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EFFECT OF PROCESS TUBE DIMENSIONS ON TUBE LIFEINTRODUCTION

In recent months, several process tubes installed during 1961 have been removed and examined out-of-pile in connection with Tube Corrosion Monitor Studies.¹ Most of the tubes were believed to be uniform-wall .080"-nominal-rib-height tubes. The ex-reactor dimensional measurements obtained near the inlet flange showed that the tubes did not have uniform walls or .080" nominal rib heights. Subsequently, dimensional measurements were obtained on approximately 200 new process tubes in an effort to determine the extent of dimensional variations in new process tubes as received from the vendors. The effects of the variations on tube corrosion and tube life are discussed in this report.

SUMMARY

Table VIII, page 52, is a summary of dimensional variations obtained from micrometer measurements made on several types of old reactor process tubes. The dimensions vary considerably resulting in a wide range of top and bottom annulus thicknesses, which in turn produce a wide range of R values.* A given extrusion usually produces a tube of acceptable uniformity over its entire length, but major variation occurs between extrusions. Tube corrosion depends highly on the R value and how it changes with time. Until recently, there was no practical way of determining individual R values for each tube. The data (Table VIII) show that about 95 per cent of all tubes of a given type would be within ± 0.06 units of some average R value initially were there little or no tube distortion during installation. Tubes at opposite ends of the 0.12 range differ in initial top-of-tube corrosion rate by a factor of two. The rates then change as corrosion alters dimensions and annuli. Based on the current corrosion model and on very limited experimental data on how R values change as corrosion proceeds, the following information was calculated to demonstrate variation in tube life due to variation in initial tube dimensions.

¹Hough, C.G., Tube Corrosion Monitor Program, HW-72499, January 26, 1962, Unclassified.

*The ratio of local end-of-charge water temperature rise to the bulk tube water temperature rise.

EXPECTED TUBE LIFE AT 110°C OUTLET TEMPERATURE

(Assumptions: 30 mils corrosion at life end; no mixer; 80% TOE; nominal fuel dimensions, growth and alignment; no installation distortion.)

<u>Tube Type</u>	<u>Effective Mean R Value</u>	<u>Expected Life in Months of Tube With Mean R Value</u>	<u>Range in Months**</u>
*ANU (.086-black)	1.23	24	12 - 25
AU (.080)	1.10	20	18 - 23
AU (.084-green)	1.19	23	21 - 25

Tube types having the higher mean R values show a much wider range of tube life. This is caused by individual tubes that have R values greater than 1.25 where top corrosion becomes limiting. For the same variation in tube dimensions, tube types with the lower mean R values show a relatively small variation in tube life. This occurs because tubes limited by bottom corrosion are less sensitive to dimensional variations.

Other factors cause tube life variation to be greater than shown in the table above. These factors include:

1. Distortion of process tubes during installation.
2. Variation in fuel dimensions and alignment.
3. Insufficient information concerning the rate of change of R values with time.
4. Corrosion rates may double for less than a 12-degree increase in water temperature at the higher operating temperatures (possibly boiling effects).
5. Changes in water quality may have produced unexpected corrosion effects.

A recent mixer recommendation² should alleviate severe top corrosion in tubes having unfavorable dimensions and in tubes having installation distortion and fuel misalignment. Recently, a program was initiated to measure all new tubes before installation, to calculate their initial R values, and to dispose of them

*ANU (.086-black) = Alcoa non-uniform wall, .086" rib height with black color code markings.
 AU (.080) = Alcoa uniform-wall, .080" rib height, no color code.
 AU (.084-green) = Alcoa uniform-wall, .084" rib height with green color code marking.

**Ninety-five per cent of the tubes in each group will fall in the range shown.

² Greager, O.H., letter to O.C. Schroeder, Mixers for B, D, DR, F, and H, dated November 2, 1962.

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according to these values. Tubes having R values greater than 1.25 or less than 1.10 are now being marked for fringe zone use only or rejected as not suitable for reactor use. Records are being kept of channel locations where all measured tubes are installed. A new air gauge was developed to allow direct simultaneous measurement of top and bottom annuli and top and bottom wall thickness and will be used by inspection personnel. A method to measure tube distortion in the reactor at the time of installation using air gauges in place of ball probing is being considered. A sector probolog and annulus thickness gauge for use in older tubes is under development. Before the present corrosion model can be improved significantly, corrosion rate data (thermocouple probe and ex-reactor tube examination or sector probolog) will be needed on tubes that have been measured both before and after installation and then charged with measured fuel (with and without mixers). This should enable evaluation of items three and four above. Other programs³ are planned to evaluate item five. An IBM 7090 program to process the tube and fuel dimensional data and to calculate both top and bottom corrosion on individual tubes is being planned.

The relationship between top annulus thickness and tube life is shown in Figure 24, page 41, and can be used as a basis for determining tube specification limits. Figure 22 (described on page 19) is a method for accepting or rejecting tubes at the time they are measured by the inspector. The new tubes now being received for the old reactors appear to be improved over past shipments. The only action as regards old reactor tube tolerance limits that can be recommended at this time would be to explore with the vendors methods of reducing dimensional variations. In this respect, a wall thickness tolerance limit aimed at controlling concentricity of the inner diameter within the outer diameter appears to be the most promising way of controlling over-all dimensional variations. Wall thickness is presently required to exceed 59 mils, but there is no maximum limit.

DISCUSSION

Process Tube Types and Their Disposition

Table I is a summary of tube types and quantities that have been received and ordered from vendors in recent years. The only types currently remaining in stock are Alcoa uniform (green), Alcoa non-uniform (black), and a few Alcoa uniform .080" rib tubes. We will henceforth refer to the latter group as AU (.080) since they do not have a color code. Similar codes will be used for the other tube types that have no color code.

Table II lists the number of tubes of each type installed each quarter at each reactor since January, 1960, as determined from Production Computing records. The number of tubes of each type installed each quarter is an estimate since tube type information was not always maintained during 1960 and 1961. Table II also lists the total number of tubes that have since been replaced for various reasons. However, tubes that were immediately replaced because they would not pass a ball gauge are not included. Tables I and II represent the best record of the disposition of the various tube types at each reactor.

³Geier, R.G., and F. W. Van Wormer, Water Treatment Program - Old Reactors, HW-75609, November 19, 1962, Secret.

Variation in Tube Dimensions and Effect on R Values

During September, 219 new process tubes were measured to determine the magnitude of dimensional variations. Ninety-one black tubes were measured at D reactor, 50 green tubes and 28 AU (.080) tubes were measured at H reactor, and 50 black tubes were measured at F reactor. All measurements were made with precision micrometers at one of the tube ends. The measurements made were top wall thickness, bottom wall thickness, tube outside diameter and both ribs from the outer wall surface to the top of each rib. One exception is that no tube outside diameter measurements were made on the 91 black tubes at D reactor.

These dimensional data were processed with an IBM 7090 program called TACT that calculates top annulus thickness, bottom annulus thickness, top, bottom and hole water temperatures and the associated R values (ratio of local water temperature rise to the bulk outlet temperature rise). Nominal O-III-N fuel dimensions were assumed in the IBM calculations. Details and limitations of the IBM calculations are presented in Appendix I. The measured data and some of the calculated data for the four groups of tubes are listed in Tables IV to VII. Table VIII is a summary of Tables IV to VII. Table III includes definitions of terms and column headings used in this report.

Rib heights above the inner tube wall were calculated by subtracting the 6 o'clock bottom wall thickness from the 4:30 and 7:30 o'clock "rib plus wall" measurements. This may not necessarily give the true rib height in view of the changing wall thickness around the tube. Based upon 13 black tubes that were measured for wall thickness at many points, we find our calculated rib heights underestimate the true rib heights on the average (about one to two mils). The reason for this is demonstrated in the following figure.

We have drawn a tube as though it were split at the top and spread out flat. In 12 of the 13 black tubes, the wall thickness at point B was equal to or greater than the wall thickness immediately adjacent to the ribs. This will cause some error in the calculated bottom annulus thickness for those tubes having a hump between the ribs.

Rib imbalance, the difference between the 4:30 and 7:30 o'clock rib-plus-wall measurements, will cause some error in the calculated top annulus thickness. The error is not significant as long as the difference between the two rib-plus-wall measurements is no greater than five mils. Tubes having rib imbalance greater than five mils should be rejected anyway as this is a strong indication of poor horizontal concentricity.

Calculated R values do not include the effect of fuel element growth during irradiation. Quality certification data and thermocouple probe data indicate

that an additional 0.05 R units should be added to R-top values to allow for the effect of fuel element growth on temperature imbalance. Effective R values are defined as those that include the fuel growth effect. In this section we will use R values without the growth effect. Subsequent sections of this report use effective R values.

A comparison of the measured tube dimensions (Table VIII) show that tube dimensions vary considerably. This variation results in a wide range of top and bottom annulus thicknesses which, in turn, lead to a wide range of R values. Figures 1, 2 and 3 show the distribution of R-top values for the 50 green tubes, the 28 AU (.080) tubes and the 50 black tubes, respectively. We have summarized the R-top distributions for the three tube types below.

<u>Type</u>	<u>R-Top Average</u>	<u>Standard Deviation</u>	<u>0.95 Confidence Interval</u>
50 Green	1.14	0.03	1.08 - 1.20
28 AU (.080)	1.05	0.03	0.99 - 1.11
50 Black	1.18	0.03	1.12 - 1.24

Tube corrosion calculations depend on the R value and how it changes with time. Because of the variation in tube dimensions, we do not know the initial R values for each tube. All we know is that about 95 per cent of all tubes of a given tube type are within $\pm .06$ units of some average R value--a total range in corrosion rate of a factor of two. In order to calculate corrosion on individual tubes, one must know the initial dimensions of each tube. Furthermore, we must know the relative effect that each dimension has upon corrosion characteristics of the tube. Individual specifications for rib height, outside diameter, inside diameter and wall thickness do not necessarily guarantee a tube will be good or bad from the corrosion standpoint. Many cases can be found in the data of Tables V to VII where combinations of "out-of-specification" dimensions produce acceptable R values and vice versa. In Figures 4 to 12, we have plotted various combinations of data from Tables V to VII in an effort to show tube dimensions are correlated one to another though the correlations are not always obvious from the data, and to show the magnitude of the effect of dimensional changes on local water temperatures.

Figure 4 is a plot of top wall thickness versus bottom wall thickness for the 50 green tubes. A strong correlation exists between top and bottom wall thickness, i.e., a tube with a thin bottom usually has a thick top while a tube with a thick bottom has a thin top. Note that this is true for tubes that are supposedly of the uniform-wall design.

Figure 5 is a plot of average rib height (calculated) versus bottom wall thickness for the same 50 green tubes. Here we see a significant correlation also, i.e., a thin bottom is associated with high ribs and a thick bottom is associated with low ribs. For the 50 black tubes, this correlation was not apparent as seen in Figure 6.

Figure 7 is a plot of average rib height versus R-top for 50 black tubes. R-top is correlated with average rib height, yet this is not apparent when the same variables are plotted for the 50 green tubes in Figure 8.

Figure 9 is a plot of average rib height versus R-bottom for the 50 black tubes. Average rib height is correlated with R-bottom as it was with R-top in Figure 7. Yet the same correlation is not apparent for the 50 green tubes in Figure 10. In other words, average rib height has a strong effect on both R-top and R-bottom for the 50 black tubes but does not appear to have as strong an effect on R-top and R-bottom for the 50 green tubes.

Figures 11 and 12 are plots of tube outside diameter versus R-top for 50 black and 50 green tubes, respectively. Here we see no correlation for the black tubes, yet a significant one exists for the green tubes.

It is not readily apparent why one tube type is more sensitive to average rib height variations while the other is more sensitive to outside diameter variations. Table VIII indicates there is more variation (standard deviation) in outside diameter for green tubes than there is for black tubes. This suggests the range of outside diameter variation for black tubes is not wide enough to produce a noticeable effect on R-top values.

Using the TACT program, we can calculate the expected or theoretical effect that each dimension has upon R values. The expected effects on R-top are shown in the following table.

<u>Dimension</u>	<u>Effect on R-Top in R-units/mil Increase</u>	<u>Relative Effect</u>
Rib plus wall	0.026	1.00
Tube O.D.	-0.017	.63
Slug O.D.	0.016	.62
Top Wall	0.013	.49
Bottom Wall	-0.006	.23
Slug I.D.	0.002	.08

The effects were calculated by holding all dimensions constant except the one of interest. Consequently, the interaction effect that changing one dimension has on the others is not considered in the above table. The negative effects in the above table can be interpreted as follows: a one mil increase in tube O.D. results in a 0.017 decrease in R-top. The effect of dimensional changes on R-bottom could be calculated in the same manner.

Knowing the effect of dimensional changes on R values makes it possible to go one step further and calculate the effect of dimensional changes on local water temperature. For example, take the case where a one-mil decrease in tube O.D. causes a 0.017 increase in R-top. A tube having an R top value of 1.15 and an outlet temperature of 100°C (zero inlet) would have a top-of-annulus outlet water temperature of $(1.15)(100) = 115^{\circ}\text{C}$. If we reduce the tube O.D. by

one mil, the change in between-tube flow distribution would result in a tube outlet temperature of about 101°C . The adjusted R value would be $1.15 + .017 = 1.167$. The top-of-annulus outlet temperature in the reduced annulus would now be $(1.167)(101) = 117.9^{\circ}\text{C}$. Thus a one-mil decrease in tube O.D. is approximately equivalent to a 2.9°C increase in top-of-annulus outlet water temperature. A four or five-mil reduction in tube O.D. would be approximately equivalent to a 12°C increase in local water temperature which would result in a doubling of aluminum corrosion rate.

Numerous combinations of rib height, wall thickness and outside diameter exist which cause changes of this magnitude. Outside diameter is related to inside diameter and wall thickness by the following:

$$\text{OD} = \text{ID} + \text{top wall} + \text{bottom wall}$$

Thus, a tube could have perfectly good rib height and outside diameter dimensions, yet have a restricted I.D. because the top and bottom walls were both unusually thick. Tube numbers 49 and 50 in Table V are examples of this combination. Several cases can be found in Table VII where a small O.D. is the main source of the high R value. In these latter cases, it could also be said a small I.D. is the source of the high R value. Either view is acceptable as this is sort of like arguing which came first, the chicken or the egg.

So far, the discussion of process tube dimensional variations is based upon tube dimensions obtained at one end of the tubes. There is the possibility that tube dimensions are not uniform over the full length of the tube. Also, measurement of the top wall thickness and bottom wall thickness does not necessarily determine the points of maximum and minimum wall thickness. To evaluate concentricity and uniformity of tube dimensions, a number of process tubes were measured in more detail.

Twenty-five process tubes were measured at one tube end by micrometer at angles between 0 and 360 degrees at 30-degree intervals. Zero degrees corresponds to the top of the tube and 180 degrees corresponds to the bottom of the tube. The resulting wall thickness data are displayed in Table IX. Tube numbers 1 to 16 are black tubes, 17 to 19 are AU (.080), 20 to 21 are the only Reynolds uniform-wall (80 mil rib) tubes that have been located, and 22 to 25 are black tubes.

The minimum wall thickness can occur anywhere between 90° and 270° . The maximum wall thickness usually occurs within 90 to 120 degrees of the point of minimum wall thickness and occasionally occurs directly opposite the minimum point. These data show limited control over concentricity of the inner diameter with respect to the outer diameter, resulting in widely variable and inconsistent wall thicknesses between different process tubes.

Twenty of the tubes in Table IX were measured at both tube ends by micrometer at 30-degree intervals to check uniformity within a given tube. The maximum

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range of wall thickness observed between the tube ends (A and B) for a given angle was four mils, and most agreed within two to three mils. As a further check, 19 of the tubes were measured at one-foot intervals using an ultrasonic Vidiguage instrument. The wall thickness measurements were made at four different angles down the length of the tube, 0° , 90° , 180° , and 270° . Some typical data are displayed in Table X. The maximum range of wall thickness down the tube for a given angle was four mils with most having a two to three-mil range for a given angle. No data is available for uniformity of rib height down the length of the tube since the Vidiguage instrument can not measure rib height. However, tube numbers 17, 18 and 19 (Table IX) are scheduled to be cut up and measured at one-foot intervals to check the Vidiguage measurements of wall thickness as well as rib height uniformity.

In summary, a given extrusion usually produces a tube of acceptable uniformity over its entire length, but lack of concentricity between extrusions is the major problem.

The Effect of R Variations on Tube Life

The effect of variations in R values can be estimated from information now available. The equation which describes the corrosion of aluminum in water, as derived by D. R. deHalas,⁴ is shown below:

$$CR = (.0083)(F_m)(E_m)2^{T_o/12} \quad (1)$$

where F_m is the correction factor for the process water pH, E_m is a correction factor for the fraction of time that the tube outlet temperature is significantly lower than the equilibrium temperature, and T_o is the tube outlet temperature, and CR is the corrosion rate in mils per month. The value of 0.25 was assigned to F_m for 7.0 pH process water and E_m was defined as $(0.90)(\text{Time}$

Operating Efficiency), and the quantity $2^{T_o/12}$ was transformed to $e^{(.057)(T_o)}$ because it is easier to use for machine calculations. The resultant equation is

$$CR = (0.0019)(TOE)\exp(0.057T_o) \quad (2)$$

Equation 2 is inadequate in that it does not take into account the temperature imbalance around the circumference of the tube. The temperature around the circumference of a tube at the end of the fuel charge in a tube of known dimensions can be determined from the calculated R value and the tube outlet temperature. The temperature at point "a" of the tube periphery at the charge end is given by the equation $T_a = R_a(T_b - T_i) + T_i$, where T_b is the tube outlet temperature and T_i is the inlet temperature. The corrosion rate at point "a" is then given by equation 3.

$$CR = (0.0019)(TOE)\exp[0.057R(T_b - T_i) + 0.057T_i] \quad (3)$$

The above equation is good at a point in time but we know that R changes with time. We have a rough correlation of effective R with corrosion index (CI) shown in Figure 13. Corrosion index is the calculated corrosion for a given tube as calculated by equation 2 and is our best measure of the corrosion environment in the tube. CI can be converted directly to time in months by dividing the CI by the rate at which CI accumulates, which is about 0.7 units per month for an average central zone tube when the reactor is operated at the bulk outlet temperature limit.

The effective R data shown in Figure 13 are based upon thermocouple probe data from D reactor and represent the average effective R versus CI data for tubes installed in 1961. The slope of the R-top and R-bottom lines in Figure 13 is very important in predicting the expected life of a tube. We have made the assumption that when a tube is calculated to have different initial R values,

⁴deHalas, D.R., An Improved Basis for Scheduling Removal of Corroded Process Tubes, HW-43956, June 27, 1956.

the rate of change of R with CI will be the same as shown in Figure 13. That is, regardless of initial R values, the R-top and R-bottom lines will always have the same slope. We do not have data to substantiate this assumption, however, we feel that this is a reasonable approximation of the actual case.

The correlation in Figure 13 can be expressed as shown in equation 4.

$$R = \alpha + \beta CI \quad (4)$$

Where α = the initial effective R value

β = slope of R with CI

CI = amount of corrosion index that the tube has accumulated.

Substituting this relationship into equation 3, we obtain the corrosion rate at any point in the life of the process tube.

$$CR = (0.0019)(TOE)\exp[0.057(\alpha + \beta CI)(T_b - T_1) + 0.057T_1] \quad (5)$$

Equation 5 is then integrated to give the total top or bottom corrosion for a given CI accumulated at a given tube outlet temperature.

$$TC = \frac{(0.0019)(TOE)\exp[0.057(\alpha)(\Delta T) + 0.057T_1] \{-1 + \exp[0.057(\beta)(\Delta T)CI]\}}{0.057(\beta)(\Delta T)} \quad (6)$$

Equation 6 can be used to study the effect of R on tube life. The useful tube life was defined as the length of time required to corrode 30 mils from either the top or bottom of the tube. This length of time was computed for five different tube designs. The cases used and the results are shown in Figure 14. In case two, both the top and bottom wall thicknesses are shown. In all other cases only the limiting case is shown. In this and succeeding figures, CI (see equation 2) is used as the measure of tube life. The relationship of CI to months, as a function of tube outlet temperature, is given in equation 7 and shown in Figure 16:

$$M = \frac{CI}{(0.0019)(TOE)\exp[(0.057)(T_o)]} \quad (7)$$

Where M = months in reactor.

Figure 14 shows that an initial R-top of 1.30 will certainly result in top-of-tube failures while an initial R-top of 1.25 produces about the same terminal wall thickness (30 mils removed) at top and bottom, which permits maximum tube life. These R values include the effect of fuel element growth which increases the R values by about 0.05 R units during the metal cycle. The R with a green fuel charge would be about 0.05 units less than the values shown.

The accumulated corrosion index necessary to corrode 30 mils from a tube was taken from Figure 14 and plotted versus the associated R value in Figure 15. The best tube life available, based upon the above calculation, is 21.5 units of corrosion index, which corresponds to about 25 months of tube life at 110°C and 80 per cent time operated efficiency (no mixer).

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The expected life of the mean tube of any group of tubes operating at 110°C outlet temperature and whose initial effective R value is known, can be found from Figure 15 and 16.

EXPECTED TUBE LIFE AT 110°C OUTLET TEMPERATURE

(Assumptions: 30 mils corrosion at life end; no mixer; 80% TOE; nominal fuel dimensions, growth and alignment; no installation distortion.)

<u>Tube Type</u>	<u>Effective Mean R Value</u>	<u>Expected Life in CI of Tube With Mean R Value</u>	<u>Expected Life in Months of Tube With Mean R Value</u>	<u>Range in Months*</u>
ANU (.086-black)	1.23	20.1	24	12 - 25
AU (.080)	1.10	16.7	20	18 - 23
AU (.084-green)	1.19	19.2	23	21 - 25

Tube types having the higher mean R values show a much wider range of tube life. This is caused by individual tubes that have R values greater than 1.25 where top corrosion becomes limiting. For the same variation in tube dimensions, tube types with the lower mean R values show a relatively small variation in tube life. This occurs because tubes limited by bottom corrosion are less sensitive to dimensional variations.

*Ninety-five per cent of the tubes in each group will fall in the range shown.

Economics of Rejecting Process Tubes

We have seen in the previous sections that the dimensions of a tube have a significant effect on its expected life. It seems logical then to examine the possibility of reducing total tube replacement costs by accepting only those tubes which will have "long" tube life. This section presents a method of calculating tube replacement costs and benefits obtained by rejecting a fraction of the tubes having unfavorable R values. The following calculations are intended to serve as an example of the calculational method.

The life of the process tube can be estimated by measuring the tube and calculating its R value as described in previous sections. The cost of replacing a process tube consist of first, the value of the outage time and manpower necessary to install the tube, and second, the cost of the tube. The lost production and manpower costs are now about \$2000 (assuming Pu value at \$50/gm) per tube and the cost of each tube has been \$31.26.⁵

The cost per month to keep a tube in a given channel is then $C = (2000 + 31.26)/L$, where L is the expected tube life in months. The total cost per month for 1000 channels operating at a uniform temperature is the sum of cost for each channel.

If these 1000 channels were to be replaced with a batch of tubes having a known distribution of R values, we could calculate the average tube replacement cost per month using the above equation. An example for a typical distribution of R values observed on black tubes is given below:

<u>Group</u>	<u>R Range</u>	<u>Per Cent of Tubes in Range</u>	<u>Expected Life (in Months at 110°C)</u>
1	Less than 1.05	0.8	18.0
2	1.05 - 1.075	2.1	19.4
3	1.075 - 1.100	5.2	20.0
4	1.100 - 1.125	11.4	20.8
5	1.125 - 1.150	16.2	21.5
6	1.150 - 1.175	15.6	22.2
7	1.175 - 1.200	22.6	23.0
8	1.200 - 1.225	13.8	23.8
9	1.225 - 1.250	8.1	24.5
10	1.250 - 1.275	3.7	23
11	More than 1.275	0.5	15
Total		100	

The expected monthly tube replacement cost for a block of 1000 tubes operating at 110°C, with the above distribution of R values associated with the new tubes, can be calculated by summing the tube replacement cost associated with each segment of the tubes as shown below.

⁵Johnson, S.R., Table issued June 4, 1962, Irradiation Processing Department, Manufacturing Section, Special Outage Service - Tube Replacement (Four Week Period 4-30-62 Through 5-27-62).

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$$C_T = \frac{N_1(2000 + 32.16)}{L_1} + \frac{N_2(2000 + 32.16)}{L_2} + \dots + \frac{N_{11}(2000 + 32.16)}{L_{11}}$$

Where C_T = total cost per month

N = number of tubes in each group

L = tube life associated with a given group.

This calculation was made for the distribution shown. The total cost of tube replacement per month was \$91,096. Now we would like to learn if this cost could be reduced by rejecting some of the tubes which are expected to have a short life. The installation cost per tube is not affected by rejecting tubes, but the cost of the accepted tubes is affected. The cost of the accepted tubes is increased by the quantity $1/(1-X)$, where X is the fraction of tubes rejected. The number of tubes in each accepted group is also increased by the same quantity. Total cost per month if the first and eleventh group were eliminated would be

$$C_T = \left(\frac{N_2}{1-X} \right) \left[\frac{2000 + 32.16/(1-X)}{L_2} \right] + \dots + \left(\frac{N_{10}}{1-X} \right) \left[\frac{2000 + 32.16/(1-X)}{L_{10}} \right]$$

This calculation was made for several rejection steps. In each case all tubes expected to fail by top corrosion were eliminated and some of the lowest-tube-life tubes were eliminated. The results are shown below.

<u>Per Cent of Tubes Rejected</u>	<u>Average Central Zone Tube Replacement Cost (per month)</u>
0	91,096
12.3	90,080
39.7	86,670
55.2	87,320
77.8	87,741

In the above example, a reduction of about four per cent in tube replacement costs could be made. The savings are dependent upon the distribution of R in the tubes being considered. In a batch of tubes with wide ranges in R values or in distributions having a high mean R value, the savings would be greater than in the example.

The example illustrates the point that it may be possible to obtain a more uniform and thus more predictable tube life as well as a reduction in tube replacement costs by rejecting a portion of the process tubes.

Tube Life Estimates From Tube Examination and Probolog Data

At present, the most reliable though expensive way to estimate corrosion rates and tube life is to periodically remove process tubes and measure actual corrosion. Recent efforts have been confined to tubes installed during 1961. Eleven tubes have been examined to date and about ten more are removed and awaiting examination. The minimum top wall and bottom wall thicknesses are plotted versus corrosion index at removal in Figure 17. Table XI is a more detailed tabulation of information on each tube. Figure 17 indicates that bottom wall corrosion is fairly consistent while top corrosion is extremely variable. Most of the tubes installed during 1961 are believed to be 80-mil uniform-wall tubes, yet Table XI shows that only three or four of the 11 tubes actually have low ribs and one of the tubes having the most severe top corrosion (1366-B) started out with low ribs.

Probolog data also provides estimates of corrosion rates. All of the 1962 probolog data (through September 1962) obtained on tubes installed in 1961 are summarized by reactor in Table XII. We have grouped the data according to the amount of corrosion index each tube had accumulated at the time of probologging. The probolog data of Table XII is plotted in Figure 18. It would appear as though H reactor corrosion is most severe while F reactor is the least severe. However, tube outlet temperatures are known to be biased low on many H reactor tubes which would cause corrosion index to be low for a given probolog wall thickness. The average of all probolog data (excluding H reactor) is plotted in Figure 19 together with straight line fits of the tube examination data of Figure 17. The tube examination curves indicate that most tubes become thinnest on top above a corrosion index of seven, on the average. The slope of the probolog curve above a corrosion index of seven is about the same as the slope of the top corrosion curve obtained from tube examination data. In general, the probolog data indicates more corrosion at a given index than tube examination data. Part of this is due to the fact that all tubes probologging more than 55 mils are assumed to be 56 mils, thus causing the average probolog wall thickness to be understated. This is particularly true at low corrosion index. Another reason may be that the tube examination curves are based upon only 11 tubes.

From these data we conclude that bottom corrosion will be limiting for most early 1961 tubes. Most of these tubes are now hot on the bottom. Top corrosion will tend to level off and "plateau" between 35 and 45 mils, on the average, while bottom corrosion accelerates. Tubes installed during January, 1961, have been in-reactor 21 months and have operated the longest time with mixers. Most of these tubes should have 30 months of life or more (at 35 mils of remaining wall thickness). However, some early 1961 tubes have already reached 35 mils of remaining wall thickness.

Tubes installed during late 1961 should last as long as early 1961 tubes at those reactors that did not remove mixers. Tubes installed during December, 1961, have been in-reactor ten months and have operated without mixers at some reactors during most of 1962. Top corrosion will be more of a problem in these tubes as some of them will not "plateau" soon enough. Late 1961 tubes that do plateau soon enough and that are charged with mixers at the earliest possible date should have a fairly normal tube life.

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Tubes that reach a top corrosion plateau near 35 mils of remaining wall thickness after about 15 to 18 months in-reactor can be expected to last from six months to a year longer before bottom corrosion requires removal. Such tubes do not have to be removed just because they probolog 35 mils. However, a few tubes that probolog at 35 mils at the early time are bottom-thin and must be removed within three to six months. To take advantage of the extra tube life in top-thin tubes that plateau near 35 mils, a method is needed to determine whether a thin tube is top-thin or bottom-thin. Early routine use of a sector probolog that can operate at nearly the same rates as the conventional probolog is needed to take advantage of the extra life in top-thin tubes.

Tubes installed during 1962 appear to be corroding faster than tubes installed during 1961. To date, seven top corrosion leakers have been reported in tubes installed during the first half of this year. Probolog data indicates faster corrosion rates than those indicated in Figure 18 for 1961 tubes. Most of the 1961 tubes operated with mixers in the seven or ten-from-rear position until recently. Most of the 1962 tubes have operated without mixers except at D and DR reactors where the change-over to no-mixers was never completed. An examination of F reactor tube corrosion profiles shows the mixer (seven-from-rear) has effectively controlled top corrosion. Tube corrosion profiles from B and H reactors show severe top corrosion without mixers. At DR reactor only one tube has been examined and the corrosion profile indicates that the mixer (ten-from-rear) was effective in controlling top corrosion. Yet, DR probolog data indicates rapid corrosion similar to that observed at B and H reactors where mixers have not been used. Using the TACT program, we calculate a mixer at ten-from-rear should be almost as effective as one at seven-from-rear. Even though the DR reactor experience does not agree with expected performance using mixers, it is advisable to re-charge mixers at all reactors as soon as possible to alleviate the severe top corrosion occurring in new tubes.²

Our calculations with the TACT program do not predict corrosion rates as high as those observed. No specific explanation can be offered for this fact. Possible explanations are: (1) corrosion rates double for less than a 12-degree increase in water temperature at high operating temperatures, (2) insufficient information concerning the rate of change of R values with time, (3) distortion of tubes during installation, (4) variation in fuel dimensions and alignment, and (5) past changes in water quality producing unexpected corrosion effects.

²ibid.

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A Method for Inspecting Process Tubes

This section demonstrates the relationship between annulus dimensions and tube life as a possible means of accepting or rejecting process tubes. The relationships are complicated and do not necessarily lend themselves to a convenient or practical method of inspecting tubes at the time they are measured. The tolerance limits used are based upon measurement data recently obtained on 236 Alcoa uniform-wall (.084 rib - green) tubes and are more representative of "observed" performance than a criteria for future performance. More study will be required before specific tolerance limits that are a reasonable compromise between vendor capability and HAPO needs can be determined.

The relationships described are based upon direct measurements of the top and bottom annulus thickness along the vertical axis, assuming a nominal 1.444" fuel element. The measurements will be obtained with an instrument recently developed by Applied Reactor Engineering utilizing Sheffield air gauges. The vertical dimensions make it possible to calculate the vertical eccentricity of a fuel element in a process tube (see Appendix I). It is also planned to use the air gauge to obtain horizontal annulus and wall dimensions which will eventually allow us to calculate the effects of horizontal as well as vertical eccentricity. However, the methods described here are confined to vertical measurements only.

The basic relationship between tube dimensions and annulus temperature is presented in Appendix I and is repeated here as

$$(R_{top})_{eff} = 0.05 + \exp(1.27)E \text{ for } 0 \leq E \leq 0.4$$

and,

$$E = (ANAV - ANT) / ANAV = (ANB - ANT) / (ANB + ANT)$$

Where: $(R_{top})_{eff} = (\Delta T_{top} / \Delta T_{bulk})$ = average top of annulus temperature rise per unit bulk temperature rise, including temperature rise due to fuel growth.

E = The degree of vertical eccentricity of the fuel in a tube.

ANT = Annulus between top of slug and tube wall.

ANB = Annulus between bottom of slug and tube wall.

ANAV = Average annulus.

This relationship is expressed graphically in Figure 20 where R-top is plotted versus E. The same relationship is shown in Figure 21 as R-top versus ANT/ANB. Until now we have essentially used this relationship to accept or reject tubes, i.e., any tube having an effective R-top greater than 1.25 or lower than 1.10 was considered not acceptable for central zone use. No R limits have been set

for rejecting fringe zone tubes. The few that have been rejected were rejected because of very extreme wall or rib dimensions. This method has disadvantages and does not yield as much information as an alternate method we now describe.

When ANT is plotted versus ANB, we obtain constant R curves for different combinations of ANT and ANB. This is shown in Figure 22 for constant curves of 1.25 and 1.10. Thus, any annulus combination falling between the two lines results in an acceptable R value. However, we wouldn't want to accept all annulus combinations between 1.25 and 1.10 R values because this would result in a wide range of tube flow between tubes having the same R value, i.e., there would be no restriction on the inside diameters of the tubes. We can correct this by imposing I.D. limits, in addition to R limits, in the form of constant I.D. curves also shown in Figure 22. We have so defined a rectangle of annulus combinations that have acceptable R values and inside diameters. We could define a series of rectangles corresponding to different reactor zones. This method could be adapted for rapid testing by inspection personnel at the time of measurement by taking advantage of the fact that the rectangle in Figure 23 is approximated by the following inequality.

$$12 \leq (ANB-ANT) \leq 22$$

$$151 \leq (ANB+ANT) \leq 159$$

The inequality could be electronically programmed into the air gauge readout instrument resulting in a simple accept or reject signal.

The inside diameter limits of Figure 22 represent the observed 0.95 confidence interval (1.599 ± 0.004) obtained from measurements made on 236 Alcoa uniform-wall (.084 rib - green) tubes. One tube was observed to be outside this interval. The observed 0.95 confidence interval for effective R-top obtained on the same tubes is 1.20 ± 0.05 . This means that we would expect about 2.5 per cent of the tubes to exceed the 1.25 upper limit on R-top with none outside the 1.10 lower limit. For 236 tubes recently measured, six were outside the 1.25 limit. All six tubes were considered acceptable for fringe zone use. The one tube that was outside the lower I.D. limit also had a high R value and was one of the six reject tubes.

Whether or not the limits of Figure 22 are reasonable or not depends upon our ability to express tube dimensions and R values as a function of aluminum corrosion rates and tube life. We have already described the basic relationships in a previous section (equation 6) and noted that the parameters of this relationship are based on very limited data. From past experience we know that we have not been very successful at predicting individual tube life using these same relationships. Some of this uncertainty can be eliminated by using the individual tube measurements in routine corrosion calculation. Other factors that have interfered with our attempts to correctly evaluate the parameters of equation 6 are tube distortion during installation and fuel misalignment. Recognizing that these uncertainties do exist, we nevertheless present our best estimate of the underlying tube life relationships for use in establishing reasonable tube dimension criteria.

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To relate tube dimensions to tube life, we must introduce two new variables, wall thickness and tube outlet temperature. We can eliminate wall thickness as a complicating factor by defining tube life as the length of time it takes to corrode 30 mils from either the top or bottom wall. For uniform-wall tubes having a nominal dimension of 65 mils, 35 mils of remaining wall thickness becomes the replacement wall thickness. However, it should be remembered that up to an additional year of tube life could be realized for some tubes that are top-thin as opposed to bottom-thin, provided a method is available for determining which tubes are top-thin.

We previously expressed R-top as a function of tube life for different tube outlet temperatures in Figures 15 and 16. Figure 23 directly expresses R-top as a function of tube life in months for 100°C and 110°C outlet temperatures. Using Figures 21, 22 and 23 we can directly express top annulus thickness as a function of tube life for a given outlet temperature. This is shown in Figure 24 for an outlet temperature of 110°C. We see that the relationship is dependent upon tube inside diameter and it would be difficult to pick one annulus thickness as the rejection criterion. For example, in order to ensure that no tubes had high top corrosion rates, we would have to reject all tubes with top annuli smaller than 68 mils. By so doing, we would reject over half of the green tubes. Many of these tubes would have acceptable tube life. We feel that rejection levels should be administered as in Figure 22 while Figure 24 would be used as the basis for determining tolerance limits on tube I.D. and R values for Figure 22.

At the present time, we have no definite revisions in current tube tolerance limits to recommend. Reduced dimensional variation would be beneficial, but any such changes must also consider vendor capability, costs, etc., which are beyond the scope of this study. One way to reduce dimensional variation without changing the current tolerance limits is to enforce the current limits. We have noted that many process tubes now being received do not meet one or more of the current tolerance limits. It is not clear whether this is due to lack of enforcement of the current limits or whether the limits are beyond vendor capability. However, many of the tubes that do not meet one or more of the current limits have acceptable R values. In some respects, the R criteria for accepting tubes is less stringent than the current tolerance limits. More time is needed to study the dimensional data now being obtained and to perfect air-gauge measurement techniques. In the meantime, it would be worthwhile to explore with the vendors methods of improving the fabrication process that would lead to lower dimensional variation. In particular, a method of controlling the concentricity of the inner diameter within the outer diameter appears to offer the greatest potential for improving over-all dimensional variations. A wall thickness tolerance limit, based upon measurements made at 0°, 90°, 180° and 270° would provide the most effective control of concentricity. At present, the observed 0.95 confidence interval on top and bottom wall thickness for green tubes is $0.066" \pm 0.0044"$ and $0.063" \pm 0.0046"$, respectively; which is an improvement over past shipments.

We have considered tightening the R limits of 1.10 and 1.25, now being used to accept tubes. This would effectively add more tube life to tubes accepted for

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central zone use. The upper limit of 1.25 leaves little margin for error as tube life decreases rapidly beyond this point, when mixers are not used. Since 1.25 is our best estimate of the R value associated with maximum tube life,* it is desirable to operate close to this value. However, we have observed corrosion rates higher than we can calculate. Thus, actual R values must be higher than those we calculate from tube dimensions because of other factors such as tube distortion, fuel dimensions or localized boiling. Mixers should eliminate early top leakers caused by such factors by lowering initial R-top values during the early life of the tube. Mixer use complicates calculation of corrosion, and there is little information concerning changes in R as a function of time when mixers are loaded.

Since mixers need to be, and are to be used, and because effects of the various undefined factors will only be lessened, not eliminated by mixers, there is a difficult question as to what range of R values should be used to accept new tubes. We suggest that the same R value limits (1.10 - 1.25) continue to be used, until more data are available, on the premise that the effects of the undefined factors are cancelled by mixers. Additional data are of little value unless obtained on tubes having known initial dimensions before, as well as after, installation. Thus we conclude the tube inspection program is worthwhile if we ever hope to be able to calculate and improve tube life for the mixer case as well as the non-mixer case.

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CGH:REF:RDJ:mf

*The no-mixer R value for maximum tube life when mixers are used is greater than 1.25; unfortunately, our estimates of how much greater are very unreliable.

FIGURE 1

Distribution of R-Top
50 Green Ring Tubes

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FIGURE 2

Distribution of R-Top
28 AV (.080 R1b)

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FIGURE 3

Distribution of R-Top
50 Black Ring Tubes

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FIGURE 4

50 Alcoa Uniform (.084 - Green)

Specification (Bot, Top) = (66,66)
Observed Average = (63.7, 66.5)

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Average Rib Height

Average Rib Height

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Average Rib Height

Average Rib Height

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Average Rib Height

Average Rib Height

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Tube OD

Tube OD

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FIGURE 13

CORRELATION OF R WITH CORROSION INDEX FOR 1961 TUBES

(measured in tubes without mixers that had mixers on all previous metal charges)

FIGURE 14

EFFECT OF R ON TUBE LIFE

(No Mixer)

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FIGURE 15

R-TOP VS. TUBE LIFE
(No Mixer)

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FIGURE 16

Relationship of CI to Months as a Function of Tube Outlet Temperature

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FIGURE 17

Tube Examination Wall Measurements
(Tubes installed during 1961)

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FIGURE 18

Probolog Wall Thickness Vs. Corrosion Index
Old Reactors

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FIGURE 19

Wall Thickness Vs. Corrosion Index
Tube Examination and Probolog Data
Old Reactors

FIGURE 20

Effective R-Top Vs. Degree of Eccentricity of Fuel in Tube

FIGURE 21

Effective R-Top Vs. ANT/ANB

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FIGURE 22
Tube Inspection Limits
(No Mixer)

FIGURE 23

Effective R-Top Vs. Tube Life
(No Mixer)

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FIGURE 24

Top Annulus Thickness Vs. Tube Life

Tube Outlet Temperature = 110°C (no mixer)

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TABLE I

NEW PROCESS TUBE ORDERS

<u>Vendor</u>	<u>Type</u>	<u>Color Code</u>	<u>Nominal Rib Height</u>	<u>Number Ordered</u>	<u>Receiving Date</u>
Reynolds	U	None	.080	1000	Nov. 1959
Reynolds	U	None	.080	1000	Feb. 1961
Alcoa	U	None	.080	3000	Nov. 1961
Alcoa	NU	Yellow	.086	500	Nov. 1961
Alcoa	NU	Black	.086	1500	Mar. 1962
Alcoa	U	Green	.084	5000	Sept. 1962
Reynolds	U	Purple	.084	1000	Oct. 1962

NOTE: U stands for uniform-wall-thickness design.

NU stands for non-uniform-wall-thickness design.

TABLE II

* TOTAL TUBES INSTALLED AND REPLACED AT OLD REACTORS - 1/1/60 TO 10/1/62

Date Installed	B Reactor			D Reactor				DR Reactor			F Reactor			E Reactor				All Reactors			
	ANU*	RU	AU1	ANU	RU	AU1	AU2	ANU	RU	AU1	ANU	RU	AU1	ANU	RU	AU1	AU2	ANU	RU	AU1	AU2
1/60-3/60	6	-		85	-	-	-	13	-	-	31	52		7	19	-	-	142	71	-	-
4/60-6/60	50	-		5	1	-	-	16	-	-	1	2		9	63	-	-	81	66	-	-
7/60-9/60	74	-		103	-	-	-	9	-	-	-	78		1	2	-	-	187	80	-	-
10/60-12/60	20	-		-	12	-	-	10	-	-	-	77		12	27	-	-	42	116	-	-
1/61-3/61	69	7		1	17	-	-	17	-	-	-	76		3	13	-	-	90	113	-	-
4/61-6/61	-	83		47	81	-	-	93	-	-	-	50		2	44	-	-	142	258	-	-
7/61-9/61	-	157		1	203	-	-	3	101	-	-	88		34	71	-	-	38	620	-	-
10/61-12/61	87	50	34	85	16	72	-	18	6	-	26	7	35	84	1	-	-	300	80	141	-
1/62-3/62	9	-	345	-	-	412	-	144	-	218	-	368	-	11	-	493	-	164	368	1468	-
4/62-6/62	-	-	357	-	-	16	-	-	-	311	144	81	132	225	-	174	-	369	81	980	-
7/62-9/62	-	-	2	287	-	23	60	-	-	4	159	-	8	8	-	6	503	54	-	43	563
ANU (Pre 10/61)**	219			242				161			32		68					722			
ANU (Post 10/61)	96			372				162			329		328					1287			
TOTALS	315	297	738	614	330	523	60	323	107	583	361	879	175	396	240	673	503	2009	1853	2632	563
Tubes Replaced	67	5	2	70	19	15	-	32	3	2	11	39	1	44	135	8	-	124	201	28	-

*ANU = Alcoa non-uniform wall (.086" rib)

RU = Reynolds uniform wall (.080" rib)

AU1 = Alcoa uniform wall (.080" rib)

AU2 = Alcoa uniform wall (.084" rib)

**AU1 tubes installed before 10/61 are assumed to be original tubes. AU1 tubes installed since 10/61 are assumed to be the yellow and black color code.

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TABLE IIIDefinition of Terms

- TOP = Top wall thickness in mils by micrometer.
- BOT = Bottom wall thickness in mils by micrometer.
- RIB 1 = Rib plus wall dimension in mils at 4:30 o'clock by micrometer.
- RIB 2 = Rib plus wall dimension in mils at 7:30 o'clock by micrometer.
- TOD = Tube outside diameter (vertical) in mils by micrometer.
- RH1 = RIB1 - BOT = calculated rib height in mils.
- RH2 = RIB2 - BOT = calculated rib height in mils.
- ANT = Calculated top annulus thickness assuming a 1.444" diameter slug.
- ANB = Calculated bottom annulus thickness assuming a 1.444" diameter slug.
- R-TOP* = Calculated ratio of top-of-annulus water temperature to bulk outlet temperature.
- R-BOT* = Calculated ratio of between-the-rib water temperature to bulk outlet temperature.
- R-HOLE* = Calculated ratio of hole water temperature to bulk outlet temperature.

*R-values do not include effects of fuel growth, tube distortion during installation or unusual fuel size or alignment effects.

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TABLE IVNEW PROCESS TUBE DIMENSIONAL MEASUREMENTS
Alcoa Non-Uniform Wall (.086 Rib - Black)¹

<u>NO.</u>	<u>TOP</u>	<u>BOT</u>	<u>RIB 1</u>	<u>RIB 2</u>	<u>TOD</u>	<u>RH1</u>	<u>RH2</u>
1	70	60	144	143		84	83
2	68	62	145	147		83	85
3	69	63	147	146		84	83
4	69	64	146	147		83	82
5	71	61	144	146		85	83
6	65	69	151	151		82	82
7	67	66	147	148		81	82
8	69	60	144	144		84	84
9	71	61	144	146		83	85
10	68	64	147	148		83	84
11	66	66	147	150		81	84
12	64	65	146	149		81	84
13	72	60	147	148		87	88
14	65	67	148	148		81	81
15	69	61	146	143		85	82
16	67	65	145	146		80	81
17	69	62	143	145		81	83
18	71	64	149	147		85	83
19	65	65	147	146		82	81
20	71	57	139	143		82	86
21	70	59	143	142		84	83
22	70	59	142	144		83	85
23	69	59	144	143		85	84
24	62	66	145	156		79	90
25	70	57	143	142		86	85
26	68	60	143	144		83	84
27	66	62	146	143		84	81
28	66	63	143	146		80	83
29	71	59	141	144		82	85
30	68	60	144	145		84	85
31	63	66	143	141		77	75
32	64	66	142	150		76	84
33	68	60	141	144		81	84
34	66	61	142	144		81	83
35	69	58	142	145		84	87
36	68	59	143	142		84	83
37	68	59	142	143		83	84
38	67	59	141	142		82	83
39	67	60	142	144		82	84
40	64	65	148	146		83	81

¹ Micrometer measurements were made at one end of tube from shipments received since March 1962. Installed at D reactor.

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TABLE IV (Continued)

<u>NO.</u>	<u>TOP</u>	<u>BOT</u>	<u>RIB 1</u>	<u>RIB 2</u>	<u>TOD</u>	<u>RH1</u>	<u>RH2</u>
41	67	58	143	142	↑ Not Measured ↓	85	84
42	70	59	143	140		84	81
43	70	59	141	144		82	85
44	69	58	142	144		84	86
45	69	54	142	144		83	85
46	62	68	148	146		80	78
47	71	59	143	142		84	83
48	72	59	143	145		84	86
49	63	66	146	148		80	82
50	67	62	144	145		82	83
51	69	64	149	146		85	82
52	68	62	146	144		84	82
53	71	62	142	145		80	83
54	71	60	142	144		82	84
55	65	65	146	147		81	82
56	69	60	148	145		88	85
57	70	58	143	143		85	85
58	68	61	145	144		84	83
59	69	64	148	144		84	80
60	69	66	141	145		75	79
61	72	57	141	145		84	88
62	66	64	146	148		82	84
63	66	63	144	146		81	83
64	72	58	144	140		86	82
65	69	61	145	144		84	83
66	65	64	146	145		82	81
67	70	59	142	144		83	85
68	68	61	143	142		82	81
69	70	60	145	143		85	83
70	65	64	146	143		82	79
71	70	60	145	145		85	85
72	68	63	144	144		81	81
73	62	71	152	152		81	81
74	60	72	155	151		83	79
75	67	64	148	150		84	86
76	68	65	147	149		82	84
77	66	67	154	146		87	79
78	69	64	146	148		82	84
79	64	69	151	150		82	81
80	71	62	146	145		84	83
81	67	64	150	147		86	83
82	69	64	149	149		85	85
83	74	59	144	145		85	86
84	63	69	152	149		83	80
85	65	67	153	147		86	80
86	69	64	148	147		84	83
87	70	64	148	146		84	82
88	62	70	153	151		83	81
89	71	61	147	146		86	85
90	69	64	147	146		83	82
91	64	68	151	149		83	81

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TABLE V

NEW PROCESS TUBE DIMENSIONAL MEASUREMENTS
Alcoa Uniform Wall (.084 Rib - Green)¹

<u>NO.</u>	<u>TOP</u>	<u>BOT</u>	<u>RIB 1</u>	<u>RIB 2</u>	<u>TOD</u>	<u>RH1</u>	<u>RH2</u>
1	71	59	145	145	1.730	86	86
2	60	70	152	154	1.730	82	84
3	65	66	148	150	1.731	82	84
4	66	64	149	149	1.731	85	85
5	69	63	149	146	1.731	86	83
6	67	64	148	148	1.729	84	84
7	68	62	146	147	1.730	84	85
8	68	62	148	147	1.729	86	85
9	65	65	149	149	1.730	84	84
10	69	67	147	147	1.731	80	80
11	64	65	151	149	1.731	86	84
12	59	71	153	154	1.730	82	83
13	67	63	147	149	1.732	84	86
14	69	61	145	149	1.730	84	87
15	65	65	149	151	1.732	84	86
16	61	69	152	154	1.732	83	85
17	69	61	146	147	1.735	85	86
18	67	62	146	149	1.730	84	87
19	65	65	149	150	1.730	84	86
20	69	61	145	148	1.731	84	87
21	70	59	146	146	1.732	87	87
22	70	60	150	143	1.730	90	83
23	65	65	151	147	1.730	86	82
24	65	64	148	147	1.729	84	83
25	68	62	152	148	1.730	90	86
26	68	62	147	146	1.731	85	84
27	68	62	148	147	1.729	86	85
28	68	61	147	147	1.730	86	86
29	65	64	148	150	1.730	84	86
30	68	61	146	147	1.731	85	86
31	62	67	149	152	1.730	82	85
32	68	61	146	148	1.730	85	87
33	61	68	151	151	1.730	83	83
34	60	69	150	149	1.731	81	80
35	67	64	148	148	1.731	84	84
36	68	61	145	149	1.735	84	88
37	68	62	148	147	1.730	86	85
38	69	61	148	145	1.729	87	84
39	68	61	145	148	1.729	84	87

¹ Micrometer measurements made at one end of tube from shipments received since September 1962. Installed at H reactor.

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TABLE V (Continued)

<u>NO.</u>	<u>TOP</u>	<u>BOT</u>	<u>RIB 1</u>	<u>RIB 2</u>	<u>TOD</u>	<u>RH1</u>	<u>RH2</u>
40	65	65	149	150	1.732	84	85
41	65	64	148	150	1.731	84	86
42	68	62	147	147	1.730	85	85
43	59	70	153	153	1.732	83	83
44	68	62	146	148	1.728	84	86
45	67	62	147	147	1.729	85	85
46	68	64	149	147	1.728	85	83
47	66	64	149	148	1.730	85	84
48	69	61	146	146	1.730	85	85
49	70	65	150	149	1.730	85	84
50	69	66	150	150	1.730	84	84

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TABLE VI

NEW PROCESS TUBE DIMENSIONAL MEASUREMENTS
Alcoa Uniform (.080" Rib)¹

<u>NO.</u>	<u>TOP</u>	<u>BOT</u>	<u>RIB 1</u>	<u>RIB 2</u>	<u>TOD</u>	<u>RH1</u>	<u>RH2</u>
1	69	62	143	144	1.730	81	82
2	70	60	139	141	1.729	79	81
3	68	61	142	142	1.729	81	81
4	68	63	144	144	1.730	81	81
5	68	64	144	147	1.735	80	83
6	70	59	140	141	1.731	81	82
7	68	62	142	142	1.730	80	80
8	70	68	147	148	1.730	79	80
9	68	63	143	145	1.731	80	82
10	68	61	143	141	1.730	82	80
11	69	60	143	141	1.730	83	81
12	66	63	142	143	1.731	79	80
13	66	63	143	143	1.731	80	80
14	69	64	143	144	1.730	79	80
15	66	65	147	146	1.730	82	81
16	67	62	144	143	1.731	82	81
17	74	57	138	141	1.729	81	84
18	67	62	145	141	1.728	83	79
19	68	61	138	142	1.728	77	81
20	67	62	142	142	1.729	80	80
21	68	62	142	143	1.729	80	81
22	69	60	142	141	1.731	82	81
23	67	62	143	144	1.730	81	82
24	72	59	141	144	1.730	82	85
25	62	67	146	147	1.730	79	80
26	72	59	142	139	1.727	83	80
27	67	62	142	144	1.729	80	82
28	68	62	142	143	1.729	80	81

¹Micrometer measurements made at one end of tubes from shipments received since November 1961. Installed at H reactor.

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TABLE VII

NEW PROCESS TUBE DIMENSIONAL MEASUREMENTS
Alcoa Non-Uniform Wall (.086" Rib - Black)¹

<u>NO.</u>	<u>TOP</u>	<u>BOT</u>	<u>RIB 1</u>	<u>RIB 2</u>	<u>TOD</u>	<u>RH1</u>	<u>RH2</u>
1	73	62	143	144	1.728	81	82
2	70	64	148	146	1.728	84	82
3	66	66	148	149	1.727	82	83
4	65	67	149	150	1.727	82	83
5	69	63	148	147	1.728	85	84
6	68	64	148	149	1.727	84	85
7	63	68	152	150	1.725	84	82
8	72	61	146	146	1.727	85	85
9	70	63	147	146	1.728	84	83
10	69	65	145	147	1.728	80	82
11	75	58	141	141	1.727	83	83
12	67	66	151	147	1.727	85	81
13	69	63	147	148	1.728	84	85
14	67	65	149	148	1.728	84	83
15	70	63	146	148	1.728	83	85
16	70	64	146	147	1.729	82	83
17	69	65	148	148	1.728	83	83
18	67	66	148	150	1.727	82	84
19	69	63	147	147	1.727	84	84
20	72	61	141	144	1.727	80	83
21	69	63	145	148	1.728	82	85
22	70	63	146	146	1.728	83	83
23	69	63	146	147	1.728	83	84
24	71	61	146	146	1.727	85	85
25	70	64	147	146	1.728	83	82
26	71	61	143	144	1.727	82	83
27	70	62	142	144	1.727	80	82
28	71	61	145	145	1.727	84	84
29	68	64	146	149	1.727	82	85
30	67	66	149	148	1.728	83	82
31	71	62	147	146	1.727	85	84
32	66	67	149	149	1.725	82	82
33	70	62	147	147	1.728	85	85
34	67	66	146	146	1.728	80	80
35	70	62	146	147	1.728	84	85
36	69	64	146	145	1.728	82	81
37	70	63	147	146	1.728	84	83
38	70	62	148	147	1.728	85	85
39	66	66	147	149	1.729	81	83

¹ Micrometer measurements made at one end of tubes from shipments received since March 1962. Installed at F reactor.

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TABLE VII (Continued)

<u>NO.</u>	<u>TOP</u>	<u>BOT</u>	<u>RIB 1</u>	<u>RIB 2</u>	<u>TOD</u>	<u>RH1</u>	<u>RH2</u>
40	66	67	151	145	1.727	84	78
41	70	62	143	146	1.728	81	84
42	68	65	150	150	1.727	85	85
43	70	63	146	145	1.728	83	82
44	65	67	146	149	1.728	79	82
45	70	63	147	146	1.728	84	83
46	71	61	146	146	1.728	85	85
47	70	62	144	146	1.728	82	84
48	71	62	144	146	1.728	82	84
49	66	66	150	145	1.727	84	79
50	65	67	150	148	1.725	83	81

TABLE VIII

SUMMARY OF NEW PROCESS TUBE DIMENSIONAL DATA

TUBE TYPE		TOP	BOT	RIB 1	RIB 2	TOD	RH1	RH2
Black (91 tubes measured)	Nominal Spec.	72	59	-	-	1.729	86	86
	Minimum	60	57	139	140		75	75
	Maximum	74	72	155	156		88	90
	Range	14	15	16	16		13	15
	Average	67.8	62.5	145.5	145.6		82.9	83.0
	Std. Dev.	2.8	3.5	3.3	2.8		2.2	2.3
AU (.080) (28 tubes measured)	Nominal Spec.	66	66	-	-	1.729	80	80
	Minimum	62	57	138	139	1.727	77	79
	Maximum	72	68	147	148	1.735	83	85
	Range	10	11	9	9	.008	6	6
	Average	68.3	62.0	142.6	143.1	1.730	80.6	81.1
	Std. Dev.	2.3	2.4	2.2	2.1	.0014	1.4	1.3
Green (50 tubes measured)	Nominal Spec.	66	66	-	-	1.729	84	84
	Minimum	59	59	145	143	1.728	80	80
	Maximum	71	71	153	154	1.735	90	90
	Range	12	12	8	11	.007	10	10
	Average	66.5	63.7	148.2	148.4	1.730	84.5	84.6
	Std. Dev.	3.0	2.9	2.2	2.3	.0014	1.8	1.9
Black (50 tubes measured)	Nominal Spec.	72	59	-	-	1.729	86	86
	Minimum	63	58	141	141	1.725	79	78
	Maximum	75	68	152	150	1.729	86	85
	Range	12	10	11	9	.004	7	7
	Average	68.9	63.7	146.7	146.8	1.7275	83.0	83.1
	Std. Dev.	2.3	2.1	2.4	1.9	.0008	1.6	1.6

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TABLE IX

CONCENTRICITY AND UNIFORMITY OF TUBE DIMENSIONS
Mils of Wall Thickness

Tube* Number	Tube End	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
1	A	68.5	66	63	58	58	61	63	65	66	65	68.5	69.5
	B	69	68	66	60	59	58	64	64	66	57	67	70
2	A	69	68	64	59	59	61	62	62	62	63	68	69
	B	70	69	66	63	61	62	63	64	63	63	64	68
3	A	68	67	63	57.5	59	61	62	63	64	63	67	69.5
	B	70	65.5	62	57	59	61.5	63	65	64	64	67.5	69
4	A	66	62	60	58	61	66.5	69	69	67	63	64	65
	B	64	65	62	59.5	60	65	67	69	66	62	65	66
5	A	73	69	66	61	61	62	62	62	61	60	65	68.5
	B	70	72	69	64	60	61	59.5	60	60	60	67	70
6	A	68	70	67	63	60	61	61	61.5	61	60	65	69
	B	71	69	65	61	62	64	64	64	62.5	60	64.5	66
7	A	70	69.5	67	63.5	62.5	63	62.5	62	60	62	66	69
	B	69	68.5	65	62	62	63	63	63	62	61	65	68
8	A	69	67	63	59	61	62	62	62	61	63	67	69
	B	67	65	63	58	60	63	64	65	63.5	62	65	67
9	A	64	64	62	59	61	65	68	67	65	63	64	65
	B	63	62	60	57	59	65	68	69	67	64	64	64.5
10	A	70	69	67	61	60.5	61	61.5	61.5	62	61	66	69
	B	68	68	65	61	60	62	63	63	61	61	65	67
11	A	69	67	64	60	62	63	63	62.5	61	62	66	68.5
	B	68	67	65	62	62	63	63	61	59	61	64	67
12	A	65.5	65	63	60	62	66	66	66	63.5	62	64	65
	B	63	62	61	59	61	67	68	68	65	61	63	62

*See page 9 for identification of tube design.

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TABLE IX(Continued)

Tube Number	Tube End	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
13	A	70	68	64	59	60	61	61	62	61	63	67	69
	B	67	66	64	59	61	63	64	63	62	60	64	66
14	A	67	65	63	60	62	64	65	64	63	61	64	66
	B	66	65	64	61	63	65	66	65	61	60	63	64
15	A	70	68	64	58	58	60	62	62	63	65	67	70
	B	69	67	64	60	60	62	63	63	62	62	65	67
16	A	65	64	62	60	62	66	67	67	64	62	64	64
	B	64	64	61	58	60	64	67	67	65	64	65	65
17	A	67	70	66	64	66	64	63	63	66	65	66	67.5
	B	68	67	65.5	64	64.5	64	61	62	64	65	67	68
18	A	67	67	67.5	67.5	67	66	65	64	63.5	64	64.5	65.5
	B	67	68	68	68	67	66	66	64	63	64	64.5	65.5
19	A	67	67	66	65	65	64	61.5	63	64	65	66	67
	B	67	66.5	66	65.5	64	63	62	62.5	64	64	65	67
20	A	-	-	-	-	-	-	-	-	-	-	-	-
	B	74	73	68	61	60	59	58	58	59	60	66	71
21	A	73	72	70	67	63	60	59	61	64.5	67	70	72
	B	72	72	72	66	63	61	60	61	65	67	69.5	71
22	A	65	64	63	61	64	68	69	68	64	62	62	64
	B	69	67	64	61	62	63	63	63	62	63	65	68
23	A	71	71	68	65	62	62	61	60	58	61	64	67
	B	72	73	71	69	65	63	60	59	56	56	61	66

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TABLE X

UNIFORMITY OF TUBE DIMENSIONS

Location Feet	Tube No. 1				Tube No. 4				Tube No. 18			
	0°	90°	180°	270°	0°	90°	180°	270°	0°	90°	180°	270°
A	68.5	58	63	65	66	59.5	67	62	67	67.5	65	64
1	69	58.5	63	64.5	66	60	67	62	66.5	67.5	65.5	63.5
2	69	58.5	62.5	65	66	59.5	66.5	62.5	66.5	67.5	65.5	63.5
3	69	58.5	63	65	66	59	66.5	62.5	66.5	67.5	65.5	63
4	69	58.5	63	65	65	58.5	67	62.5	67	68	65.5	63
5	69	58.5	63.5	65	65	59	67	63	66.5	68	65.5	63
6	69	58.5	63	65.5	64.5	59	67	63	66.5	68	66	63.5
7	68.5	58.5	63.5	65	64.5	59	67	62.5	66	68	66	63.5
8	69	58.5	63.5	65	64.5	59	67	62.5	66	67.5	66	63.5
9	69	58.5	63.5	65.5	64	59	68.5	63	66.5	67.5	66	64
10	69	58	63	65.5	64	58.5	69	63	66	67.5	66	63.5
11	69	58	63	65.5	64	58.5	68.5	63.5	66	67	66	63.5
12	69	58.5	64	65.5	64	58.5	68.5	63.5	66	67	66	63.5
13	68.5	58	63.5	66	64	58.5	68.5	64	66.5	67	66	63
14	69	58	63	65.5	63.5	58.5	68.5	63.5	66	67.5	66	63.5
15	69	58.5	64	66	63	58.5	68.5	63.5	66	67.5	66	63.5
16	68.5	58	64	66	63.5	58	69	63.5	66.5	67	66	63.5
17	68.5	58.5	63.5	66	63.5	58	69.5	64	66.5	67.5	66	64
18	68	58	64	66	63.5	58	70	64	66	67.5	66	64
19	68.5	58	64	66	63	58.5	69.5	64	66	67	66	63.5
20	68.5	58.5	64	66	63.5	58.5	70	64	66	68	66	63
21	68.5	58	64	66.5	63	58	70	63.5	66	67.5	66.5	63.5
22	68.5	58	64	66	63.5	58.5	69.5	63	66	67.5	66	63.5
23	68.5	58	64	66	63	58	70	63.5	66	67.5	66	63.5
24	68	58.5	64	66	62.5	58	70	63.5	66.5	68	65.5	63
25	68	58	64	66	63	58.5	70	63.5	66.5	67.5	66	64
26	68	58.5	64.5	66	63	58	70	64	66	67.5	66	64
27	68	58.5	64	66	63	58	70	64	66.5	68	66	63.5
28	68.5	58.5	64.5	66	63.5	58	70	64	66.5	68	66	63
29	68	59	64	66	62.5	58	70	64	67	68	66	63
30	68	59	64.5	66	62.5	57.5	70	64	65	68	66	63
31	68	59	64.5	66	62.5	57.5	69.5	64	66.5	68	65.5	64
32	68.5	59	64.5	66	62.5	57.5	70	64	67	67.5	65.5	64
33	68.5	59	64	66	62.5	57.5	70	64	67	67.5	65.5	63.5
34	69	58.5	64.5	66	62.5	57.5	70.5	64	67	67.5	65	64
35	68.5	59	64	66	63	57.5	70	63.5	67	67.5	65	64
36	69	59	64.5	66	62.5	57.5	69	63.5	67	68	65	64
37	69	59	64.5	66	62.5	57.5	69.5	64	67	67.5	65.5	64
38	69	59.5	64.5	66	63	57.5	69.5	63	67	67.5	65.5	64
39	69	59.5	64	66	63	57.5	69	63	67	67	65	64
40	69	60	64.5	66	63	57	69.5	62.5	67	67.5	65	64.5
41	69	60	64	66.5	64	57	69.5	63	67	67.5	65.5	64
B	69	60	64	67	64	58	69	63	67	68	66	64

TABLE XI

TUBE EXAMINATION DATA

Tube	2577-F	2570-F	3663-F	0965-D	0882-D	2481-D	1283-D	0766-DR	1474-B	1372-B	1366-B
Date In	10/3/61	7/11/61	1/29/61	12/16/61	7/11/61	10/10/61	1/21/61	4/4/61	9/9/61	6/17/61	1/19/61
Date Out	5/31/62	5/31/62	5/31/62	4/14/62	5/29/62	8/1/62	1/15/62	7/16/62	8/8/62	8/8/62	8/8/62
Months in Reactor	8	10.5	16	4	10.5	10	12	15.5	11	14	19
Corrosion Index	3.2	6.4	9.2	1.5	4.9	5.5	8.2	6.3	4.5	7.5	10.9
Index per Month	0.4	0.6	0.57	0.37	0.47	.55	0.68	0.41	0.41	0.54	0.57
Initial Bottom Wall Thickness	-	63	58	61	61	62	-	61	62	61	62
Initial Top Wall Thickness	68	-	73	70	69	68	72	71	70	70	69
Initial Rib 1 Plus Wall	-	141	143	147	144	145	-	139	145	143	142
Initial Rib 2 Plus Wall	-	144	143	148	146	146	-	139	146	145	145
Initial Rib Height 1	-	78	85	86	83	83	-	78	83	82	80
Initial Rib Height 2	-	81	85	87	85	84	-	78	84	84	83
Minimum Bottom Wall Thickness	58	-	53	60	58	55	52	52	56	55	49
Minimum Top Wall Thickness	61	55	57	63	58	56	55	62	53	43	43
Minimum Rib Plus Wall (Average)	141	-	132	141	137	138	130	122	134	131	122
Initial R-Top	-	-	1.14	1.21	-	1.12	-	1.00	1.15	1.12	1.08
Initial R-Bottom	-	-	.88	.84	-	.89	-	.999	.88	.90	.92
Initial R-Hole	-	-	1.01	1.01	-	1.01	-	.999	1.00	1.01	1.01
Final R-Top	-	-	1.02	1.16	-	1.03	-	.91	1.03	.98	.93
Final R-Bottom	-	-	1.03	.86	-	.95	-	1.08	.95	.99	1.05
Final R-Hole	-	-	.96	1.02	-	1.03	-	1.03	1.03	1.04	1.05
Last Probolog Date	-	-	2/62	-	-	-	-	7/62	7/62	7/62	7/62
Pr. Wall Thickness	-	-	50	-	-	-	-	55	51	42	41

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TABLE XII

1962 PROBOLOG SUMMARY FOR TUBES INSTALLED DURING 1961

<u>Corrosion Index</u>	<u>B</u>		<u>D</u>		<u>DR</u>		<u>F</u>		<u>H</u>		<u>All Reactors</u>	
	<u>No. Tubes</u>	<u>Ave. PR WT</u>	<u>No. Tubes</u>	<u>Ave. PR WT</u>	<u>No. Tubes</u>	<u>Ave. PR WT</u>	<u>No. Tubes</u>	<u>Ave. PR WT</u>	<u>No. Tubes</u>	<u>Ave. PR WT</u>	<u>No. Tubes</u>	<u>Ave. PR WT</u>
0-1			2	56	4	56					6	56
1-2	6	55.7	4	56	4	56					14	55.9
2-3	3	52.0	14	56	11	55.2			2	54.0	30	55.2
3-4	8	52.6	13	55.1	27	54.0	1	55	20	50.1	69	53.0
4-5	4	52.5	18	53.8	29	54.0	3	56	29	48.7	83	52.1
5-6	12	51.9	16	52.7	39	50.6	10	53.8	21	44.8	98	50.2
6-7	7	49.3	8	53.3	24	50.6	19	52.4	13	46.0	71	50.4
7-8	11	48.7	15	47.9	17	48.5	11	51.4	3	41.0	57	48.6
8-9	10	46.6	6	46.7	6	48.0	3	54			25	47.8
9-10	14	47.4	6	44.5	4	45.0	7	50.3			31	47.2
10-11	19	44.4	6	42.0	1	46.0					26	43.9
11-12	4	44.0	3	42.3							7	43.3
12-13	5	41.8	1	41.0							6	41.7
13-14			2	43.5							2	43.5

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APPENDIX I

ESTIMATION OF TEMPERATURE IMBALANCE

The amount of temperature imbalance within a new process tube can be estimated from the degree of eccentricity of the slugs within the tube. Temperature imbalance (R) has been correlated with eccentricity (E) for a round or "unsquashed" tube.

$$E \text{ or } E = (ANAV - ANT) / ANAV = (ANB - ANT) / (ANB + ANT)$$

Where: ANT = annulus between top of slug and tube wall

ANB = annulus between bottom of slug and tube wall

ANAV = average annulus

Laboratory and in-reactor temperature imbalance data have been taken and the relationships derived therefrom are shown on Figures 1 and 2. Figure 1 shows the relative heat transfer per unit flow of water to the top-of-annulus $(q/F)_T$ as a function of slug eccentricity. Figure 2 shows heat transfer to the bottom-of-annulus $(q/F)_B$ as a function of $(q/F)_T$.

To determine R-top where:

$$R_{top} = (\Delta T_{top} / \Delta T_{bulk}) = \text{top of annulus temperature rise per unit bulk temperature rise}$$

the relative heat transfer per unit flow to the annulus $(q/F)_A$ and hole $(q/F)_H$ must also be known. These have also been experimentally determined for current design I&E slug-in-tube geometries and are independent of E for any given geometry. They do, however, vary slightly with tube internal diameter variation. Available data on this effect is not conclusive but it does appear the variation is proportional to the change in cross-sectional area available to flow. Thus, to estimate top, bottom, and hole water temperature relative to bulk water temperature, the following equations apply:

$$R_{TOP} = (q/F)_A \exp(1.27E)$$

$$R_{BOT} = (q/F)_A \left[(q/F)_T + 1 \right] / \left[3(q/F)_T - 1 \right]$$

$$R_{HOL} = (q/F)_H$$

It remains then to determine the degree of eccentricity of slugs within a particular tube to estimate its temperature imbalance. Direct annuli measurements are preferable; however, in the absence of annuli measuring equipment, they can be calculated from over-all rib height, top and bottom wall thickness and tube outside diameter, all of which can be measured with a micrometer.

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A 7090 FORTRAN computer program has been written which uses the calculational technique described above and permits rapid assessment of acceptability of each tube on large quantities of tube measurement data. The program is called TACT (Tube Acceptance Test) and it permits calculation of R values from either top and bottom annuli measurements or over-all rib, wall thickness, and tube outside diameter measurements. In addition, average values and standard deviations are calculated for R_{TOP}, R_{BOT}, R_{HOL}, ANT, ANB, rib height, tube I.D., top and bottom walls, rib plus wall, and tube O.D. The program also classifies tubes according to the magnitude of R_{TOP} and prints out the corresponding frequency distribution.

Revision of the computer program to permit use of horizontal annulus and wall thickness measurements is presently being contemplated.

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FIGURE 1

Heat Transfer per Unit Flow to Top Annulus
as a Function of Slug Eccentricity

FIGURE 2

Heat Transfer per Unit Flow to Bottom Annulus
as a Function of Top Annulus

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