	1.34	0.021
19	177	57.300	227.780	67.35	64.64	2.71	0.042
20	34	21.000	180.000	65.14	65.61	-0.47	-0.007
21	47	30.510	83.410	65.64	64.64	1.00	0.016
22	106	32.080	109.110	65.76	64.63	1.13	0.017
23	110	50.480	73.900	66.98	65.69	1.29	0.020
24	210	56.000	120.000	67.51	63.78	3.73	0.059
25	214	50.480	106.100	67.09	64.10	2.99	0.047

Sum of pressure errors: 18.46 psia
Sum squared pressure errors: 94.03 psia

Sum of relative errors: 0.296
Sum squared relative errors: 0.021

"Interp.out" File for AC4M Step 29

The RELAP5 pressures for the different cells are:

N	Pa	psia
1	447730.69	64.94
2	447875.81	64.96
3	447867.00	64.96
4	447192.69	64.86
5	446817.00	64.81
6	447034.69	64.84
7	462703.81	67.11
8	463108.69	67.17
9	462659.19	67.10
10	458601.69	66.51
11	453288.00	65.74
12	458505.19	66.50
13	482524.31	69.98
14	482932.19	70.04
15	482240.50	69.94
16	475378.00	68.95
17	461025.50	66.87
18	475242.31	68.93
19	539841.50	78.30
20	541232.00	78.50
21	540399.50	78.38
22	526793.00	76.40
23	481320.19	69.81
24	526392.50	76.35

the inner and outer radii are 44.88 63.47 77.73 90.39
The number of assemblies considered is 25

n	olc	radius	theta	p, interp	p, L data	(I - L)	(I - L)/L
1	198	61.020	156.590	67.64	71.26	-3.62	-0.051
2	201	42.580	145.280	66.24	65.62	0.62	0.009
3	100	25.240	133.900	65.10	65.21	-0.11	-0.002
4	54	37.040	19.110	65.76	65.98	-0.22	-0.003
5	127	54.670	26.330	67.11	68.74	-1.63	-0.024
6	242	73.080	24.500	70.91	74.42	-3.51	-0.047
7	59	30.510	23.410	65.36	65.29	0.07	0.001
8	115	56.000	60.000	67.28	70.69	-3.41	-0.048
9	124	49.000	38.210	66.72	65.63	1.09	0.017
10	129	50.480	13.900	66.68	64.93	1.75	0.027
11	238	67.510	38.950	69.00	69.17	-0.17	-0.002
12	243	67.510	21.050	68.85	67.45	1.40	0.021
13	248	71.040	9.830	69.79	66.13	3.66	0.055
14	15	24.250	330.000	64.91	65.33	-0.42	-0.006
15	148	50.480	313.900	66.11	64.16	1.95	0.030
16	71	32.080	289.110	65.12	64.79	0.33	0.005
17	161	54.670	273.670	65.81	65.17	0.64	0.010
18	83	38.970	231.050	65.51	64.61	0.90	0.014
19	177	57.300	227.780	66.45	65.96	0.49	0.007
20	34	21.000	180.000	64.85	65.23	-0.38	-0.006
21	47	30.510	83.410	65.40	65.53	-0.13	-0.002
22	106	32.080	109.110	65.50	63.84	1.66	0.026
23	110	50.480	73.900	66.87	67.98	-1.11	-0.016
24	210	56.000	120.000	67.27	63.77	3.50	0.055
25	214	50.480	106.100	66.87	64.83	2.04	0.031

Sum of pressure errors: 5.37 psia
Sum squared pressure errors: 85.88 psia

Sum of relative errors: 0.101
Sum squared relative errors: 0.019

"Interp.out" File for AC4M Step 44

The RELAP5 pressures for the different cells are:

N	Pa	psia
1	449263.50	65.16
2	449267.50	65.16
3	449137.50	65.14
4	448617.00	65.07
5	448681.00	65.08
6	448981.19	65.12
7	464419.50	67.36
8	464136.31	67.32
9	461113.00	66.88
10	455250.00	66.03
11	460125.00	66.74
12	463466.19	67.22
13	484535.19	70.28
14	483613.00	70.14
15	477869.19	69.31
16	463079.69	67.16
17	477088.31	69.20
18	483217.50	70.08
19	542587.00	78.70
20	541222.00	78.50
21	529616.50	76.81
22	483568.50	70.14
23	529133.50	76.74
24	541122.00	78.48

the inner and outer radii are 44.88 63.47 77.73 90.39
The number of assemblies considered is 25

n	olc	radius	theta	p, interp	p, L data	(I - L)	(I - L)/L
1	198	61.020	156.590	67.26	69.52	-2.26	-0.033
2	201	42.580	145.280	66.21	65.77	0.44	0.007
3	100	25.240	133.900	65.27	65.63	-0.36	-0.005
4	54	37.040	19.110	66.02	66.17	-0.15	-0.002
5	127	54.670	26.330	67.39	69.05	-1.66	-0.024
6	242	73.080	24.500	71.31	75.53	-4.22	-0.056
7	59	30.510	23.410	65.59	65.49	0.10	0.001
8	115	56.000	60.000	67.48	71.26	-3.78	-0.053
9	124	49.000	38.210	66.94	65.33	1.61	0.025
10	129	50.480	13.900	67.03	65.02	2.01	0.031
11	238	67.510	38.950	69.26	69.74	-0.48	-0.007
12	243	67.510	21.050	69.25	67.53	1.72	0.025
13	248	71.040	9.830	70.38	66.80	3.58	0.054
14	15	24.250	330.000	65.20	65.63	-0.43	-0.007
15	148	50.480	313.900	66.83	65.48	1.35	0.021
16	71	32.080	289.110	65.54	64.03	1.51	0.024
17	161	54.670	273.670	66.79	66.73	0.06	0.001
18	83	38.970	231.050	65.64	65.53	0.11	0.002
19	177	57.300	227.780	66.37	65.19	1.18	0.018
20	34	21.000	180.000	65.06	66.07	-1.01	-0.015
21	47	30.510	83.410	65.60	65.77	-0.17	-0.003
22	106	32.080	109.110	65.67	64.86	0.81	0.012
23	110	50.480	73.900	67.05	68.77	-1.72	-0.025
24	210	56.000	120.000	67.22	64.80	2.42	0.037
25	214	50.480	106.100	66.94	65.39	1.55	0.024

Sum of pressure errors: 2.21 psia
Sum squared pressure errors: 81.63 psia

Sum of relative errors: 0.052
Sum squared relative errors: 0.017

END

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9/13/93