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PATHFINDER ATOMIC POWER PLANT

ANALYSIS OF CLUSTERED-PIN SUPERHEATER LATTICE EXPERIMENTS

Submitted to
U. S. ATOMIC ENERGY COMMISSION
NORTHERN STATES POWER COMPANY
and
CENTRAL UTILITIES ATOMIC POWER ASSOCIATES

by

ALLIS-CHALMERS MANUFACTURING COMPANY
ATOMIC ENERGY DIVISION

Bethesda, Maryland n

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ANALYSIS OF CLUSTERED-PIN

SUPERHEATER LATTICE EXPERIMENTS

By P. S. Lacy and J. W. Lewellen

Submitted to

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ALLIS-CHALMERS MANUFACTURING COMPANY

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Approved: D. A. Lampe
Project Manager
PATHFINDER ProjectAllis-Chalmers Manufacturing Company
Atomic Energy Division
Bethesda, Md. 20014Approved: Hibbert Hill
Vice President -
EngineeringNorthern States Power Company
15 South Fifth Street
Minneapolis 2, Minnesota

PATHFINDER ATOMIC POWER PLANT
ANALYSIS OF CLUSTERED-PIN
SUPERHEATER LATTICE EXPERIMENTS

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Total	<u>98</u>

FOREWORD

One of a series of reports on research and development in connection with the design of the Pathfinder Atomic Power Plant, this particular report deals with Analysis of Clustered-Pin Superheater Lattice Experiments. The Pathfinder Plant is located at a site near Sioux Falls, South Dakota and reached criticality early in 1964. Owners and operators of the plant will be Northern States Power Company of Minneapolis, Minnesota. Allis-Chalmers is performing the research, development and design, as well as being responsible for plant construction.

The U. S. Atomic Energy Commission, through Contract No. AT(11-1)-589 with Northern States Power Company, and Central Utilities Atomic Power Associates (CUAPA) are sponsors of the research and development program. The reactor will be of the Controlled Recirculation Boiling Reactor type with Nuclear Superheater.

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1. INTRODUCTION

1.1 EXPERIMENTAL WORK

A variety of clustered-pin superheater test cells were irradiated in the Allis-Chalmers critical facility. During irradiation, bare uranium-235, aluminum-monitoring foils were fixed transversely in the cells to give relative experimental values of the uranium fission rate over the entire cell cross-sectional area. A cadmium-covered foil was fixed at a representative point in the cell to isolate the thermal component of the total fission rate. The results lead to experimental thermal utilization values. Separate experimental runs using bare and cadmium-covered U-238 foils fixed transversely in the fuel-bearing region provided the additional information necessary to infer experimental U-238 resonance integrals.¹

1.2 ANALYTICAL WORK

The experimental cell configurations were calculated by a sequence of analytical techniques so that verified design procedures could be established before the superheater for Pathfinder Core II is designed. Both lattice criticality and localized absorption rates within cells under operational conditions must be accurately calculated if a superheater physics design, which meets steam temperature requirements through life, is to be successfully executed. The temperature and pressure conditions at operation make valid experimental data for direct application in design work difficult and expensive to obtain. Therefore, analytical procedures were sought that would permit reliable physics design work independent of experimental programs.

The clustered-pin cell analysis presents several problems in addition to those encountered in simpler boiling water reactor lattices. Also, these cells are smaller than the clustered ones which have been used in deuterium-moderated and gas-cooled reactors, and their averaged absorption cross section is rather high. Large flux variations over a small distance may therefore be expected. In addition, there is the analytical requirement imposed by the necessity of knowing both flooded and voided cell characteristics.

Initial attempts to duplicate measured, region-dependent U-235 thermal fission rates were made by using the SOFOCATE - P3 calculational model, which gives good results when applied to boiling reactor lattices. However, poor results were obtained. This model assumes that the thermal spectrum is independent of position and that a suitable one-dimensional (radial) cell representation, including a cylindrical outer cell boundary, can be devised. The complex geometry which characterizes the clustered-pin superheater cell renders these assumptions invalid.

A series of trial thermal activation calculations was performed in which separate investigations were made of the effects of space and spectrum inseparability (SLOP - 1 code) and two-dimensional transport effects (TRAC - 1 code). Neither method was in adequate agreement with experiment, but improvement over the initial calculations was noted in each case.

A two-dimensional transport method that implicitly allowed for spectrum inseparability (MARC code) was the next step in the trial sequence. Because these calculations were in good agreement with the experiments and because the generality inherent in the last method accommodated the major aspects of the physics problems that arise in calculating the thermal absorption properties of the clustered-pin cell, no further steps in the calculational sequence were taken.

Resonance integrals were computed by Hellstrand's empirical formulation. It was necessary to investigate the manner of applying Dancoff-type interaction corrections to the clustered-pin geometry so that a meaningful surface-to-mass ratio could be defined for use in the Hellstrand formula. However, when this definition was obtained, good agreement between calculated and experimental resonance integrals resulted.

Some comparative work was performed using the Adler, Hinman and Nordheim, and Stein resonance absorption methods. Good agreement between the different techniques was obtained, although the value of this confirmation is marginal because the same Dancoff correction technique was used in each case.

1.3 CONCLUSIONS

It seems possible to design a clustered-pin superheater using the most advanced techniques reported here. The best method for calculating the cell thermal absorption properties—that using the MARC code—can give results associated with an acceptable steam temperature uncertainty band of about ± 25 F. This method is regarded, therefore, as the present reference. The simplest and least expensive technique—that employing the standard SOFOCATE - P3 code combination—appears to be valid only for initial estimate and survey work, and its usefulness, even in these cases, is restricted to situations where reference MARC or equivalent results are available.

The experimental cells used in the Allis-Chalmers critical facility are simpler than those that will be used in the power-producing Core II superheater. The latter ones will be complicated by the addition of structural spacer wires and burnable poison elements. Adapting the analysis to include these features will be the object of continued study, but major changes in the reference analytical procedure are not anticipated.

Satisfactory resonance integrals have been obtained by applying several techniques. Therefore, it is concluded that the resonance escape probability in the clustered-pin cells can be computed with a reliability adequate for core design. However, it is recommended that the definition of the effective surface-to-mass ratio of the fuel pin clusters be subjected to further verification.

2. TEST CONFIGURATION

All test cell irradiations took place in a reproducible position in the critical facility superheater core; this location was on the core radial center and 18 in. below the top of the core. Figure 1 shows the location in a cross-sectional diagram. Eighty clustered-pin fuel elements surrounded the test cell. Of these, the 24 elements nearest the cell were made identical to the cell. The remaining clustered-pin elements were of a nominal configuration.

A buffered test region, isolated from core irregularities and with low flux gradients, was thus established.

Figure 2 shows a typical cell cross section, and Table 2-1 lists the cell configurations studied. Five variables were used to obtain the variety of configurations measured. These variables are:

- (1) flooding and voiding the steam flow and insulation areas,
- (2) fuel enrichment,
- (3) central fuel pin present or absent,
- (4) inner insulating tube present or absent, and
- (5) fuel pin spacing within the cluster.

Cell-type B denotes an intracluster spacing (indicated by R in Fig. 2) of B, 0.2875 in., C, 0.3250 in., and D, 0.3750 in.

TABLE 2-1

EXPERIMENTAL CLUSTERED-PIN CELLS FLOODED AND VOIDED

<u>number of pins</u>	<u>enrichment, %</u>	<u>wall</u>	<u>type</u>
7	3.5	single	B
		single	C
		single	D
		double	B
		double	C
		double	D
7	7.0	single	D
		double	B
		double	C

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The I_2 code requires a one-dimensional, infinite cylindrical representation of the cell. The actual geometry, shown in Fig. 2, was therefore approximated by six concentric, annular zones. From the center outward, these zones represent the center pin homogenized with its clad, void (or flooding water), homogenized fuel and clad of reduced density (mixed also with water in flooded cells), void (or flooding water), the steel wall (homogenized with void or water in double-walled cases), and the moderator water.

The annulus representing the six outer fuel pins was defined by replacing the clad pins with area-equivalent squares having two sides perpendicular to cell radials. Two circles, tangent to these sides at their intersections with their bisecting radials, form the boundaries of the fuel annulus. The excess volume of this annulus over that of the fuel and clad is occupied by either void or water. For voided cells, fuel ring constants were volume-averaged between void and fully dense fuel and clad. When flooded cells were analyzed, the slab-geometry SIMPL code (P_3 approximation) was used to prepare volume-flux-averaged parameters. The SIMPL geometry was defined by the fuel ring volume, the volume of each pin, and the width of the fuel-pin equivalent squares.

Normal design procedure begins with the estimated cell flux weighting factors which are used to compute average number density input to initial SOFOCATE problems. The initial spectrum cases provide cross section information for a P_3 cell calculation. This P_3 flux distribution provides the basis for reaveraged cell number densities, and these densities are fed into a second SOFOCATE case which yields the final thermal parameter set.

This iteration between space and the energy spectrum was not performed here. Instead the first-round SOFOCATES were run with input number densities averaged by the experimental g -factors. The associated set of P_3 flux distribution calculations following these SOFOCATES terminated the sequence for this experimental work.

3.2.2 Refined Calculation Models

Table 4-1 includes experimental fission activation distributions and those calculated by the method described in Sec. 3.2.1. A comparison of these two information blocks shows that the analysis fails to duplicate the measured results by an appreciable margin. In every case, the degree of flux variation in the clustered-pin cell—from the high value in the moderator to the low value in the central fuel pin—is underestimated. Analytical methods capable of accommodating more complex representation of the problem were thus sought.

The first modification of the SOFOCATE-12 routine was a trial application of the SLOP₁ code.³ This space-spectrum code imposes the same geometrical restraints as the initial calculational procedure and is limited to the P₁ approximation in cylindrical geometry. It was therefore obvious that this phase of investigation could not, by itself, give acceptable results. However, there was evidence that a spectral shift through the cell might be contributing to the experimental-analytical discrepancies, and the SLOP₁ analysis was performed to verify this assumption. In addition, it was felt that combining regionwise SLOP₁ spectra with higher-order flux distribution calculations in a manner analogous to using the SOFOCATE-12 design procedure, might give good results. Table 3-1 lists the cases analyzed by SLOP₁.

TABLE 3-1
VOIDED CELLS ANALYZED BY SLOP₁

<u>number of pins</u>	<u>enrichment, %</u>	<u>wall</u>	<u>type</u>
7	3.5	single	B
7	3.5	single	D
7	3.5	double	B
7	7.0	double	B

Comparison of SLOP₁ results with SOFOCATE-P₁ and of SLOP₁ - P₃ with SOFOCATE-P₃ shows that a significant spatial spectral shift effect does occur. However, neither SLOP nor the SLOP₁ - P₃ combination gives good agreement with the experimental and flux distributions. At this point, the inaccuracies arising from the gross geometrical approximations necessary for one-dimensional analysis were considered to present the most serious unresolved problem.

Two attempts, using different methods, were then made to achieve a design procedure accommodating improved geometrical representations. Both attempts were based upon the monte carlo method of solving the neutron transport equation, and both deal with XY (rectangular) geometry. These methods are therefore appropriate for the small clustered-pin cell size and can handle discrete pin geometrical approximations of the cell.

These two methods involve usage of the TRAC-1⁴ and MARC⁵ codes. Analyses using these codes are quite similar, as indicated above. However, the MARC code solves the thermal multigroup transport equations and therefore generates a space-dependent thermal spectrum in its operation. The TRAC-1 code is used for solving the mono-energetic transport equation and requires an independent neutron spectrum determination.

The experimental g-based SOFOCATE spectra have been used with the TRAC-1 cases run in the course of this work. MARC requires a hydrogen scattering matrix to formulate group-to-group transfer coefficients for the thermal multigroup treatment. Nelkin-Kernel results were used.^{6, 7}

Because TRAC-1 and MARC use the statistical monte carlo technique, estimates of the transport solutions were obtained. In addition, the sample size, or number of neutron histories allowed per run, determines the estimated precision.

Figure 2 shows a typical cell. The XY limitation of the two monte carlo codes makes it necessary to approximate the cylindrical fuel pins and cell wall with rectangles. Figure 3 shows a typical quarter-cell representation as set up for TRAC-1 and MARC.

Table 3-2 lists the experimental cell configurations which were analyzed by these two XY transport methods.

TABLE 3-2

CASES CALCULATED BY TRAC-1 AND MARC VOIDED CELLS

<u>number of pins</u>	<u>enrichment, %</u>	<u>wall</u>	<u>type</u>	<u>TRAC-1</u>	<u>MARC</u>
7	3.5	single	B	10,000	15,000
7	3.5	single	D	10,000	15,000
7	3.5	double	B	20,000	20,000
7	7.0	double	B	10,000	15,000
6	3.5	double	B	10,000	---
<u>flooded cells</u>					
7	3.5	single	B	10,000	10,000
7	3.5	single	D	10,000	---

The entries in the TRAC-1 and MARC columns indicate the number of neutron histories included in the run for the respective cell configuration. If no number is given, the case was not run. This work terminated the study of the experimental cell thermal absorption properties.

CLUSTERED PIN SUPERHEATER ELEMENT X - Y
QUARTER CELL REPRESENTATION

FIG. 3

3.3 RESONANCE ABSORPTION ANALYSIS

Hellstrand's empirical expression for the U-238 resonance integral was used to compute values for comparison with the results of all experimental cases. The formula for cylindrical UO_2 rods including the $1/v$ absorption contribution is:

$$\sigma_{\text{eff}}^{28} = 5.35 + 26.6 \sqrt{S/M} \quad (3)$$

Two factors apply when adopting this equation to the clustered-pin situation that prevails in the superheat lattices under study. First, some equivalent cylinder must be selected so that the fuel surface-to-mass ratio (S/M) can be defined. Second, the resonance flux depletion attributable to adjoining pins with clusters and to adjoining clusters must be accounted for by Dancoff-Ginsburg or similar corrections.

The voided cells were analyzed by representing the hexagonal fuel cluster as a single, large pin of reduced UO_2 density with a radius the same as that of the cluster circumscribing circle. There is no moderating material inside the voided cluster, and there are no chords through the seven-pin clusters which do not intersect material if the pin-to-pin spacing is restricted to the experimental range. In addition, the S/M values arising from applying this model to the geometry of the superheater cells fall within the range in which the Hellstrand formula is valid.

When the voided cell is handled by this large pin (or "rubber band surface") model, the Dancoff shielding effect must be included only for interactions between the fuel clusters because the interactions inside the clump are reflected implicitly in the S/M definition. Dancoff corrections accounting for the four nearest-neighbor, cluster-to-cluster interactions were included by correcting the rubber band surface S/M :

$$(S/M)_{\text{eff}} = S/M (1 - \delta) \quad (4)$$

where:

$$\delta = 0.1277 N \exp \left[1.76 (d/r - 2.05) r \Sigma_s \right] \quad (5)$$

N is the number of neighboring fuel pins a distance, d , (on-centers) away from the reference pin in the lattice. The pin radius is r . In the voided case, d and r pertain to the rubber band surface.

Σ_s is the scattering cross section between fuel lumps. Regions of void, steel, and water are interposed between fuel clusters in the superheater lattice, thus requiring

that Σ be averaged over the average "path fractions" of these materials. The path fraction averages were obtained by integrating over all chords that connect the periphery of adjoining fuel lumps (rubber band surfaces). The integrations were performed numerically using distances measured from scale drawings of the fuel element geometry.

The flooded-cell problem is less subject to interpretation than the one presented in the voided case, because the water present between the fuel pins inside the cluster makes it necessary to compute S/M from the individual pin geometry. The Dancoff correction-reflecting interactions in the cluster were computed by Equation (5) with appropriate d, r, and Σ values. N was set equal to three and six for the outside and inside pins, respectively.

No cluster-to-cluster Dancoff corrections were made for the flooded lattice. The flooding water between cluster surfaces - that between the inner and outer wall and that inside the inner wall, but exterior to the cluster - was assumed to be sufficient to make cluster-to-cluster corrections unimportant. Investigation has shown that this assumption is good for the cells with the "B" and "C" pin spacings. Some error should result for "D" cells; however, the consequences of this analytical deficiency are not apparent when comparing experimental and analytical resonance integrals for these cases.

All double-walled "B" and "C" and single-walled "D" cells indicated in Table 2-1 were analyzed in the manner just described. The seven pin, 3-1/2 percent enriched cells were also computed using results of the QUERY code⁹ and of Stein's method¹⁰ instead of the Hellstrand formulation. The surface-to-mass ratios were defined as described above. The Dancoff corrections computed for the Hellstrand treatment were also used for the QUERY application.

4. RESULTS

4.1 THERMAL ABSORPTION

4.1.1 Comparative Experimental and SOFOCATE-12 Analytical Results

Experimental, regionwise fission responses and corresponding flux (g) factors obtained by the SOFOCATE-12 model are listed in Table 4-1.

TABLE 4-1
EXPERIMENTAL AND CALCULATED g-FACTORS

A. Seven-pin 3-1/2% Enriched Cells
Single-walled

<u>Voided</u>						
<u>region</u>	<u>B</u>		<u>C</u>		<u>D</u>	
	<u>experiment</u>	<u>analysis</u>	<u>experiment</u>	<u>analysis</u>	<u>experiment</u>	<u>analysis</u>
center pin	0.756	0.810	0.770	0.834	0.794	0.862
outer pins	0.821	0.894	0.820	0.914	0.850	0.935
all pins	0.812	0.882	0.814	0.902	0.834	0.925
void	0.923	0.957	0.931	0.949	0.921	0.942
well	1.091	1.032	1.089	1.027	1.085	1.019
moderator water	1.210	1.127	1.197	1.126	1.198	1.123
<u>Flooded</u>						
center pin	0.677	0.714	0.718	0.771	0.785	0.831
outer pins	0.770	0.796	0.807	0.833	0.840	0.859
all pins	0.746	0.784	0.788	0.824	0.837	0.855
flooding water	0.966	0.978	0.961	0.980	0.957	0.987
wall	1.128	1.091	1.106	1.057	1.079	1.048
moderator water	1.185	1.129	1.170	1.125	1.149	1.100

<u>Double-walled</u>				
<u>Voided</u>				
<u>region</u>	<u>B</u>		<u>C</u>	
	<u>experiment</u>	<u>analysis</u>	<u>experiment</u>	<u>analysis</u>
center pin	0.738	0.802	0.772	0.827
outer pins	0.799	0.884	0.825	0.903
all pins	0.789	0.873	0.815	0.892
void	0.927	0.946	0.917	0.937
wall	1.035	1.015	1.029	1.010
moderator water	1.211	1.142	1.208	1.140

Double-walled (cont'd)

<u>Flooded</u>				
<u>region</u>	<u>B</u>		<u>C</u>	
	<u>experiment</u>	<u>analysis</u>	<u>experiment</u>	<u>analysis</u>
center pin	0.679	0.735	0.723	0.789
outer pins	0.754	0.810	0.807	0.840
all pins	0.748	0.799	0.797	0.832
flooding water	0.963	0.973	0.946	0.972
wall	1.074	1.085	1.055	1.066
moderator water	1.182	1.140	1.177	1.126

B. Seven-pin 7% Enriched Cells

<u>region</u>	<u>double-walled</u>				<u>single-walled</u>	
	<u>B</u>		<u>C</u>		<u>D</u>	
	<u>experiment</u>	<u>analysis</u>	<u>experiment</u>	<u>analysis</u>	<u>experiment</u>	<u>analysis</u>
center pin	0.617	0.669	0.671	0.709	0.715	0.762
outer pins	0.710	0.807	0.738	0.838	0.773	0.889
all pins	0.697	0.787	0.729	0.820	0.765	0.871
void	0.887	0.924	0.873	0.907	0.878	0.908
wall	1.061	1.038	1.055	1.032	1.126	1.045
moderator water	1.309	1.215	1.308	1.216	1.295	1.199
<u>Flooded</u>						
center pin	0.563	0.592	0.625	0.665	0.684	0.729
outer pins	0.670	0.705	0.718	0.748	0.768	0.779
all pins	0.654	0.689	0.705	0.736	0.756	0.772
flooding water	0.927	0.962	0.905	0.957	0.931	0.978
wall	1.121	1.110	1.104	1.085	1.124	1.098
moderator water	1.271	1.210	1.265	1.194	1.230	1.160

C. Six-pin 3-1/2% Enriched Cells

region	double-walled				single-walled	
	B		C		D	
	experiment	analysis	experiment	analysis	experiment	analysis
<u>Voided</u>						
fuel pins	0.814	0.893	0.830	0.910	0.857	0.939
void	0.914	0.945	0.911	0.940	0.914	0.948
wall	1.027	1.009	1.020	1.005	1.069	1.010
moderator water	1.204	1.126	1.202	1.124	1.191	1.107
<u>Flooded</u>						
fuel pins	0.780	0.816	0.827	0.849	0.852	0.858
flooding water	0.954	0.962	0.952	0.983	0.983	1.003
wall	1.065	1.044	1.036	1.027	1.045	1.030
moderator water	1.160	1.136	1.145	1.096	1.098	1.069

D. Six-pin 7% Enriched Cells

region	<u>Double-walled</u>							
	<u>Voided</u>				<u>Flooded</u>			
	B		C		B		C	
	exper.	anal.	exper.	anal.	exper.	anal.	exper.	anal.
fuel pins	0.772	0.826	0.754	0.854	0.701	0.731	0.743	0.762
void	0.939	0.919	0.888	0.909	--	--	--	--
flooding water	--	--	--	--	0.929	0.962	0.933	0.943
wall	1.096	1.026	1.052	1.020	1.104	1.080	1.036	1.052
moderator water	1.275	1.191	1.286	1.191	1.236	1.172	1.215	1.150

4.1.2 Fission Response Distributions from Refined Models

Table 4-2 shows relative response levels, or g-factors, computed by the various techniques described in Sec. 3.2.2. The experimental and SOFOCATE-12 results listed in Table 4-1 are repeated to facilitate comparison. The experimental, SLOP₁ and MARC results are fission responses. The SOFOCATE-12 and SOFOCATE-TRAC-1 models use the one-velocity approximation so no distinction between fluxes and responses can be inferred. The uncertainties with the experimental results reflect the uncertainty in the counting statistics, while those for TRAC-1 and MARC indicate the 95 percent confidence intervals arising from the statistical nature of the transport equation solution.

TABLE 4-2

COMPARATIVE FISSION RESPONSE DISTRIBUTIONS

A. Voided Seven-pin 3-1/2% Enriched Single-walled "B" Cell

<u>method</u>	<u>center pin</u>	<u>outer pins</u>	<u>wall</u>	<u>moderator</u>
experiment	0.756±0.008	0.821±0.003	1.091±0.010	1.210±0.011
SOFOCATE-12	0.810	0.894	1.032	1.127
SLOP ₁ -12	0.783	0.873	1.021	1.157
SOFOCATE-TRAC-1	0.769±0.024	0.817±0.017	1.037±0.021	1.147±0.026
MARC	0.727±0.024	0.799±0.018	1.037±0.017	1.205±0.0174

B. Voided Seven-pin 3-1/2% Enriched Single-walled "D" Cell

experiment	0.794±0.007	0.850±0.003	1.085±0.009	1.198±0.011
SOFOCATE-12	0.862	0.935	1.019	1.123
SLOP ₁ -12	0.830	0.917	1.009	1.157
SOFOCATE-TRAC-1	0.826±0.029	0.840±0.015	1.013±0.021	1.139±0.020
MARC	0.821±0.022	0.829±0.017	1.013±0.020	1.211±0.026

C. Voided Seven-pin 3-1/2% Enriched Double-walled "B" Cell

experiment	0.738±0.008	0.799±0.003	1.035±0.010	1.211±0.010
SOFOCATE-12	0.802	0.884	1.015	1.142
SLOP ₁ -12	0.770	0.856	0.996	1.181
SOFOCATE-TRAC-1	0.777±0.020	0.825±0.010	0.983±0.016	1.160±0.015
MARC	0.724±0.020	0.793±0.013	0.983±0.017	1.238±0.021

D. Voided Seven-pin 7% Enriched Double-walled "B" Cell

experiment	0.617±0.005	0.710±0.002	1.061±0.009	1.309±0.010
SOFOCATE-12	0.669	0.807	1.038	1.215
SLOP ₁ -12	0.644	0.787	1.022	1.252
SOFOCATE-TRAC-1	0.634±0.034	0.731±0.012	1.005±0.019	1.216±0.020
MARC	0.576±0.020	0.693±0.014	1.005±0.016	1.325±0.023

E. Voided Six-pin 3-1/2% Enriched Double-walled "B" Cell

<u>method</u>	<u>center pin</u>	<u>outer pins</u>	<u>wall</u>	<u>moderator</u>
experiment	--	0.814±0.003	1.027±0.010	1.204±0.013
SOFOCATE-12	--	0.893	1.009	1.126
SOFOCATE- TRAC-1	--	0.860±0.010	1.000±0.025	1.181±0.024

F. Flooded Seven-pin 3-1/2% Enriched Single-walled "B" Cell

	<u>center pin</u>	<u>outer pins</u>	<u>wall</u>	<u>moderator</u>	<u>flooding wtr.</u>
experiment	0.677±0.005	0.770±0.002	1.128±0.007	1.185±0.008	0.966±0.006
SOFOCATE-12	0.714	0.796	1.091	1.129	0.978
SOFOCATE- TRAC-1	0.694±0.016	0.794±0.017	1.103±0.026	1.158±0.021	0.975±0.022
MARC	0.642±0.025	0.732±0.022	1.134±0.033	1.187±0.035	0.979±0.021

G. Flooded Seven-pin 3-1/2% Enriched Single-walled "B" Cell

experiment	0.785±0.008	0.840±0.003	1.079±0.009	1.149±0.010	0.957±0.009
SOFOCATE-12	0.831	0.859	1.048	1.100	0.987
SOFOCATE- TRAC-1	0.746±0.032	0.814±0.019	1.088±0.032	1.135±0.029	0.982±0.020

Voided cell TRAC-1 results were normalized to the MARC output or to 1.0 for the wall region because flux estimates in void regions are not obtainable from the former. Selected results in Tables 4-2A and 4-2G are plotted in Figs. 4 and 5.

MARC-computed nominal fission and I/v responses and fluxes are listed in Table 4-3 for general information purposes.

TABLE 4-3

MARC FISSION RESPONSE, I/v RESPONSE, AND FLUX

A. Voided Seven-pin 3-1/2% Enriched Single-walled "B" Cell

<u>quantity</u>	<u>center pin</u>	<u>outer pins</u>	<u>wall</u>	<u>moderator</u>	<u>flooding water</u>
fission response	0.727	0.799	1.037	1.206	--
I/v response	0.736	0.806	1.037	1.198	--
flux	0.796	0.850	1.042	1.148	--

LEGEND:

COMPARATIVE FISSION RESPONSES IN THE 7 PIN,
3-1/2% ENRICHED, VOIDED SINGLE WALL B CELL

FIG. 4

LEGEND:

— P_3 - SOFOCATÉ

• Nominal values

▤ EXPERIMENT

▨ MARC

COMPARATIVE FISSION RESPONSES IN THE 7 PIN,
3-1/2% ENRICHED, FLOODED SINGLE WALL B CELL

FIG. 5

B. Flooded Seven-pin 3-1/2% Enriched Single-walled "B" Cell

<u>quantity</u>	<u>center pin</u>	<u>outer pins</u>	<u>wall</u>	<u>moderator</u>	<u>flooding water</u>
fission response	0.642	0.732	1.134	1.187	0.979
1/v response	0.649	0.740	1.131	1.182	0.979
flux	0.699	0.790	1.113	1.151	0.980

Some nominal computed, 1/v unit "A" values are given in Table 4-4 to indicate the spectral shift in the superheater cells and to provide a comparison of the spectra computed by different methods.

TABLE 4-4
COMPUTED UNIT A VALUES

A. Voided Seven-pin 3-1/2% Enriched Single-walled "B" Cell

<u>method</u>	<u>center pin</u>	<u>outer pins</u>	<u>wall</u>	<u>moderator</u>
SOFOCATE	0.722	0.722	0.722	0.722
SLOP ₁	0.646	0.663	0.681	0.708
MARC	0.637	0.654	0.686	0.719

B. Voided Seven-pin 7.0% Enriched Double-walled "B" Cell

SOFOCATE	0.678	0.678	0.678	0.678
SLOP ₁	0.561	0.592	0.625	0.678
MARC	0.563	0.590	0.646	0.686

C. Flooded Seven-pin 3-1/2% Enriched Single-walled "B" Cell

					<u>flooding water</u>
SOFOCATE	0.791	0.791	0.791	0.791	
MARC	0.720	0.725	0.786	0.795	0.773

Each of the three spectrum calculational methods indicated above by the associated machine code has used a different hydrogen scattering treatment (respectively free gas, Radkowsky kernel, and Nelkin kernel) in application to this work. However, SLOP₁ agrees very well with MARC in spite of the different treatment and the geometrical restrictions on SLOP₁. The high cell average unit A obtained from SOFOCATE may result from high free-gas moderating efficiency.

4.2 RESONANCE ABSORPTION

Measured and calculated U-238 resonance integrals are listed in Table 4-5. The parameters used in the Hellstrand formulation are also given. The values include 1.2 barns to account for 1/v absorption above 0.5 ev.

TABLE 4-5
U-238 RESONANCE INTEGRALS IN CLUSTERED
PIN LATTICES

A. Voided Cells

no. of pins	enrichment	wall	type	σ^{28}_a	σ^{28}_a	S/M	(1- δ)
				experiment	Hellstrand		
7	3.5	double	B	20.3 $\pm$ 1.3	20.2	0.383	0.809
7	3.5	double	C	20.2 $\pm$ 1.3	20.7	0.419	0.797
7	3.5	single	D	21.9 $\pm$ 1.5	21.3	0.468	0.766
7	7.0	double	B	22.3 $\pm$ 1.5	20.4	0.397	0.809
7	7.0	double	C	21.0 $\pm$ 1.7	21.0	0.435	0.797
7	7.0	single	D	21.7 $\pm$ 1.5	21.6	0.485	0.766
6	3.5	double	B	20.8 $\pm$ 1.5	21.3	0.447	0.809
6	3.5	double	C	21.2 $\pm$ 1.4	21.9	0.489	0.797
6	3.5	single	D	--	22.5	0.546	0.766
6	7.0	double	B	20.7 $\pm$ 1.4	21.6	0.463	0.809
6	7.0	double	C	21.6 $\pm$ 1.5	22.2	0.507	0.797

B. Flooded Cells

no. of pins	enrichment	wall	type	σ^{28}_a	σ^{28}_a	S/M	(1- δ)
				experiment	Hellstrand		
7	3.5	double	B	24.4 $\pm$ 1.6	24.2	0.727	0.478
7	3.5	double	C	25.8 $\pm$ 1.7	25.1	0.727	0.596
7	3.5	single	D	26.6 $\pm$ 2.5	26.0	0.727	0.713
7	7.0	double	B	26.2 $\pm$ 1.3	24.5	0.754	0.478
7	7.0	double	C	25.7 $\pm$ 2.1	25.5	0.754	0.596

<u>no. of pins</u>	<u>enrichment</u>	<u>wall</u>	<u>type</u>	σ^{28}_a <u>experiment</u>	σ^{28}_a <u>Hellstrand</u>	<u>S/M</u>	<u>(1-δ)</u>	
7	7.0	single	D	26.7 ± 1.8	26.4	0.754	0.856	0.713
6	3.5	double	B	26.3 ± 2.0	25.2	0.727	0.772	
6	3.5	double	C	27.5 ± 2.0	25.9	0.727	0.831	
6	3.5	single	D	31.6 ± 3.0	26.6	0.727	0.885	
6	7.0	double	B	28.0 ± 2.0	25.6	0.754	0.772	
6	7.0	double	C	26.7 ± 1.8	26.3	0.754	0.831	

Two values of (1- δ) are given for each flooded, seven-pin cell. The first entry gives the correction for the outer six pins, and the second is that for the central pin.

The seven-pin, 3-1/2 percent enriched cells have also been computed from QUERY code results for both the flooded and voided condition and by the Stein method in the voided case. The S/M and Dancoff corrections were determined exactly as for the Hellstrand analysis. The results are given in Table 4-6 and are repeated graphically in Fig. 6.

TABLE 4-6

ALTERNATE RESONANCE INTEGRAL COMPUTATIONS
SEVEN-PIN, 3-1/2% ENRICHED CELLS

<u>voided</u>	<u>Hellstrand</u>	<u>QUERY</u>	<u>Stein</u>
B	20.2	21.0	20.5
C	20.7	21.5	21.2
D	21.3	22.2	22.9
<u>flooded</u>			
B	24.2	24.3	---
C	25.1	25.3	---
D	26.0	26.2	---

The resonance escape probabilities corresponding to the experimental and Hellstrand-computed integrals in Table 4-5 are given in Table 4-7.

EXPERIMENTAL RESONANCE INTEGRALS
7 PIN - 3.5% ENRICHED LATTICES

FIG. 6

TABLE 4-7

RESONANCE ESCAPE PROBABILITY

no. of pins	enrichment	wall	type	voided		flooded	
				exper.	analysis	exper.	analysis
7	3.5	double	B	0.848±0.009	0.848	0.912±0.005	0.913
7	3.5	double	C	0.848±0.010	0.845	0.908±0.006	0.910
7	3.5	single	D	0.836±0.010	0.841	0.905±0.009	0.907
7	7.0	double	B	0.839±0.010	0.851	0.910±0.004	0.915
7	7.0	double	C	0.847±0.011	0.846	0.912±0.006	0.912
7	7.0	single	D	0.843±0.010	0.842	0.908±0.006	0.908
6	3.5	double	B	0.864±0.009	0.862	0.922±0.005	0.925
6	3.5	double	C	0.862±0.009	0.858	0.919±0.006	0.923
6	3.5	single	D	0.828±0.022	0.855	0.907±0.009	0.921
6	7.0	double	B	0.869±0.008	0.865	0.920±0.005	0.927
6	7.0	single	D	0.864±0.009	0.861	0.923±0.005	0.925

4.3 DERIVED RESULTS

The direct results of the thermal analyses were used to obtain thermal utilization, thermal multiplication, and experimental lattice criticalities. Table 4-8 gives the thermal parameters.

TABLE 4-8

THERMAL PARAMETERSA. Thermal Utilization (f)Voided Cells

no. of pins	enrichment	wall	type	experiment	TRAC-1	MARC
7	3.5	single	B	0.793±0.003	0.798±0.009	0.792±0.006
7	3.5	single	D	0.798±0.003	0.804±0.006	0.800±0.009
7	3.5	double	B	0.704±0.004	0.718±0.006	0.715±0.006
7	7.0	double	B	0.786±0.003	0.802±0.009	0.785±0.007

Flooded Cell

7	3.5	single	B	0.717±0.002	0.724±0.010	0.698±0.012
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B. Thermal Multiplication (ηf^2)

Voided Cells

no. of pins	enrichment	wall	type	experiment	1-2	TRAC-1	MARC
7	3.5	single	B	1.355	1.394	1.362±0.015	1.355±0.025
7	3.5	single	D	1.361	1.405	1.372±0.011	1.355±0.025
7	3.5	double	B	1.202	1.247	1.226±0.010	1.208±0.020
7	7.0	double	B	1.474	1.522	1.504±0.016	1.468±0.029

Flooded Cell

7	3.5	single	B	1.226	1.249	1.238±0.019	1.222±0.037
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The basis for the uncertainty intervals is the same as for the g -factors listed in Table 4-2. The experimental ηf^2 values carry a fractional uncertainty equal to that of the thermal utilization values. Clad steel absorption is included in the entries for the latter quantity.

Finally, energy- and space-averaged thermal diffusion parameters have been computed from MARC output. They are listed in Table 4-9 for comparison with corresponding SOFOCATE results.

TABLE 4-9

CLUSTERED CELL THERMAL DIFFUSION PARAMETERS

Voided Cells

no. of pins	enrichment	wall	type	D	Σa	$\nu \Sigma f^2$
7	3.5	single	B			
			MARC	0.352	0.0743±0.0011	0.1007±0.004
			SOFOCATE	0.332	0.0807	0.1094
7	3.5	single	D			
			MARC	0.331	0.0773±0.0013	0.1048±0.0002
			SOFOCATE	0.325	0.0819	0.1115
7	3.5	double	B			
			MARC	0.334	0.0814±0.0011	0.0979±0.0004
			SOFOCATE	0.332	0.0871	0.1047
7	7.0	double	B			
			MARC	0.323	0.1096±0.0014	0.1608±0.0012
			SOFOCATE	0.307	0.1187	0.1751

Flooded Cell

7	3.5	single	B			
			MARC	0.1706	0.0854±0.0018	0.1044±0.0008
			SOFOCATE	0.1667	0.0905	0.1109

5. DISCUSSION

5.1 GENERAL

The fission response g-factors in Table 4-2 show that two-dimensional transport and spectrum space dependence effects are important in the clustered-pin super-heater cells. The method employing the MARC code—the only one attempted which is general enough to include simultaneously a treatment of both effects—is the only method attempted that shows a potential for enabling accurate, straightforward cell calculations. Comparisons of measurements and MARC results indicate that the moderator-to-center-pin response ratios, which are indicative of the overall flux variation, are in reasonable agreement. The calculated results tend to overestimate these ratios.

The discrepancies in wall region response levels are not believed to present a problem because direct flux measurements in the outer wall section were not made. When reducing the experimental data, it was assumed that the outer wall flux or fission response is equal to the average response level of the moderator and inner wall regions. All analytical investigations indicate that this arbitrary interpretation is not correct.

The calculated (MARC) fuel region response levels show relationships which are not yet understood. Those results for the B cells show a tendency for excessive fuel shielding. The D cell case also overpredicts the total fuel shielding, but contrary to B cell results, underpredicts the center pin shielding relative to the outer pins. It is reasonable to expect some error to arise from the XY fuel pin representation, but pin-to-pin effects should be less for the loosely clustered D cell. More experience with these calculations is required before effects such as this can realistically be evaluated. However, better fuel pin representations will be used when further work is performed.

Table 4-4 contains data showing that the SLOP₁ code application gives very good spectrum space dependence, relative to the monte carlo results, in spite of the necessary geometrical and transport approximations. Thus, good analyses could probably be made by combining SLOP₁ and TRAC-1. However, this procedure would not be as efficient operationally as that of running MARC directly, because TRAC-1 and MARC runs require approximately equal machine time allowances, and SLOP₁, by itself, is an expensive code to use.

The calculated resonance integrals listed in Table 4-5 are, for the most part, within the uncertainty intervals associated with the values inferred from measurements. Therefore, the Hellstrand formulation, or equivalent, will be used for design calculations.

The agreement between Hellstrand, QUERY, and Stein results (Fig. 6) indicates that the U-238 resonance absorption problem is essentially solved after an adequate S/M definition and Dancoff treatment are found. Further work should be performed on these last two problems because the rubber band surface model is not fully applicable to loosely clustered, voided, seven-pin (D cells) or to all six-pin clusters, where neutrons are able to stream along some chords without encountering fuel. In addition, it is difficult to apply Dancoff corrections which account for cluster-to-cluster shielding to flooded cells.

5.2 NOTES ON DESIGN PROCEDURE

Thermal multigroup lattice analyses can be used directly in few-group (one thermal group) gross core calculation for overall reactivity and power distributions. Volume-energy integrated averages of the diffusion parameters, D ($1/3 \Sigma_{tr}$), Σ_a , $\nu \Sigma_f$, can easily be obtained from MARC code output, and these correspond to the results obtained by the more familiar SOFOCATE-1₂ routine. One variation from normal procedure will arise because of the statistical nature of monte carlo results (provided a monte carlo space spectrum transport code is used). Table 4-9 shows the one-thermal-group parameters from the MARC cases. At times, the normal procedure would be to run two separate full core calculations using respective (Σ_a , $\nu \Sigma_f$) pairs for maximum and minimum reactivity. As an example, these calculations would be $\Sigma_a = 0.0743 - 0.0011$, $\nu \Sigma_f = 0.1007 + 0.0004$, $\Sigma = 0.0743 + 0.0011$, and $\nu \Sigma_f = 0.1007 - 0.0004$ respectively, for the seven-pin, 3-1/2 percent single-walled B cell. A pair of calculations incorporating these data would give the range in which lattice performance would fall 19 times out of 20 with respect to statistical uncertainty.

The data cited indicate an uncertainty of 0.05 in thermal multiplication. A nominal thermalization probability equal to 0.7 is valid, so the statistics of the 15,000 history MARC calculation correspond to a 95 percent confidence interval in criticality of 3-1/2 percent. Preliminary superheater design surveys show that a steam temperature band of ± 40 F may be associated with this criticality interval. Increasing the calculational run to 50,000 neutron histories would cut this band approximately in half on an average. However, including the uncertainty accruing from calculating epithermal processes and from the errors in basic cross section data will provide a countering increase in the temperature uncertainty band.

Codes like MARC yield thermal multigroup data which enable gross core calculations using several thermal groups. The MARC energy structure would, in general, be collapsed before performing these calculations. A general multigroup code which allows neutron upscatter must be used for this work.

For clustered-pin lattices, incorporating computed resonance integrals in core analyses does not differ from the procedure used when simpler lattices are studied. The resonance integral governs the MUFT L -factor in both cases.

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