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TITLE

OUTER ANNULUS IMBALANCE STUDY

MARK I FUEL

□

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TABLE OF CONTENTS

	<u>Page No.</u>
ABSTRACT	3
I. INTRODUCTION	4
II. SUMMARY AND CONCLUSIONS	5
III. DISCUSSION	6
Definitions	6
Correlation of Experimental Data	6
Some Possible Methods for Limiting Imbalance	9
(1) Tightening Fuel Tolerances and Clearances	9
(2) Matching Fuel Elements to Process Tubes	12
(3) Other Methods	13
Miscellaneous	13
ACKNOWLEDGEMENTS	14
APPENDIX	15

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ABSTRACT

Results of an investigation of fuel element outer annulus enthalpy imbalance are reported and analytical results of suggested methods to limit this imbalance are presented. Also included are comparisons of calculated and experimental enthalpy imbalance ratios along with other quantities.

Results indicate that tightening fuel tolerances and clearances can substantially reduce the present outer annulus imbalance thereby increasing power capability. A basic pre-requisite to reduction of clearance between fuel support diameter and process tube diameter is a test establishment of the minimum allowable clearance compatible with charging requirements. Matching fuel elements to process tube diameters will also reduce the imbalance but is in general not feasible at the present time.

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OUTER ANNULUS IMBALANCE STUDY
MARK I FUEL

INTRODUCTION

In order to obtain maximum power from each process tube within the limitations of no boiling, it is of fundamental importance to achieve subchannel enthalpy balance. This study is specifically concerned with the outer annulus enthalpy imbalance caused by the fuel being eccentric in the process tube and with methods of limiting this imbalance. The two principal methods which were investigated are (1) decreasing clearance between fuel support diameter and process tube diameter, and (2) matching fuel elements of certain dimensions with process tubes of certain diamentions.

Considerable attention is also given to correlation of experimental results obtained from in-core thermocouple data and to the comparison of various calculated and experimental values.

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SUMMARY AND CONCLUSIONS

A computerized correlation has been developed which satisfactorily correlates experimental outer annulus bottom to top imbalance ratios. For the five cases considered, calculated and experimental values agree within the range of +3.6 percent to -5.8 percent.

Two methods investigated to reduce the outer annulus imbalance were as follows:

- (1) Tightening fuel tolerances and clearances
- (2) Matching fuel elements to process tubes.

Tightening the fuel tolerances and reduction of fuel support diameter to process tube clearance shows promise of effectively reducing the imbalance while matching is not considered feasible at the present time. However, in order to properly reduce the clearance, a test should be conducted to determine the minimum clearance compatible with charging requirements. To date the smallest clearance used has been approximately 14 mils. Two suggested alternatives to limit the outer annulus imbalance are mixing devices and development of a fuel-centering support.

Related topics studied were fuel exposure effects on the outer annulus imbalance and comparison of calculated and measured values of imbalance ratios at various angles of thermocouple train rotation. It was found that exposure (over period observed) had very little noticeable effect on outer annulus bottom to top imbalance ratio as shown by thermocouple data. Comparison of calculated and measured values of imbalance ratios at various angles of thermocouple rotation shows wide variations could not be explained definitively.

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DISCUSSION

Definitions

There are certain definitions pertinent to this study which are as follows:

- (1) Bottom to Top Imbalance Ratio - The enthalpy change (tube inlet to outlet) of the water at the bottom of the outer annulus divided by the enthalpy change (tube inlet to outlet) of the water at the top of the outer annulus.
- (2) Bottom to Bulk Imbalance Ratio - The enthalpy change (tube inlet to outlet) of the water at the bottom of the outer annulus divided by the enthalpy change (tube inlet to outlet) of the water at bulk conditions of the outer annulus.
- (3) Clearance - The difference between process tube inside diameter and support circle diameter.

Correlation of Experimental Data

Experimental imbalance ratios are obtained from coolant temperatures measured by thermocouples which are mounted on a spacer assembly and located at the downstream end of the fuel column. The thermocouples which measure outer annulus temperatures are positioned 180 degrees apart and are generally oriented to measure the top and bottom temperatures but can be turned to measure other outer annulus temperatures by rotating the spacer. With temperatures of the bottom and top (or other orientations) of the outer annulus, it is possible to calculate enthalpy imbalance ratios assuming the specific heat of water is constant. Enthalpy imbalance ratios for five thermocouple trains are considered in this study.

A correlation (developed by P. Riggle, Thermal Hydraulics) was used to calculate the bottom to top imbalance ratios of process tubes which have been instrumented with thermocouple trains. Basically, this correlation (computer code OFCENT) relates the enthalpy change at the bottom and top of the outer annulus of each fuel element to geometric eccentricity in the process tube where the eccentricity of each fuel element is calculated for the hot pressurized operating conditions.

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The fundamental relationship of the correlation is as follows:

$$R_{A/B} = (\delta_B / \delta_A)^{1.57}$$

where

- $R_{A/B}$ = enthalpy imbalance ratio, point A to point B, for an individual fuel element. Generally A = bottom and B = top.
- δ_A = radial distance from fuel outside diameter to process tube inside diameter at point A.
- δ_B = radial distance from fuel outside diameter to process tube inside diameter at point B.

A summation is then performed to obtain the total enthalpy change of the top and bottom and these total enthalpy changes expressed as a ratio of bottom to top imbalance. Basic assumptions used for correlation are as follows:

- (1) No circumferential mixing in the outer annulus
- (2) Power along the process tube varies as a cosine function
- (3) Negligible density and viscosity effects due to outer annulus temperature variation and process tube inlet to outlet temperature variation.
- (4) Uniform circumferential fuel element heating
- (5) Friction factor is proportional to Reynold's number raised to a constant power
- (6) Momentum losses are proportional to friction losses
- (7) Constant specific heat for the coolant.
- (8) Fuel elements have four equally spaced supports
- (9) Fuel elements are oriented for maximum eccentricity
- (10) Fuel elements are centered in the support circle
- (11) Process tube inside diameter is constant at a value equal to the average.

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In order to satisfactorily correlate the experimental results, it was necessary to introduce a constant correlation factor (1.0039 times fuel diameter at room temperature) which accounts for unknown quantities such as fuel swelling and mixing. The necessary computer input for the correlation is as follows:

- (1) Fuel outside diameter
- (2) Process tube average diameter
- (3) Average support height of fuel
- (4) Fuel cladding thickness
- (5)* Inlet water temperature
- (6)* Inlet to outlet water temperature change
- (7)* Temperature change across process tube wall
- (8)* Difference between average fuel driver temperature and water temperature at the process tube midpoint.

Correlation of experimental imbalance ratios is presented in the following table and in graphical form (Figure 1) of the Appendix. Included are the results of test PT-NR-33 ADD2 which consists of fuel fabricated to yield maximum and minimum eccentricity.

TABLE I

<u>Tube No.</u>	<u>Experimental Bottom to Top Imbalance Ratio</u>	<u>Calculated Bottom to Top Imbalance Ratio</u>	<u>Variation</u>
2960	1.436	1.378	-0.058
1657	1.325	1.361	+0.036
2855	1.300	1.270	-0.030
0962**	1.354	1.381	+0.027
1051**	1.057	1.044	-0.013

* Operating conditions determine these values.

** Tubes used in Production Test PT-NR-33, "In-Reactor Enthalpy Imbalance Measurements Addendum 2 - Eccentricity Experiments," R. H. Shoemaker, May 18, 1965.

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Some Possible Methods for Limiting Imbalance

(1) Tightening Fuel Tolerances and Clearances:

Since the fuel elements expand radially (due to thermal expansion) at a higher rate than the process tube, it is theoretically possible to tighten tolerances and lower clearances sufficiently to achieve a forced fit of fuel elements in the process tubes when hot. However, due to the fact that specific tests have not been performed to determine the maximum allowable support diameter that can be charged, it is not possible to specify a minimum allowable clearance. It is for this reason that conductance of tests yielding the minimum allowable clearance would be helpful in attaining the most favorable outer annulus imbalance. To date, the largest fuel support diameter charged in the reactor has been 2.690 inches (PT-NR-33 ADD2) which would have approximately 10 mils minimum clearance for a process tube with the minimum diameter of 2.700 inches. However, this fuel was loaded in a process tube of 2.704 minimum diameter (14 mils clearance) with no apparent difficulty and therefore no conclusion could be drawn as to the maximum allowable support diameter.

There is also a possibility that several (exact number unknown) inlet and outlet nozzles have a backroll upset (Figure 2) which was caused during rolling of the nozzle-tube joint and which could result in the minimum inlet nozzle diameter being smaller than manufactured dimensions (2.700 to 2.715 inches). In cases where this condition exists there is a possibility of shearing shoes from the fuel supports with increased support diameters during charging. Since the maximum allowable support diameter is not known, calculations were made for several different possible ranges with results of most probable, best possible, and worst possible cases of bottom to outer annulus bulk imbalance ratios shown as follows:

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TABLE II

Fuel Diameter Range	Support Diameter Range	Average Tube Diameter Range	Bottom to Outer Annulus Bulk Imbalance Ratio*		
			Best Possible	Most Probable	Worst Possible
2.389-2.409	2.675-2.685	2.703-2.715	1.038	1.124	1.245
2.389-2.409	2.680-2.690	2.703-2.715	1.000	1.080	1.193
2.389-2.409	2.690-2.700	2.703-2.715	1.000	1.000	1.098
2.389-2.409	2.694-2.700	2.703-2.715	1.000	1.000	1.064
2.389-2.409	2.695-2.700	2.703-2.715	1.000	1.000	1.055

Calculations were also made with the conditions of maximum process tube diameter and average fuel diameter with various support diameters. The results of these calculations indicate the worst imbalances due to maximum process tube diameter that are possible when using otherwise average conditions and are shown in the following table.

TABLE III

Average Fuel Diameter	Average Support Diameter	Maximum Process Tube Diameter	Bottom to Outer Annulus Bulk Imbalance Ratio*	
				S. N.
2.400	2.670	2.715	1.291	1.274
2.400	2.675	2.715	1.236	1.238
2.400	2.680	2.715	1.187	1.203
2.400	2.685	2.715	1.139	
2.400	2.690	2.715	1.095	
2.400	2.695	2.715	1.053	
2.400	2.700	2.715	1.015	1.0796

* These are approximate imbalance ratios which were calculated using an average eccentricity for the entire tube of fuel elements.

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It should be noted that several process tubes exceed the process tube diameter of 2.715 inches but these isolated cases were ignored for this study.

From calculations such as these it was confirmed that the support diameter and process tube diameter are the most critical parameters that affect the outer annulus imbalance. The following table illustrates, in order of increasing imbalance, the relative importance of the support diameter, fuel diameter, and process tube diameter as effecting the imbalance of the outer annulus.

TABLE IV

<u>Process Tube Diameter</u>	<u>Support Diameter</u>	<u>Fuel Diameter</u>	<u>Outer Annulus Imbalance Ratio</u>
Minimum	Maximum	Minimum	Lowest
Minimum	Maximum	Maximum	
Maximum	Maximum	Minimum	
Maximum	Maximum	Maximum	
Minimum	Minimum	Minimum	
Minimum	Minimum	Maximum	
Maximum	Minimum	Minimum	Highest
Maximum	Minimum	Maximum	

The table also shows that the most favorable imbalance ratio will be obtained when using maximum possible support diameter, minimum possible tube diameter and minimum possible fuel diameter.

Since these parameters influence the eccentricity, which in turn effects the imbalance, a plot of imbalance ratio versus eccentricity is presented in Figure 3. This plot uses the experimental and calculated imbalance ratios shown earlier in Table I along with an average calculated eccentricity for each case. This average eccentricity introduces some error but it is not thought to be excessive.

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(2) Matching Fuel Elements to Process Tubes:

Since it is possible to decrease the eccentricity by selecting fuel elements to more closely fit the individual process tubes, a matching scheme was studied to determine its desirability.

In order to investigate this scheme it was first necessary to collect data showing the average and minimum diameter of each process tube. From this data (obtained from D. H. Curtiss, Chemistry and Metallurgy) reactor face maps and distribution curves were made to more easily determine individual and statistical dimensions of the process tubes. See Figures 4, 5, 6, and 7. It should be noted that some error is inherent in these figures, mainly due to approximating the average flow diameter from measurements taken at intervals along the tube. The etching process also complicated obtaining accurate dimensions because some tubes were etched several times and in local areas.

Basically the scheme consists of dividing the average and minimum process tube diameters into three groups, with a corresponding support diameter range for each group. Clearances are also specified. Calculations were then made of best, most probable, and worst cases of imbalance ratios for each group. Results for conditions considered are shown graphically in Figures 8 and 9.

Two basic assumptions made for this matching scheme were the following:

- (a) The smallest diameter of a given segment of the minimum-process-tube-diameter-spectrum equals the smallest diameter of the corresponding average-diameter-spectrum. Stated differently, the minimum and average distributions have a one to one proportionality.
- (b) The minimum process tube diameter is the controlling minimum dimension. In other words, inlet nozzle dimensions were not considered smaller than process tube minimum diameters.

The first of these assumptions is thought to be nearly correct; however, it was not completely evaluated because of more pressing aspects of the study. The second assumption was found to be not necessarily correct since the inlet nozzle minimum diameter was manufactured to the same tolerances (2.700 inches to 2.715 inches) as the process tubes thereby making it impossible to know the actual controlling minimum diameter in all cases without actually measuring the nozzles. However, the matching scheme calculations were completed since it was considered plausible to enlarge the nozzles with minimum diameters smaller than the corresponding minimum process tube diameters.

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(3) Other Methods:

Although the following methods were not thoroughly investigated they are listed as possible alternatives for limiting the outer annulus imbalance.

- (a) Mixing device
- (b) Fuel-centering support.

The mixing device might be a void (spacing device) near the downstream end of the fuel column, while the support might be a thermal expanding type which would center the fuel element in the process tube when hot.

Miscellaneous

It was decided, since data were available, to compare calculated and experimental values of imbalance ratios taken at various angles of rotation about the outer annulus periphery. Experimental results are shown in Tables V and VI along with Figures 10 and 11 of the Appendix. The average values of these imbalance ratios for each rotation are plotted in Figures 12 and 13. The wide variation between calculated and experimental results could not be explained definitively. However, since only approximate angular measurements were made of rotation, some error (of unknown magnitude) exists in the experimental points.

An investigation was also made to determine the effects of exposure (swelling) on the imbalance ratio, since theoretically, radial swelling would increase the support diameter thereby reducing the outer annulus imbalance. The results of this investigation are shown in Figures 14 and 15. Tables V and VI also show the exposure effects on outer annulus bulk to tube bulk imbalance ratios. It is important to note that only a slight decrease in the imbalance ratio is noted over the period checked.

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ACKNOWLEDGEMENTS

Special recognition is given to P. Riggle for his development of the correlation which successfully orders the experimental data and also for his guidance throughout this study. J. L. Rash also contributed by developing the initial computer program for the correlation.

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APPENDIX

TABLE V

OUTER ANNULUS BOTTOM TO TOP
IMBALANCE RATIOS

<u>Date</u>	<u>Tube 1651</u>	<u>Tube 1849</u>	<u>Tube 2050</u>	<u>Tube 2250</u>
10/20/65	1.356	1.301	1.306	1.028*
29	1.348	1.277	1.309	1.019*
11/11/65	1.365	1.274	1.347	1.018*
15	1.368	1.283	1.380	1.044*
18	1.374	1.276	1.371	1.037*
23	1.379	1.307	1.346	1.036*
29	1.362	1.307	1.345	1.026*
12/09/65	1.349	1.267	1.315	1.215
14	No Data	1.258	1.313	1.197
16	1.354	1.252	1.331	1.189
21	1.346	1.264	1.342	1.228
28	1.354	1.279	1.361	1.196
01/03/66	1.356	1.264	1.330	1.222
10	1.380	1.272	1.347	1.245
21	1.349	1.229	1.125**	0.950**
02/01/66	1.352	1.253	1.118**	0.984**
07	1.350	1.265	1.128**	1.004**
14	1.338	1.198	1.138**	0.999**
21	1.334	1.241	1.172**	0.995**
03/01/66	1.346	1.242	1.180**	0.995**

ALL VALUES INDICATE BOTTOM TO TOP IMBALANCE UNLESS ROTATED AS NOTED BELOW.

VALUES ARE COMPUTED FROM THERMOCOUPLE VOLTAGE RATIOS WITH NO CALIBRATION CORRECTIONS.

• Thermocouple train rotated approximately 30 degrees from vertical.

** Thermocouple train rotated approximately 45 degrees from vertical.

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TABLE VI
OUTER ANNULUS BULK TO TUBE BULK
IMBALANCE RATIOS

<u>Date</u>	<u>Tube 1051</u>	<u>Tube 0962</u>	<u>Tube 1651</u>	<u>Tube 1849</u>	<u>Tube 2050</u>	<u>Tube 2250</u>
10/20/65	.9417	.8991	.9066	.9359	.9193	.9041*
29	.9489	.9028	.9074	.9313	.9235	.9117*
11/11/65	.9454	.9013	.9114	.9382	.9227	.9144*
15	.9521	.9134	.9082	.9417	.9281	.9168*
18	.9497	.9061	.9122	.9357	.9257	.9218*
23	.9511	.9151	.9143	.9527	.9258	.9251*
29	.9543	.9103	.9197	.9539	.9323	.9202*
12/09/65	.9523	.9113	.9154	.9448	.9334	.9224
13	No Data	No Data	No Data	.9438	.9289	.9123
16	.9530	.9175	.9153	.9449	.9285	.9113
21	.9534	.9005	.9146	.9467	.9331	.9194
28	.9567	.9089	.9160	.9449	.9328	.9199
01/03/66	.9563	.9089	.9193	.9484	.9333	.9180
10	.9581	.9126	.9190	.9510	.9313	.9193
21	.9560	.9157	.9162	.9387	.9436**	.9346**
02/01/66	.9587	.9105	.9177	.9488	.9491**	.9366*
07	.9591	.9150	.9200	.9476	.9567**	.9392**
14	.9654	.9197	.9231	.9501	.9636**	.9419**
21	.9657	.9201	.9238	.9523	.9591**	.9422**
03/01/66	.9699	.9219	.9269	.9531	.9646**	.9474**
07	.9736	.9216	.9329	.9602	.9680**	.9497**

ALL VALUES INDICATE OUTER ANNULUS BULK TO TUBE BULK IMBALANCE UNLESS ROTATED AS NOTED BELOW.
RATIOS ARE COMPUTED FROM THERMOCOUPLE VOLTAGE DATA WITH NO CALIBRATION CORRECTIONS.

* Thermocouple train rotated approximately 30 degrees from vertical.

** Thermocouple train rotated approximately 45 degrees from vertical.

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FIGURE 1

CORRELATION OF
IMBALANCE RATIOS

FIGURE 2

NOZZLE AND PROCESS TUBE
DIMENSIONS WITH BACK-
ROLL UPSET

NOTE: ALL DIMENSIONS ARE FOR ROOM TEMPERATURE CONDITIONS

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FIGURE 4

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Page 20

100-N AREA

PROCESS TUBE AVERAGE DIAMETER

	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74
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FIGURE 6

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Page 22

100-N AREA
PROCESS TUBE MINIMUM DIAMETER

	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74
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FIGURE 1

FIGURE 2

Piston and Cylinder Head

1/2 inch = 1 inch

10/10/10

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KE 10 X 10 TO 1/4 INCH 46 1320
7 X 10 MICRONS
MADE IN U.S.A.
KEUFFEL & ESSER CO.

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FIGURE 13

MEANLINE RATIO
BOTTOM TO TOP
VS.
APPROXIMATE ANGLE
OF THERMOCOUPLE
TRAIN ROTATION

TUBE NO. 2250

MEANLINE RATIO - BOTTOM TO TOP

1.220
1.200
1.180
1.160
1.140
1.120
1.100
1.080
1.060
1.040
1.020
1.000
0.980

0° 15° 30° 45° 60° 75° 90°

ROTATION FROM VERTICAL - DEGREES

THEORETICAL
EXPERIMENTAL

DECLASSIFIED

FIGURE 17

OUTER ANNULUS - BOTTOM TO
TOP IMMERGENCE RATIO
VS.
TIME

DECLASSIFIED

CONFIDENTIAL

FIGURE 15

OUTER ANNULUS - BOTTOM TO
TOP INERTIAL RATIO
VS.
TIME

1.390
1.380
1.370
1.360
1.350
1.340
1.330
1.320
1.310
1.300

OUTER ANNULUS - BOTTOM TO TOP INERTIAL RATIO

EXPOSURE - 1053 MWDT

TUBE NO. 0005

SUPPORTS ON FIELD YIELDING
MAXIMUM ECCENTRICITY

EXPOSURE - 1013 MWDT

1.070
1.060
1.050
1.040
1.030
1.020
1.010
1.000

OUTER ANNULUS - BOTTOM TO TOP INERTIAL RATIO

EXPOSURE - 1053 MWDT

TUBE NO. 1051

SUPPORTS ON FIELD YIELDING
MINIMUM ECCENTRICITY

EXPOSURE - 1083 MWDT

21 29 OCT

15 18 23 29 NOV

9 16 21 28 DEC

10 21 JAN

1 7 14 21 FEB

TIME - 1965, 1966

DECLASSIFIED