Journal of the Korean Nuclear Society
Volume 33, Number 4, pp.441 ~456, August, 2001

《Technical Note》

A Review on the Regionalization Methodology for Core Inlet Flow Distribution Map

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(Received February 27, 2001)

Abstract

ABB-CE's regionalization methodology for the core inlet flow distribution map is reviewed. This methodology merges the test data of fuel assembly locations which are either in symmetry or strongly correlated with others. It increases the number of available test data for each regional flow factor. It makes up effectively for the deficiency due to limited number of test data. It also contributes to making the core inlet flow distribution smoother not only locally but also over the entire core, and to relieving the impacts of test errors that may happen due to some de-calibrated local pressure measurement taps. As a result, the core inlet flow distribution data becomes more statistically useful and thus the conservatism involved in handling the core inlet flow factors for the thermal margin analysis is expected to be reduced.

Meanwhile, the regionalized map may lose the unique local characteristics in core inlet flow distribution too much. By an alternative approach introduced in the present work, it is shown that such a disadvantage can be mitigated somewhat if the engineering judgement is made more prudently for the so-called initial grouping and the t-Test technique is more appropriately used.

Key Words : core flow distribution map, t-Test, regionalization

1. Introduction

Some of system parameters indicating the physical status of a system are not monitored during operation. ABB-CE's methodology for statistical combination of uncertainties (SCU)[1] statistically combines all the uncertainties of system parameters involved in the thermal margin analysis. If some parameters are not applicable for the SCU, however, they may be treated in a deterministic manner which is usually conservative.

One of the system parameters relevant to the thermal margin is the core inlet flow distribution. It is mostly obtained from a reactor flow model test, which has long been believed to be the most practical and dependable for design verification since the physical phenomena involved are so highly complex that prediction by analytical means is not feasible. ABB-CE has carried out several reactor flow model test programs mostly for its prototype reactors. In the period of 1978-1980 when the prototype System 80 reactor internals design was being developed, a series of tests was run using a 3/16 scale reactor model. The model was built in accordance with the affinity law to represent the geometric features of the reactor internals. The hydraulic characteristics including the core inlet flow distribution were measured. Until the final version of the System 80 reactor internals design was set, several design changes were made and evaluated by model tests. Eventually, three test runs were completed for the final design[2, 3].

Core inlet flow factors of 241 individual fuel assemblies were defined as the ratios of the coolant local flow velocities to the average at core inlet plane. Unable to treat the core inlet flow factors in a statistical manner due to the insufficient number of test runs and data, ABB-CE chose a deterministic approach. The lowest measured core inlet flow factors were forced to be matched with the hottest fuel assembly locations for the thermal margin model. Resultingly, an excessive conservatism was included in the calculated core thermal margin.

On the other hand, after an extensive reactor flow model test program in 1989 for the Yonggwang Nuclear Power Plant (YGN) 3&4 reactor, it was recognized that there should be a certain physical correlation between the core inlet flow distribution and the geometric configuration of the lower support structure (LSS) located just below the core. It was also thought that similar correlation could be found in the System 80 flow model test data.

In light of this correlation, the core inlet flow distribution and the upstream geometry of System 80 were re-examined. Core area was divided into 12 regions, each of which included fuel assembly locations presumably under a similar influence of the upstream geometric configuration. Average flow factors and standard deviations were calculated for each region. This process was entirely based on engineering judgement, which can be called the "initial grouping". Then any two regions among 12 regions of the initial grouping were examined to see if they have a close relationship in flow distribution with each other. Statistical t-Test technique was employed for it. If the t-Test result indicated that two regions were likely to have common characteristics, they were merged into one. An average flow factor and standard deviation were calculated again. A series of statistical t-Test was done for all combinations of pair regions of the initial grouping. As a results, available test data were substantially increased for each core inlet flow factor, and thus the core inlet flow distribution data became more statistically useful for the System 80 SCU analysis. Excessive conservatism imposed by the deterministic approach could be reduced to some extent[4]. This approach was approved in 1993 by USNRC[5].

In the following sections, ABB-CE's work for regionalizing the core inlet flow distribution map will be reviewed. An alternative work will be tried in an effort to enhance its applicability to the Korean reactors.

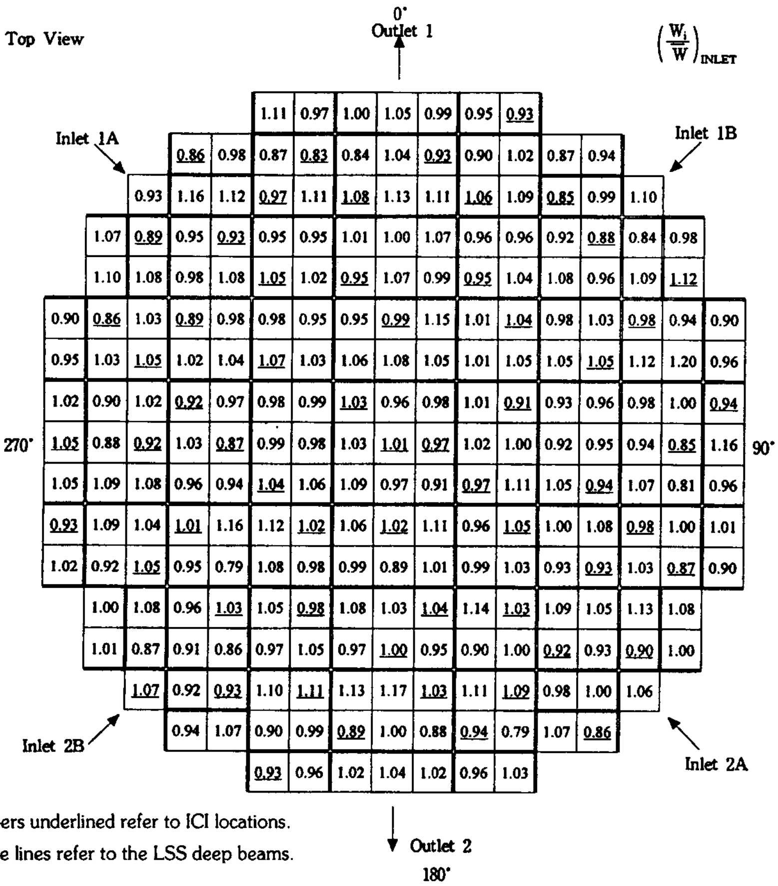
2. ABB-CE's Regionalization Methodology

Provided in Table 1 are the core inlet flow factors from three selected runs of the System 80 reactor flow model test, which are applicable only to the final version of the System 80 reactor internals design[6]. In-core instrumentation (ICI) locations in the core are provided too. The core inlet flow distribution map shown in Figure 1 was

Table 1. Original Core Inlet Flow Factors for System 80

I.D.	ICI	Run No.			I.D.	ICI	Run No.			I.D.	ICI	Run No.			I.D.	ICI	Run No.		
		29	32	33			29	32	33			29	32	33			29	32	33
1		1.17	1.11	1.04	61	Y	1.00	1.23	1.14	121	Y	1.00	1.07	0.96	181		0.98	0.99	1.02
2		0.92	0.95	1.04	62		0.93	0.86	0.90	122	Y	1.03	0.90	0.97	182		1.06	1.10	1.07
3		0.93	1.05	1.03	63	Y	0.84	0.79	0.96	123		0.99	1.01	1.07	183		0.99	0.96	0.93
4		1.06	1.03	1.07	64		0.96	1.11	1.01	124		1.03	1.00	0.96	184	Y	1.05	1.06	0.98
5		0.98	0.97	1.01	65	Y	0.93	0.88	0.86	125		0.94	0.90	0.93	185		1.04	1.04	1.08
6		0.96	0.92	0.97	66		0.88	1.07	1.00	126		1.01	0.94	0.91	186	Y	1.03	0.97	0.94
7	Y	0.87	1.00	0.92	67		1.03	0.98	0.94	127		0.96	0.95	0.90	187		0.97	1.13	1.13
8	Y	0.81	0.86	0.91	68		0.97	1.00	0.88	128	Y	0.82	0.87	0.86	188		1.06	1.04	1.00
9		1.01	0.96	0.98	69		1.02	0.95	0.88	129		1.18	1.17	1.12	189	Y	1.07	1.03	1.03
10		0.93	0.80	0.89	70	Y	0.99	1.05	0.94	130		1.09	1.04	1.03	190		1.15	1.06	1.20
11	Y	0.73	0.84	0.92	71		1.19	1.15	1.11	131		1.03	1.10	1.13	191	Y	0.99	1.12	0.97
12		0.88	0.88	0.77	72		1.00	0.97	1.06	132		1.05	1.15	1.04	192		1.08	1.07	1.12
13		1.14	1.01	0.97	73	Y	0.99	1.00	1.13	133		0.93	0.97	0.98	193		1.09	1.05	1.00
14	Y	0.94	0.99	0.87	74		0.96	0.95	1.04	134		1.01	0.89	0.93	194		1.13	1.12	1.13
15		0.89	0.89	0.93	75		1.01	1.03	1.06	135	Y	1.05	1.08	1.00	195		1.06	1.10	1.08
16		0.91	1.11	1.04	76	Y	0.97	0.96	1.01	136		1.03	1.04	1.11	196		1.02	1.01	1.00
17		1.10	0.86	0.88	77		0.91	0.90	1.02	137		1.16	1.08	1.03	197		0.87	0.87	0.86
18		0.89	0.95	0.97	78		0.92	0.84	0.94	138		0.97	0.97	0.96	198		0.89	0.92	0.92
19		0.90	0.97	0.91	79		0.95	0.95	0.96	139		0.95	0.93	0.85	199		0.86	0.86	0.87
20		1.23	1.15	1.09	80		1.07	1.01	1.01	140	Y	0.94	0.96	1.02	200		0.98	1.13	0.80
21		1.22	1.09	1.04	81	Y	1.02	1.03	1.10	141		1.10	1.08	1.15	201		0.96	1.08	1.11
22	Y	0.97	0.99	0.96	82		1.02	0.99	1.05	142		0.97	1.09	1.10	202		1.01	0.97	0.93
23		1.09	1.15	1.09	83		1.09	1.01	1.02	143	Y	0.92	0.94	0.96	203	Y	0.90	0.97	1.14
24	Y	1.12	1.03	1.09	84	Y	1.06	1.06	1.08	144		1.10	1.10	1.01	204		0.88	1.04	0.92
25		1.17	1.11	1.11	85		0.99	1.08	1.08	145		0.82	0.79	0.83	205		0.88	0.95	0.86
26		1.20	1.06	1.06	86		1.04	1.06	1.06	146		0.95	0.98	0.96	206		0.97	1.03	1.00
27	Y	1.09	0.97	1.13	87		0.98	1.20	1.20	147	Y	0.93	0.94	0.93	207	Y	0.99	0.89	0.89
28		1.17	0.95	1.14	88		1.05	1.02	1.02	148		1.07	1.07	1.13	208		0.92	0.92	0.96
29	Y	0.72	0.98	0.86	89		1.02	0.95	0.95	149		1.06	1.03	1.04	209	Y	0.89	0.93	0.89
30		0.96	0.97	1.05	90		1.07	1.02	1.02	150	Y	1.08	0.98	0.97	210		0.99	1.01	1.00
31		1.15	1.19	0.96	91		1.03	1.11	1.11	151		1.27	1.17	1.04	211	Y	1.11	1.06	1.06
32		1.09	0.97	1.14	92	Y	0.99	1.12	1.12	152		1.12	1.11	1.12	212		0.95	0.92	0.89
33	Y	0.88	0.91	0.89	93		1.09	1.18	1.18	153	Y	0.99	1.11	0.97	213	Y	1.00	0.79	0.99
34		0.94	1.00	0.91	94		1.25	1.13	1.13	154		1.00	1.01	1.16	214		1.08	1.09	1.13
35	Y	0.94	0.93	0.92	95		0.94	0.92	0.92	155	Y	1.10	0.94	1.02	215	Y	1.16	1.06	1.12
36		0.95	1.00	0.91	96		1.06	0.98	0.98	156		1.07	1.14	1.39	216		1.13	1.08	1.18
37		0.92	0.96	0.97	97		0.94	0.87	0.87	157		0.99	1.01	0.89	217		1.21	1.15	1.14
38		1.02	0.97	1.05	98		1.04	1.00	1.00	158	Y	1.02	1.08	1.04	218	Y	1.06	1.00	1.04
39		0.86	1.04	1.09	99	Y	0.91	0.90	0.90	159		1.00	1.08	0.92	219		1.12	1.11	1.11
40		1.02	1.10	1.09	100		0.96	0.97	0.97	160		1.08	1.05	1.11	220	Y	1.11	1.04	1.12
41		0.94	1.01	0.92	101		0.97	1.02	1.02	161	Y	1.01	0.97	0.95	221		0.98	1.00	0.97
42		0.91	0.93	1.03	102		0.97	0.92	0.92	162		0.95	1.07	0.98	222		0.99	1.02	1.00
43		1.00	0.92	0.83	103	Y	1.07	1.09	1.09	163		1.03	1.00	1.00	223		1.08	1.05	1.04
44	Y	0.91	0.88	0.86	104		0.98	0.95	0.95	164		1.02	1.02	1.02	224		0.93	0.95	0.93
45		0.79	0.91	0.81	105		0.93	0.99	0.99	165		0.92	0.91	0.94	225		1.06	1.10	1.06
46		0.98	0.93	1.02	106		0.99	1.05	1.05	166	Y	1.07	1.02	1.06	226		0.90	0.92	0.88
47		1.17	1.14	1.12	107	Y	0.78	1.04	1.04	167		0.96	0.94	0.95	227		0.98	0.97	1.02
48		1.41	1.03	1.12	108		0.95	0.80	0.80	168		0.80	0.78	1.07	228	Y	0.90	0.94	0.84
49		0.97	1.03	0.94	109		0.96	0.97	0.97	169		1.14	1.06	1.05	229		0.99	1.00	1.01
50		1.08	1.06	1.09	110		1.02	0.95	0.95	170		1.00	0.95	0.99	230		0.91	0.89	0.85
51	Y	0.98	1.04	1.14	111		1.03	0.99	0.99	171		0.91	0.98	1.08	231	Y	0.90	0.93	1.01
52		1.03	0.97	1.05	112	Y	1.19	0.93	0.93	172		1.01	0.87	0.79	232		0.78	0.81	0.79
53	Y	0.97	1.03	0.85	113	Y	1.13	1.02	1.02	173		0.98	1.02	1.03	233		1.10	1.06	1.05
54		1.16	0.99	1.06	114		0.77	0.93	0.93	174		0.96	1.05	0.96	234	Y	0.83	0.86	0.88
55		0.95	0.95	1.06	115	Y	0.91	0.92	0.92	175		1.01	1.01	1.07	235	Y	1.02	0.92	0.85
56	Y	0.97	0.95	0.93	116		0.97	1.05	1.05	176		0.96	0.92	0.90	236		0.91	0.91	1.06
57		1.02	1.05	1.05	117	Y	0.89	0.82	0.82	177	Y	0.96	0.94	0.90	237		1.01	1.02	1.04
58		1.08	1.04	1.13	118		0.92	1.00	1.00	178		1.03	1.03	1.02	238		1.01	1.01	1.11
59		0.99	0.92	1.20	119		1.08	0.93	0.93	179	Y	0.88	0.87	0.87	239		1.03	1.01	1.02
60		1.07	1.05	1.15	120		1.01	1.04	1.04	180		0.95	0.88	0.87	240		0.97	0.96	0.94
															241		1.05	1.05	0.99

made by averaging the three data sets - three measured flow factors for each fuel assembly location. ICI locations are also marked in the map. The core inlet flow distribution looks rather peaky



Notes: 1. Numbers underlined refer to ICI locations.
2. Double lines refer to the LSS deep beams.

Fig. 1. Original Core Inlet Flow Distribution for System 80

locally, but fairly flat over the entire core. The regionalzing process of the core inlet flow distribution map is as follows[4]:

1) Geometric features of the reactor internals which seemed to have significant influences on the core inlet flow distribution were identified. Considering the hydraulic influences of the upstream structure, the core was divided into 12 regions as shown in Table 2 and Figure 2; 6 main regions each having 2 sub-regions for ICI and non-ICI locations. The core inlet flow within a region was considered to have a common link with the upstream conditions.
2) Average flow factors and standard deviations for each of 12 regions were calculated as shown in Table 2 together with the associated test data.
3) A series of statistical t-Tests[7] was carried out for all pair-combinations of 12 regions. A null hypothesis was then set forth that "the core inlet flow factors of the selected two regions were originated from a same population." The level of significance α for equal-tails test was set at 0.05. The null hypothesis was not rejected, if

$$-t_{\alpha/2,\, n1+n2-2} < t < t_{\alpha/2,\, n1+n2-2},$$

where

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}, \text{ and } s_p^2 = \frac{s_1^2(n_1-1) + s_2^2(n_2-1)}{n_1+n_2-2};$$

Table 2. Regional Core Inlet Flow Factors for System 80 by ABB-CE

Initial Grouping

Initial Region ID	ICI	Mean Value	Standard Deviation	Number of Measurements
1	N	1.01	0.082	237
2	N	1.08	0.068	60
3	N	0.96	0.100	90
4	N	1.10	0.100	18
5	N	0.96	0.115	18
6	N	1.01	0.082	117
1'	Y	0.99	0.076	78
2'	Y	1.03	0.065	36
3'	Y	0.89	0.060	30
4'	Y	0.89	0.118	6
5'	Y	0.90	0.018	6
6'	Y	0.98	0.113	27

Final Grouping

Final Region ID	Initial Regions Combined	ICI	Mean Value	Standard Deviation	Number of Measurements
A	1, 6	N	1.01	0.082	354
B	2, 4	N	1.08	0.076	78
C	3, 5	N	0.96	0.102	108
A'	1', 6'	Y	0.99	0.087	105
B'	2', 4'	Y	0.89	0.065	42
C'	3', 5'	Y	1.03	0.065	36

α: level of significance,

n_1, n_2 : numbers of data points of sample 1 and sample 2, respectively, and

$t_{\alpha/2, n1+n2-2}$: limit determined from the t-distribution table.

4) If the null hypothesis was rejected for a selected pair, the flow factors of the two regions were considered to be distinct from each other; in other words, the two regions were independent of each other in terms of core inlet flow distribution. If not rejected, the two were considered to belong to a same population.

5) Upon the completion of the t-Tests, the fuel assembly locations were finally merged into 6 regions as shown in Table 2 and Figure 3. The regionalized core inlet flow factors and standard deviations were obtained as shown in Table 2. The resulting flow distribution map is provided in Figure 4.

ABB-CE's work succeeded to increase the number of available test data for each flow factor. It also contributed to making the core inlet flow distribution even smoother not only locally but also over the entire core, and to relieving the impacts of test errors that may happen due to some de-calibrated local pressure measurement taps. The conservatism involved in handling the core inlet flow factors for the thermal analysis was reduced. Meanwhile, the regionalized map might lose the local uniqueness in core flow distribution too

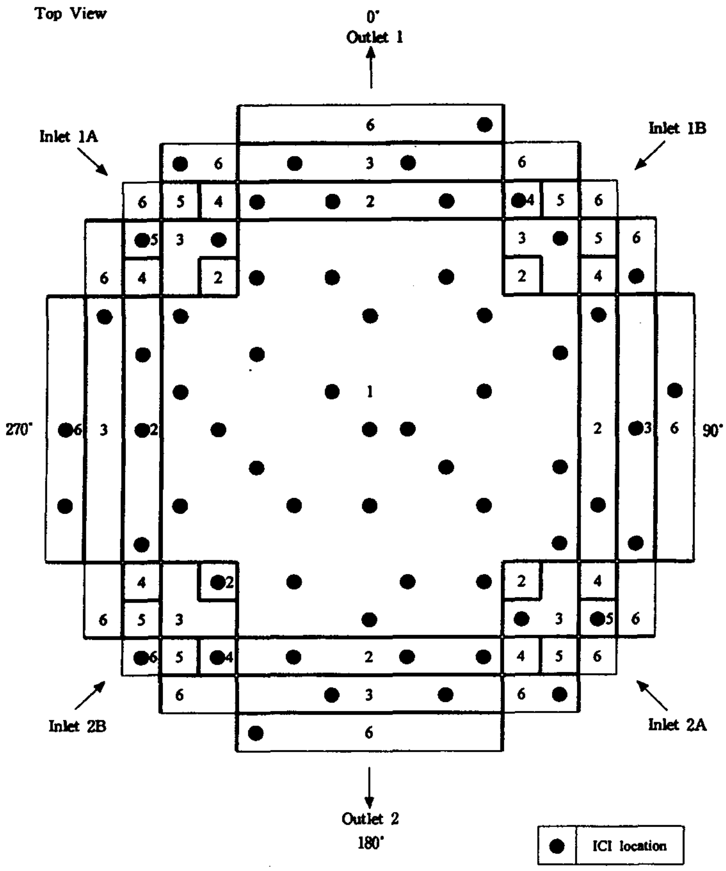


Fig. 2. Initial Grouping of Fuel Assembly Locations for System 80 by ABB-CE

much, which was due to the following:

1) Effects of the upstream structures were not examined in detail so that the rules of the initial grouping were set up somewhat too loosely. For instance, the circumferential variation in the upstream geometry was not accounted for, and thus the core was initially grouped into several ring-shaped regions only. As a result, there were some cases that the fuel assembly locations under apparently different upstream influences were merged together.
2) In the process of lumping the initially established regions further, t-Test was applied even to those pairs which were so remotely located from each other that they should be physically independent; for example, the inner-most region and the outer-most region. In those cases, two physically separate regions could be merged if they had similar mean flow factors by coincidence.
3) The criterion for rejecting the null hypothesis was rather too loose to preserve the distinctness between regions.

3. An Alternative Approach

An alternative approach is tried to set up more deliberate rules for the so-called initial grouping, and to apply the t-Test technique more appropriately.

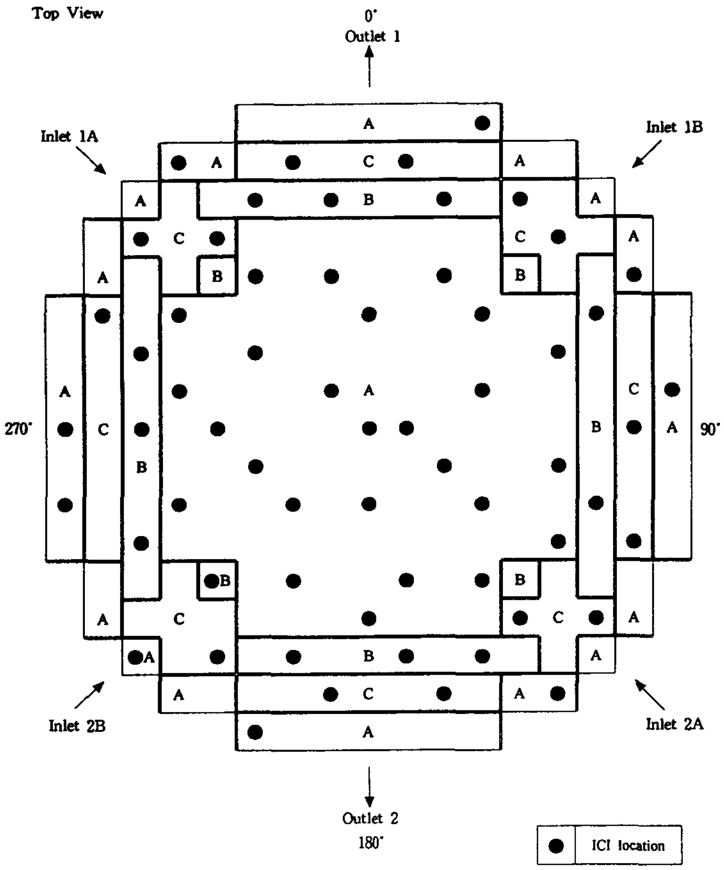


Fig. 3. Final Grouping of Fuel Assembly Locations for System 80 by ABB-CE

3.1. Effects of the Upstream Geometric Configuration

Reactor internals that may be influential to the core inlet flow distribution are depicted in Figures 5 and 6. Reactor internals are complex structures which support the fuel, control rods and instrumentations; they are particularly complex in the lower plenum region just below the bottom of core because of the presence of ICI nozzles. Flow distribution at the core inlet plane is believed to be affected by the shapes and relative locations of the upstream structures. The intensity of influence grows with narrowing distance in between. Details are discussed below:

1) Inlet Nozzles and Annular Downcomer: Coolant enters the four inlet nozzles of reactor vessel and impinges upon the core support barrel (CSB) wall. It then spreads away in all directions in the downcomer annulus having 10-inch gap between the reactor vessel and CSB. Flow eventually converges and proceeds downwards until reaching the flow skirt at the downcomer lower end. All these processes contribute to flow mixing. As the coolant flow runs down, the flow distribution over the circumference becomes less and less correlated with the un-symmetry and non-uniformity of the inlet nozzle locations and coolant supply. The blockage of six snubbers near the downcomer lower end,

Top View

Outlet 1

$\left(\frac{W_i}{W}\right)_{INLET}$

Inlet 1A

Inlet 1B

						1.01	1.01	1.01	1.01	1.01	1.01	0.99						
				0.99	1.01	0.96	0.89	0.96	0.96	0.89	0.96	0.96	1.01	1.01				
			1.01	0.96	1.08	1.03	1.08	1.03	1.08	1.08	1.03	1.08	0.89	0.96	1.01			
		1.01	0.89	0.96	0.89	1.01	1.01	1.01	1.01	1.01	1.01	1.01	0.96	0.89	0.96	1.01		
		1.01	1.08	0.96	1.08	0.99	1.01	0.99	1.01	1.01	0.99	1.01	1.08	0.96	1.08	0.99		
	1.01	0.89	1.08	0.99	1.01	1.01	1.01	1.01	0.99	1.01	1.01	0.99	1.01	1.01	1.03	0.96	1.01	
	1.01	0.96	1.03	1.01	1.01	0.99	1.01	1.01	1.01	1.01	1.01	1.01	1.01	0.99	1.08	0.96	1.01	
	1.01	0.96	1.08	0.99	1.01	1.01	1.01	0.99	1.01	1.01	1.01	0.99	1.01	1.01	1.08	0.96	0.99	
270°	0.99	0.96	1.03	1.01	0.99	1.01	1.01	1.01	0.99	0.99	1.01	1.01	1.01	1.01	1.08	0.89	1.01	90°
	1.01	0.96	1.08	1.01	1.01	0.99	1.01	1.01	1.01	1.01	0.99	1.01	1.01	0.99	1.08	0.96	1.01	
	0.99	0.96	1.08	0.99	1.01	1.01	0.99	1.01	0.99	1.01	1.01	0.99	1.01	1.01	1.03	0.96	1.01	
	1.01	0.96	1.03	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	0.99	1.08	0.89	1.01	
		1.01	1.08	0.98	1.03	1.01	0.99	1.01	1.01	0.99	1.01	0.99	1.08	0.96	1.08	1.01		
		1.01	0.96	0.96	0.96	1.01	1.01	1.01	0.99	1.01	1.01	1.01	0.89	0.96	0.89	1.01		
			0.99	0.96	0.89	1.08	1.03	1.08	1.08	1.03	1.08	1.03	1.08	0.96	1.01			
				1.01	1.01	0.96	0.96	0.89	0.96	0.96	0.89	0.96	1.01	0.99				
						0.99	1.01	1.01	1.01	1.01	1.01	1.01						

Inlet 2B

Inlet 2A

Notes: 1. Numbers underlined refer to ICI locations.
2. Double lines refer to the LSS deep beams.

Outlet 2
180°

Fig. 4. Revised Core Inlet Flow Distribution for System 80 by ABB-CE

60° apart from each other in circumferential direction, may have a local influence on the downstream, which, however, would be washed out to a large degree by flow mixing on the way to the core inlet.

2) Flow Skirt: Coolant flow near the downcomer lower end, just before the flow skirt holes, starts to change its progressing direction following the curvature of vessel bottom head. The vertical component of velocity, however, pushes the velocity profile towards the bottom wall of lower plenum. Unless properly controlled, the bulk flow would be extremely skewed towards the bottom wall and large scale swirls would be generated. They are stabilized by the flow skirt, which is a perforated cylinder ring about 30 inches high and 160 inches in diameter with lots of tiny flow holes distributed in a designed manner over the entire ring; smaller sizes in the upper rows and bigger ones in the lower rows. Flow through the smaller holes in the upper rows splits into many smaller scale flows, which easily mix with neighboring flows near the periphery of the lower plenum and readily turn up towards the peripheral core region because they don't have enough momentum to reach

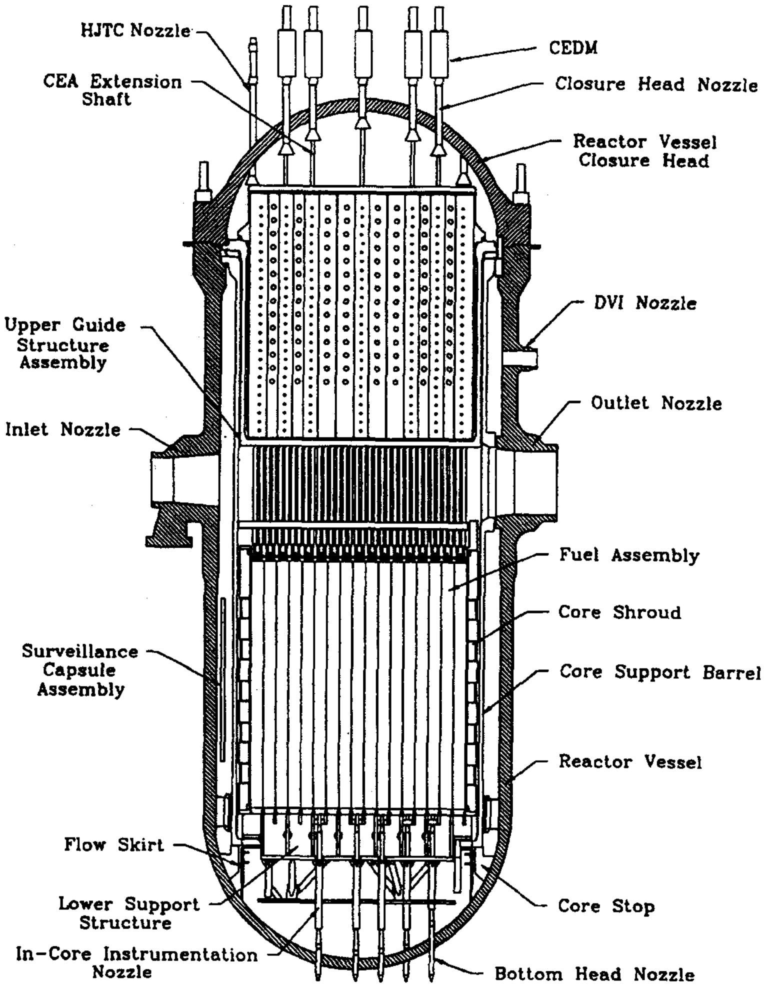


Fig. 5. Reactor Vessel Assembly

far into the center. On the other hand, flow through the bigger holes in the lower rows, having relatively large jets, easily reaches the central region of the lower plenum and proceeds up to the core inner region. However, because of the remoteness from the core inlet, the flow skirt is not likely to have a direct and significant influence on the local flow distributions at the core inlet plane.

3) Lower Support Structure (LSS) Bottom Plate: The LSS bottom plate is a perforated plate having many small flow holes distributed over the entire body in a designed manner. Flow holes in the inner area are sized small relatively to those in the outer region; otherwise, coolant flow would rush to the core inner area because flow in the lower plenum tends to pile up in the inner region. The bottom plate contributes to achieving, with the help of the flow skirt, a uniform flow distribution at the core inlet plane, though the flow distribution may show a unique pattern in radial direction. Meanwhile, the flow

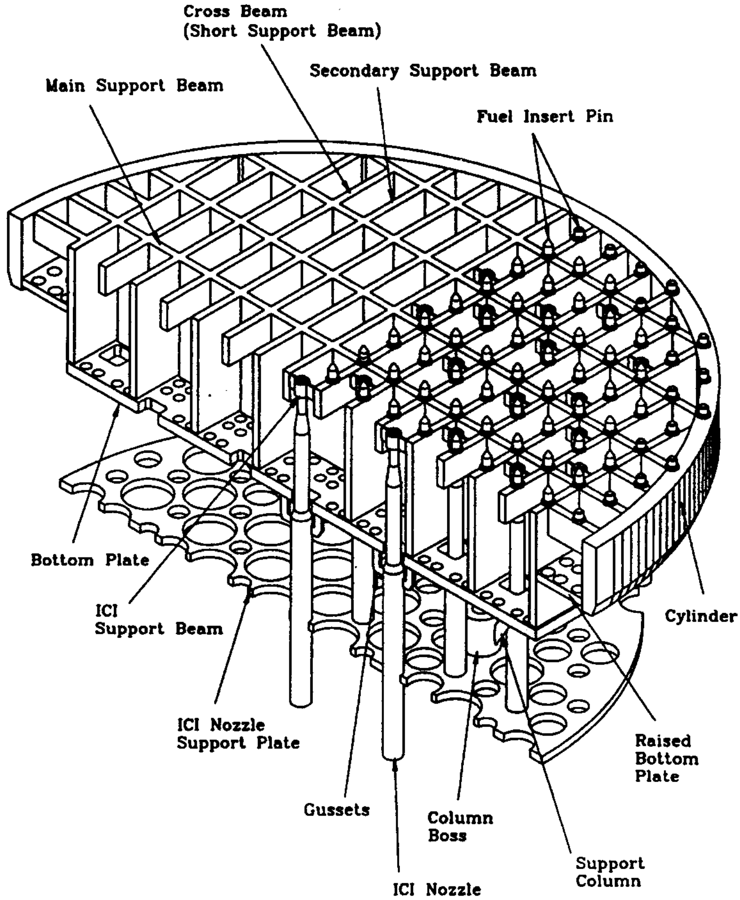


Fig. 6. Lower Support Structure and ICI Nozzle Assembly

distribution in the outer-most region may vary in circumferential direction due to the following: Peripheral part of the LSS bottom plate is raised by approximately 17 inches to ease the bottle-neck flow area between the edge of the CSB lower flange and the reactor vessel bottom wall, and the outer profile of LSS bottom plate presents a saw-tooth geometry to the flow approaching radially inwards from the flow skirt. This configuration deflects the radially directed flow to have a circumferential velocity component, which may enhance the flow near the "valleys" and reduce the flow near the "peaks".

4) Beams in the LSS: There are core supporting beams in lattice shape between the LSS bottom plate and core inlet plane, which form many "flow confining" square cells as shown in Figure 6. When coolant flow comes up out of the LSS bottom plate flow holes, it is split by the beams and proceeds upwards within the square cells until the core inlet. The path length is about 30 inches in the inner area of the LSS bottom plate, and about 15 inches in the periphery; it may not be long enough for complete flow mixing, but partial mixing would occur between adjacent assembly channels within the same square cell. Then, flow proceeding upwards to

Table 3. Regional Core Inlet Flow Factors for System 80 by the Alternative Approach

Initial Grouping

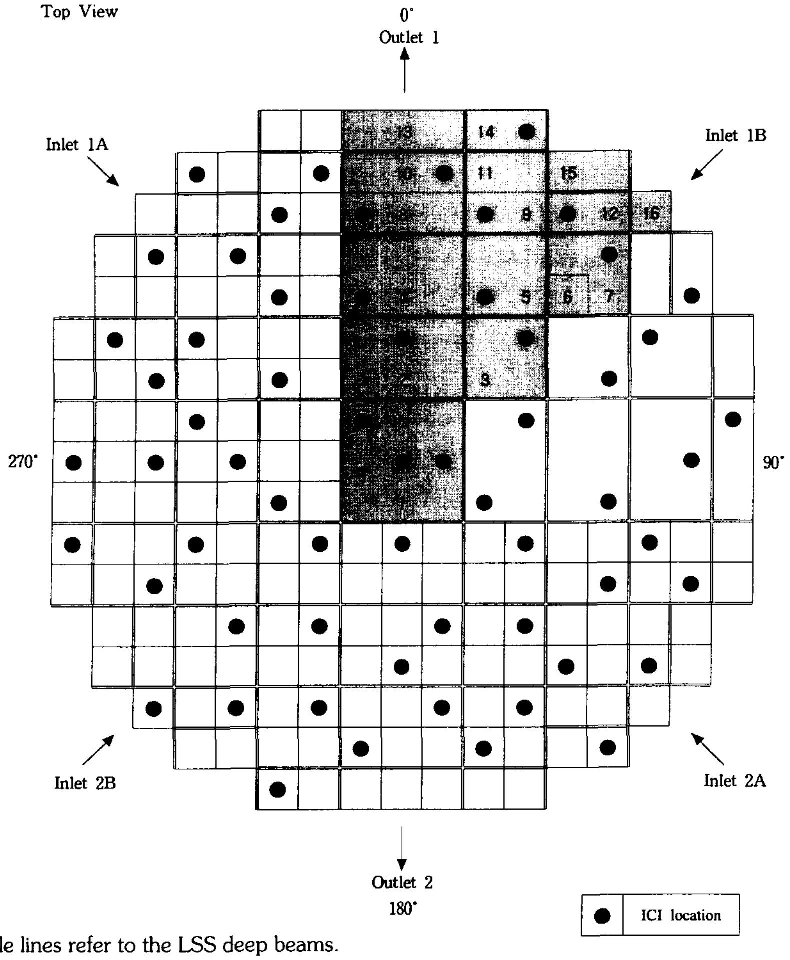
Initial Region ID	ICI	Mean Value	Standard Deviation	Number of Meas' nts	Initial Region ID	ICI	Mean Value	Standard Deviation	Number of Meas' nts
1	N	0.99	0.068	18	1'	Y	1.01	0.062	9
2	N	1.03	0.093	57	2'	Y	0.99	0.080	15
3	N	1.02	0.061	36	3'	Y	1.04	0.051	12
4	N	0.99	0.074	54	4'	Y	0.95	0.081	18
5	N	1.00	0.088	72	5'	Y	0.99	0.074	24
6	N	1.08	0.028	9	6'	Y	1.03	0.044	3
7	N	0.96	0.078	27	7'	Y	0.91	0.039	9
8	N	1.07	0.083	27	8'	Y	1.01	0.075	9
9	N	1.08	0.060	24	9'	Y	1.04	0.064	24
10	N	0.94	0.102	27	10'	Y	0.89	0.055	9
11	N	0.97	0.112	36	11'	Y	0.88	0.075	12
12	N	1.03	0.126	36	12'	Y	0.89	0.081	12
13	N	1.04	0.085	30	13'	Y	1.04	0.104	6
14	N	0.97	0.069	39	14'	Y	0.93	0.054	9
15	N	1.02	0.075	39	15'	Y	0.95	0.147	9
16	N	1.03	0.102	9	16'	Y	1.08	0.029	3

Final Grouping

Final Region ID	Initial Regions Combined	ICOI	Mean Value	Standard Deviation	Number of Measurements
A	1, 1′	N, Y	1.00	0.065	27
B	2, 2′, 3, 3′	N, Y	1.02	0.080	120
C	4, 5	N	1.00	0.082	126
C'	4′, 5′	Y	0.97	0.078	42
D	6, 8, 9	N	1.07	0.072	60
D'	6′, 8′, 9′	Y	1.03	0.067	36
E	7, 10, 11, 14	N	0.96	0.092	129
E'	7′, 10′, 11′, 14′	Y	0.90	0.060	39
F	12, 13, 15, 16	N	1.03	0.098	114
F	12′, 13′, 15′, 16′	Y	0.96	0.122	30

fuel assemblies above the same cell tends to become averaged somewhat. However, where there is strong cross flow beneath the LSS bottom plate such as in the periphery, flow above the LSS bottom plate would pile up inwards in the cells; for instance, enhanced flow inside and deficient flow outside in a cell.

5) ICI Guide Tubes and Supports: ICI guide tubes and their supports in the lower plenum and LSS region present local blockages to coolant flow approaching the core inlet. As a result, the fuel assemblies just above ICI guide tubes would see reduced coolant supply. To compensate for the blockage effect, the flow holes are made bigger at ICI locations. ICI arrangement shows a random and asymmetric pattern, which disturbs



Notes : Double lines refer to the LSS deep beams.

Fig. 7. Initial Grouping of Fuel Assembly Locations for System 80 by the Alternative Approach

the systematic pattern of flow hole arrangement in the LSS bottom plate and contributes partially to the peaky local flow distribution. The flow distribution is hard to predict and control by analytical means due to the complicated nature involved. However, the overall core inlet flow distribution would not be profoundly distorted by this.

6) Combined Effects: As discussed above, the coolant flow undergoes an extensive mixing as it runs from the inlet nozzles, down the long annular downcomer, through the flow skirt holes, across the complex geometry of ICI guide structures, and through the LSS bottom plate flow holes and core supporting beams, and to the core inlet. Even with the non-uniformity of the inlet nozzle and snubber locations, the coolant flow would be largely uniform in circumferential direction until just after the exit of the flow skirt holes. The uniformity would begin to be locally disturbed in the lower plenum and LSS region due to the rather randomly arranged ICI guide structures and the non-uniform outer profile of the LSS. The overall core inlet flow distribution would have an octant (1/8) symmetry in plane view since the most influential upstream

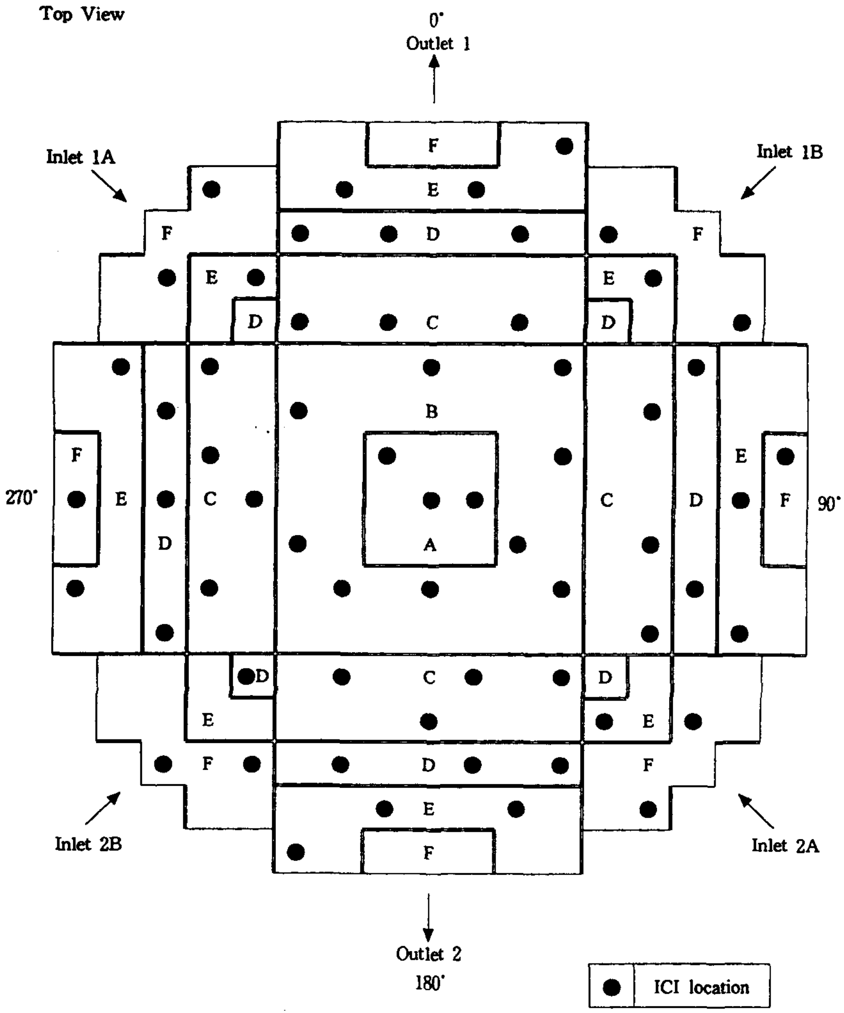


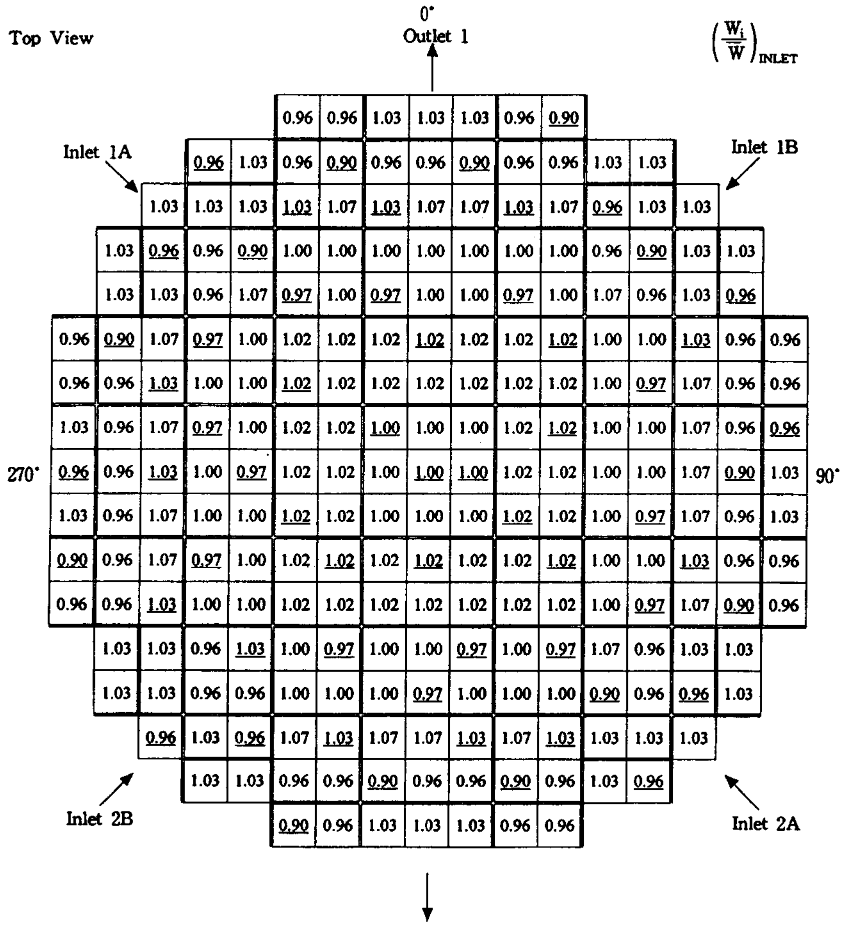
Fig. 8. Final Grouping of Fuel Assembly Locations for System 80 by the Alternative Approach

geometry - the LSS outer profile and the flow hole arrangement in it - has an octant symmetry as does the core. It also would vary in radial direction from the core center to the periphery, and from the inside to the outside within the cells of the core support beams.

3.2. Initial Grouping and t-Test

Rules for the initial grouping of core area are established by engineering judgement based on the reasoning above. Rules are as follows:

1) Use the outer profile of the LSS bottom plate as a guide for the regionalization in circumferential direction assuming a variation in circumferential direction and an octant symmetry in the plane view of the core inlet flow distribution.
2) Use the flow hole patterns in the LSS bottom plate as a guide for the regionalization in radial direction assuming a variation in radial direction of the flow distribution.



Notes : 1. Numbers underlined refer to ICI locations.
2. Double lines refer to the LSS deep beams.

Fig. 9. Revised Core Inlet Flow Distribution for System 80 by the Alternative Approach

3) Use the core support beams as the boundaries of unit cells assuming that each unit cell by the core support beams has a unique flow pattern, distinctly from others.
4) Account for the effects of cross flow in the core periphery when dividing a region into two sub-regions of low flow and high flow, particularly in the second outer-most row of fuel assembly locations; it is caused by the flow piling up near the inside corners and walls of the cells.
5) Consider the ICI and non-ICI locations as separate regions.

According to the initial grouping rules, 241 fuel assembly locations in the core are grouped into 32 regions as shown in Table 3 and Figure 7; 16 main regions, each consisting of 2 sub-regions for ICI and non-ICI locations. Average core inlet flow factors and standard deviations for the initially grouped regions are provided in Table 3, together with the associated test data.

Next step is to see if the number of regions of the initial grouping can be reduced further. If any two regions are either in close neighborhood or conceivably correlated with each other though not in direct contact, they are chosen as candidates for the statistical t-Test. Care is taken not to choose pairs which are located so remotely from each other that they can hardly have a physical link, unless there are any over-riding reasons to do. Then, a series of t-Tests is carried out for every one of chosen pairs. The null hypothesis for the t-Test is made that "the inlet flow factors of the two regions of a selected pair are originated from a same population". The level of significance α for the t-Test is set at 0.1. According to the t-Tests, 241 fuel assembly locations in the core are finally grouped into 10 regions as shown in Table 3 and Figure 8. The corresponding average core inlet flow factors and the associated standard deviations are provided in Table 3. The resulting core inlet flow distribution is provided in Figure 9.

3.3. Discussion

Effects of the upstream structures on the regional flow distribution at core inlet plane have been examined in more detailed manner. In addition to the flow change in radial direction, the flow variation in circumferential direction and the octant-symmetrical characteristics have been taken into account. The effects of the core support beams, the cross flow in the lower plenum, and the ICI guide tubes have also been accounted for.

Statistical t-Test technique has been applied more prudently. If two regions are located so remotely from each other that they hardly have a physical link, they are excluded from candidates for t-Test. From a purely statistical standpoint, it can be valid to merge any two regions relying on the t-Test results only, no matter how much they are physically correlated. But if any two regions in the core are connected to different upstream flow paths where there occur apparently different flow phenomena, they should be considered to be independent of each other and should not be merged. In other words, it should be meaningful from both the statistical and physical standpoints. The level of significance α of the t-Test has been increased from 0.05 to 0.1 as a way of better preserving the regional uniqueness of the core inlet flow distribution. With α=0.1, the chance of rejecting the null hypothesis is higher than with α =0.05, which means the risk grows with a higher level of significance that the judgement of rejecting the null hypothesis can be wrong; in other words, with a higher significance level, the initially grouped regions are more difficult to be further merged. As a result, the lower level of significance would eventually lead to fewer grand regions, and the regional characteristics of core inlet flow distribution would become more blurred. Thus, as the need grows to preserve the regional uniqueness in flow distribution, the level of significance should be increased. It may depend on the engineering judgement of designer's own whether to use either 0.05 or 0.1 or even higher for α However, α=0.1 appears to be more appropriate than α=0.05 for the present case.

Owing to the changes discussed above, results of ABB-CE's work and the present work are different, which are summarized below: The number of regions by ABB-CE's initial grouping was 12 which were later merged into 6 regions, while the initial regions of the present work are 32 which are later reduced to 10. The flow factors of the ABB-CE's core map ranged from 0.89 to 1.08 with standard deviations of 0.065 to 0.102, while those of the present core map range from 0.90 to 1.07 with standard deviations of 0.060 to 0.122, as shown in Tables 2 and 3. From a statistical standpoint, there is not much difference between two results. However, from a physical standpoint, the core inlet flow distribution map of the present work better preserves the regional uniqueness as can be found in comparison between Figures 4 and 9.

4. Conclusions

In the present work, ABB-CE's regionalization methodology for the core inlet flow distribution map has been reviewed. By merging the test data for the fuel assembly locations which are either in symmetry or strongly correlated with others, it increases the number of available test data for each flow factor. This methodology is considered to be effective in making up for the deficiency owing to limited number of test data. It contributes to making the core inlet flow distribution smoother not only locally but also over the entire core, and also to relieving the impacts of test errors that may happen due to some de-calibrated local pressure measurement taps. As a result, the core inlet flow distribution data become more statistically useful and thus the conservatism involved in handling the core inlet flow factors for the thermal margin analysis is expected to be reduced.

Meanwhile, the regionalized map can lose the local uniqueness in core inlet flow distribution too much. By an alternative approach introduced in the present work, it has been shown that such a disadvantage can be mitigated somewhat if the engineering judgement is made more prudently for the initial grouping and the t-Test technique is more appropriately used. On the whole, the regionalization methodology is considered to be applicable to the Korean reactors.

Acknowledgement

The work described in this paper was performed by the financial support of KEPCO in accordance with the Contract for the KNGR development between KEPCO and KOPEC.

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