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by

R. R. Bloomstrand
Advance Fuel Engineering
Fuels Preparation Department

May 21, 1962

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INTRODUCTION

For approximately the past two years, alloyed dingot uranium has been irradiated on a production scale^(1,2,3) for evaluation of rupture performance relative to ingot uranium. Supplementary data on dimensional behavior and certain pre-irradiation measurements have been accumulated under the Quality Certification Program.⁽⁴⁾ This report presents a comparison of ingot and dingot performance based on data obtained to date from this testing program. The discussion consists of three sections: I) dimensional stability, II) external bond quality, and III) reactor rupture performance.

SUMMARY AND CONCLUSIONS

Based on analyses of the data summarized in this report, significant differences in dimensional stability and over-all rupture resistance between "ingot" and "dingot" uranium fuel elements have been shown to exist. The data analyzed covered a span of about two years of canning and irradiation experience. The salient conclusions drawn are as follows:

- (1) Warp characteristics of dingot and ingot material were not significantly different. Tendency of the fuel elements to warp, however, was not constant. Significant differences between-lots and within-lots were routinely observed in both uranium types over the short-run; and long-term trends, i.e. real changes in warp as a function of time, were also indicated from the data. Again, there were no detectable differences, in these data, between ingot and dingot material.
- (2) With respect to fuel element diametral changes (ΔOD 's) ingot and dingot materials were significantly different. Within-lot and between-lot variabilities were equivalent for both materials. The long-term trends, however, were different. In general, over the time period examined, the dingot material exhibited more diametral growth, as measured at the center of the fuel element (ΔOD_2), than ingot material. Dingot ΔOD_2 , however, exhibited a consistent downward trend. The ingot ΔOD_2 curve exhibited an upward swing during the latter part of the period examined, i.e. about June, 1961 canning. The two materials may be equivalent at

-
- (1) HW-63595, "PITA-IP-10-I, Irradiation of Alloyed Dingot Uranium Fuel Elements," R. D. Shimer, January 21, 1960 (Secret).
 - (2) HW-63595 Sup A, "Supplement A to PITA-IP-10-I, Irradiation of Alloyed Dingot Uranium Fuel Elements," R. D. Shimer, April 29, 1960 (Secret).
 - (3) HW-63595 Sup B, "Supplement B to PITA-IP-10-I, Irradiation of Alloyed Dingot Uranium Fuel Elements," R. D. Shimer, June 30, 1960 (Secret).
 - (4) HW-58271, "PI-IP-216-A, Evaluation of Performance of Normal Production I&E Fuel Elements," R. E. Hall and R. R. Bloomstrand, January 6, 1959, (Secret).

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that point. The differences in diametral non-uniformity between the two uranium types were also evident in tube filling capacity (TFC), where effects of warp and diametral change are combined. The TFC values were consistently higher for dingot material.

- (3) Possible heat treatment "effects" on dimensional behavior that might be feed-site related are completely intermingled in the data. The analysis cannot objectively attest either the presence or absence of such effects. The apparent similarity in warp for dingot and ingot fuel elements could be related to some common "treatment" such as rolling or canning. Some question remains, however, as to whether the lack of an observed difference in warp was real or was simply undetectable with these data.
- (4) Over the test period improvements in external bond quality, as measured by total external bond count, were observed. Under the assumption that testing bias is random, no significant differences between ingot and dingot material were discerned in the data. There were no data available for comparison of internal bond quality.
- (5) With respect to over-all rupture performance, the failure rate of dingot fuel elements was significantly higher than that of ingot fuel elements. For non-bumper fuel the observed difference in the over-all failure rate, under equivalent irradiation conditions, was a factor of about 2.6, based on experience through April, 1962.
- (6) The cause(s) of the reduced rupture resistance are not clearly identifiable from the available reactor and ex-reactor data.

The rupture classification data suggest that the "difference" may largely be due to dingot fuel elements being less resistant to non-side failure types of ruptures. This is possibly the case because:

- a) In the non-bumper fuel, although the over-all rupture rate of dingot is higher than ingot, there is no discernible difference between ingot and dingot with respect to resistance to side failure.
- b) Statistically conservative analysis of the combined bumper and non-bumper experience, excluding ruptures classified as side-hot spot failures, tends to indicate a relatively higher rupture rate for the dingot fuel. The difference between dingot and ingot is significant at the 92 per cent level.
- c) The combined data indicate that dingot fuel is more susceptible to ruptures classified as cleavage (split) failures. This comparison, however, is a questionable one. The failure mechanism(s) controlling the split rupture rate is not known; they may not be "unique" enough to justify rupture performance comparisons of such limited scope.

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DISCUSSION

I. Dimensional Stability

A. General

It is known that differences in irradiation conditions affect observed dimensional behavior. It is also known that for constant irradiation conditions uranium behavior changes from time to time. Comparisons of ingot and dingot dimensional behavior were made using observed minus expected (o-e) values of the various statistics, the expected values being calculated from previously developed mathematical models.⁽⁵⁾

The data analyzed were not from designed experiments, rather they were entirely accumulated from Quality Certification samples drawn from FPD production. As a result, in general, dingot material for the first "half" of the test was predominantly heat treated at NLO and material for the last "half" was predominantly heat treated at MCW. Ingot material was exclusively heat treated and rolled at NLO. Furthermore, within each dingot heat treatment type, i.e., MCW versus NLO, there were quantities of both vacuum outgassed and non-outgassed material. Because warp, TFC, etc., are highly variable, there is, at best, only a rather limited amount of data when all dingot material is grouped into one category for analysis. Possible effects that might be "heat treatment" or "uranium" dependent are completely intermingled in the data. This confounding of possible variables is technically undesirable and, in our judgment, has markedly reduced the effectiveness of our attempts to now distinguish between ingot and dingot materials.

The data, while limited to OIIN and OIIIN material, represent essentially all the data for "normal" production types of dingot material currently available for analysis. The ingot material is a rather large sample of the total available for the time period studied, and, with little doubt, is sufficient for comparative purposes and is representative of ingot behavior. Canning dates ranged from October, 1959 through June, 1961 for the sixty tubes of ingot material analyzed, and from November, 1959 through June, 1961 for the twenty-nine tubes of dingot material used. Data from four tubes of dingot material and two tubes of the original ingot sample drawn were excluded prior to the statistical analysis because of probable gross measurement error.

Five statistics (o-e)warp, (o-e) ΔOD_1 , (o-e) ΔOD_2 , (o-e) ΔOD_3 , and (o-e)TFC, were analyzed to determine trends, if any, with time (HAPO canning date) and the curves for each statistic for each type material were compared.⁽⁶⁾ The dimensional data used in this analysis are in Appendix B.

(5) HW-67530, "Analysis of Quality Certification Data - Warp, TFC, and ΔOD_2 As A Function of Reactor Operating Conditions," L. T. Hagie and J. L. Jaech, November 23, 1960 (Secret).

(6) Statistical calculations were made using the generalized regression analysis program, "George" developed by Operational Research and Synthesis Operation, HLO.

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In succeeding sections, the term (o-e) is sometimes dropped for simplification, but warp means (o-e)warp, etc. "Expected" values were relatively stable over the period examined because changes in operating conditions were compensatory in nature. The trends and magnitudes of changes of the (o-e) values, therefore, are usually quite similar to those exhibited by the "observed" values.

- B. Warp - Based on these data, there were no significant differences between ingot and dingot material(s) with respect to warp, either in short-term or long-term behavior. Average warp was not constant over the time period examined; the trends exhibited are shown in Figure 1.* The shaded area represents the 95% confidence level band within which the true curve lies. As pointed out in the previous section, however, possible "heat treatment" and "uranium" effects are completely intermingled and cannot be identified in these data.

Tendency to warp was generally "stable" during the period through approximately August, 1960 (HAPO calendar date 5800), trended downward until approximately March, 1961 (HAPO calendar date 6000), and then has tended to rise again. We cannot provide a rational explanation for this behavior. The observed changes in warp level, however, are undoubtedly significant in terms of potential effects on fuel performance. (7)

- C. Diametral Changes (ΔOD_1 , ΔOD_2 , ΔOD_3) - Ingot and dingot material(s) differ with respect to fuel element diametral change, based on these data. This is illustrated in Figures 2, 4, and 5.*

In general, diametral change(s) for ingot material have trended upward -- with some cyclic behavior also evident in ΔOD_2 -- over the period examined. Perhaps of most concern is the indication of an upward swing in ΔOD_2 during the latter part of the period examined, i.e., about June, 1961 canning.

For dingot material, while there are significant variations between lots over short periods of time, no significant long-term trends in ΔOD_1 and ΔOD_3 with time were discerned from these data. Diameter change at the center of the fuel element (ΔOD_2), Figure 2,* has shown a downward trend over the period examined, and dingot is essentially equivalent to ingot at the end of the period. We would venture that this trend is more likely a "uranium" oriented effect, rather than say a "heat treatment" effect on the basis that the trend is evidenced for both NLO heat treated material and MCW heat treated material when they are separately examined.

- D. Tube Filling Capacity (TFC) - Ingot and dingot material(s) differ with respect to TFC, as would be expected from the warp and diametral behavior of the two categories, since the TFC statistic combines both the effects of warp and OD changes. In each material, there were wide variations between lots on the short-term, but no significant long-term trends with time were detected in the data, Figure 3.* One might have expected a downward trend in TFC for the dingot material, similar in shape perhaps, to the warp curve and there was some tendency in that direction, but it was not significant.

(7) HW-67120, "Analysis of Quality Certification Data Effect of Warp on the Incidence of Hot-Spots," L. T. Hagie and J. L. Jaech, October 14, 1960 (Unclassified).

The difference in TFC, 0.3 units, is in the direction to make dingot material slightly less resistant than ingot material to side failures, perhaps by one fourth for equivalent external bond quality.⁽⁸⁾ This magnitude of difference would not be readily detected with "normal" failure frequencies.

- E. Within-Lot Variation ("Uniformity") - There were no significant differences between ingot and dingot material(s) with respect to within-lot variability of any of the statistics examined. Individual fuel element lots, however, can hardly be termed homogeneous. For example, the within-lot standard deviation of $(o-e)\Delta OD_2$ was 4.5 mils. This means typically that in a lot with an average $(o-e)\Delta OD_2$ value of say 1.0 mil, about one fuel element in three would have $(o-e)\Delta OD_2$ values outside the range of -3.5 to +5.5 mils and about one in twenty would fall outside the range of -8 to +10 mils.
- F. Profile Types - Comparison of ingot and dingot material was also made on the basis of profile types. Profile type, a recent development, is an objective classification scheme supplementing warp, TFC, etc. for characterizing both fuel element bending (no bend, single bend, double bend) and diameter change non-uniformity (uniform, barrel shape, dog-bone, etc.).⁽⁹⁾ The results of this comparison are summarized as follows:
- (1) Ingot and dingot materials were not different with respect to proportion of fuel elements exhibiting double bending -- the proportion being 26 per cent for these data.
 - (2) A higher proportion of dingot fuel elements are barrel shaped -- 35 per cent for dingot, 21 per cent for ingot. This would be expected from the ΔOD_1 , ΔOD_2 and ΔOD_3 data.
 - (3) Unusual profile types, i.e., those evidently resulting from measurement error (type 80) and those which more likely are truly "unusual" in shape (type 90), occurred with the same frequency in both ingot and dingot material, and were 8.6 per cent and 1.2 per cent, respectively.
- G. Review of Significant Observations - The differences in dimensional behavior between ingot and dingot materials observed in these data are entirely consistent with other experience. In general, tests comparing ingot and dingot dimensional stability (a) usually indicate little or no difference between the two types with respect to warp, (b) consistently

-
- (8) HW-72239, "Effects of Bond Quality and Dimensional Stability on Side Failure Resistance of Non-Bumper Fuel Elements," R. R. Bloomstrand, January 5, 1962 (Confidential).
 - (9) HW-70643, "Describing Fuel Element Distortion Using Orthogonal Polynomials," J. L. Jaech, August 4, 1961 (Unclassified).

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indicate larger diametral change at the center of the fuel elements for dingot material, and (c) usually greater TFC for the dingot material. This holds true for solid fuel, (10,11) I&E fuel, (12,13) and overbore I&E fuel, (14) dating back to irradiations in 1957.

II. External Bond Quality

Comparison of ingot and dingot external "bond quality" was made using total external bond count data. These data are routinely accumulated for Quality Certification Program samples. In analyzing total count data the customary logarithmic transformation has been made. The basis for this transformation is documented; (15) the primary advantage comes from the fact that the variance (square of the standard deviation) of the distribution of total count data is stabilized by this transformation. Thus one can statistically compare the tails of the bond count distributions (frequencies in the "high" count regions), between groups of fuel elements, say fuel element lots, by simply comparing the lot averages of the transformed data.

It is known that bond count data are highly variable with time; how much is due to tester variability and how much is due to product variability has not been determined. Thus, in comparing bond quality" between two types of material the analysis must treat "time" as a variable. One method is to select "pairs" of data, from lots canned about the same time, and analyze for a consistent (in direction) difference between the two categories. In so doing, randomly occurring sources of bond count variation, e.g., random tester bias, would probably be balanced out for both groups. Another method is to perform a regression analysis of bond count data versus time similar to that which was done with the dimensional stability data, and the curves for the two types could be compared. Again, the random nature of possible biases must be assumed, for the results to have meaning. The former method was chosen, since it was the easiest. The data are graphically presented in Figure 6.* Average lot total external bond count (LBC) and within-lot-standard deviation (σ_L) are plotted for both ingot and dingot lots versus HAPC canning date.

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- (10) HW-53358 RD, "Analysis of Dimensional Distortion Data from Production Test IP-56-A," J. L. Jaech, October 25, 1957 (Secret).
 - (11) HW-58081 RD, "Analysis of Production Test IP-120-A-94-FP, Comparison of Performance of Ingot and Low Hydrogen Dingot Fuel Elements, K. B. Stewart, November 5, 1958 (Secret).
 - (12) HW-59944 RD, "Analysis of Data from PT-56-A-86 MT, Evaluation of Dimensional Stability Characteristics of Low Hydrogen Uranium I&E Fuel Elements," K. B. Stewart, April 9, 1959 (Secret).
 - (13) HW-66284 RD, "Statistical Analysis of Data from PT-IP-280-A-FP," K. B. Stewart, August 2, 1960 (Secret).
 - (14) Based on data from five tubes of ingot and seven tubes of dingot (PT-381), reported in the undocumented November, 1961 "Fuels Evaluation Memorandum" K. W. Norwood to R. L. Dickeman.
 - (15) HW-61394, "Basis for Logarithmic Transformation of Total Count Data," J. L. Jaech, August 4, 1959 (Unclassified).

* See Appendix A.

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It is concluded, under the assumption that testing bias is random, that ingot and dingot materials do not differ from each other with respect to average total external bond count (LBC). Also it is concluded that lot "uniformity," as measured by σ_L , is the same for both dingot and ingot materials. The conclusions are clear by inspection of the data, as well. The data of Figure 6,* which represent only a portion of the total Quality Certification sample(s) are consistent with the bond count trends exhibited by the total data, the behavior of which is shown by the dashed line.

III. Rupture Performance

A. Chronology and Background Information

A test to compare the rupture performance⁽¹⁾ of X-8001 clad alloyed dingot uranium I&E fuel ("test" material) with X-8001 clad ingot uranium I&E fuel ("control" material) was initiated during the last quarter of CY-1959 with sequential canning and irradiation of the OIIN product. In the first quarter of CY-1961 a shift to the OIIN product was made. During the third quarter of CY-1961 testing of the two "uranium" types in bumper I&E fuel elements (OIINB's) was initiated. On the grounds that different mechanisms may control the over-all rupture rates of bumper and non-bumper fuel, the testing programs of bumper and non-bumper material have been carried on independently. (As of this date, only six failures have been incurred in the bumper phase of the test. The bumper experience, of itself, is insufficient for drawing any meaningful conclusions with respect to relative performance levels of "test" and "control" materials.)

A sequential test procedure was designed such that ultimately one of two decisions would be reached, namely: (1) the over-all rupture rates of test and control material are equal, or alternately (2) the over-all rupture rate of test material is two-fold worse than control material, i.e., for equal irradiation conditions the test material would suffer twice as many failures as the control material. The risk of falsely rejecting the equal performance hypothesis was set at 0.05; the risk of falsely rejecting the alternate hypothesis was set at 0.10.

Theoretically, the "break-point" (50-50 chance of reaching either decision) would be a factor of 1.5 times worse for the test material. That is, if the true performance of the test material were less than 1.5 times worse than the control -- this would include its being better -- it is most likely that the equal performance hypothesis would be accepted. If the true performance of the test material is greater than 1.5 times worse, the odds would favor accepting the alternate (factor of two worse) hypothesis. Clearly, if the true situation were far removed from the alternate hypothesis, e.g., the test material were five-fold worse, the alternate hypothesis would be accepted in short order, and vice versa.

(1) Ibid, page 3.

* Apper.dix A.

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Concurrently, fuel elements clad in X-8001 components supplied by alternate vendors (Harvey, Bridgeport Brass) were under test.⁽¹⁶⁾ To provide against the possibility of "component" effects influencing the "uranium" comparison, provisions were made to distribute alternate vendor components approximately equally between the test and control materials.

By April 20, 1962, rupture experience under this controlled test indicated that the alternate hypothesis should be accepted, Figure 7.* It was concluded, therefore, that the over-all performance level of dingot material is more likely half as good as that of ingot material, than equivalent.

B. Analysis of Reactor Test Results

1. Relationship of Rupture Classification and Failure Mechanism

Ruptures classified as side-hot spot failures are believed to result from accelerated non-uniform corrosion attack associated with abnormally high jacket surface temperatures. The temperature elevation can be caused by fuel cocking or misalignment, undoubtedly a primary factor, and can be accentuated by dimensional instability, and heat transfer anomalies related to bond quality.

Under present reactor operating conditions the use of projections to provide reasonable assurance against the fuel elements being in contact with the process tube effectively eliminates this type of rupture. From the over-all plant experience of the past eighteen months, it is clear that bumper fuel is markedly less susceptible to side-hot spot failures; none have been incurred in more than twenty bumper lots that have sustained ruptures.

In non-bumper fuel, the frequency with which hot spots are observed on unfailed elements is high, normally ranging between 5 and 25 per cent of the elements examined. Thus, for non-bumper fuel, there is a reasonable chance that a rupture unrelated, in fact, to the hot spot mechanisms can be classified as a side-hot spot failure.

In normal production non-bumper fuel the side-other classification is truly a "catchall" grouping; some indeterminate proportion is probably caused by defective end closures, some failures are caused by inclusions, some by non-uniform jacket corrosion, and some are probably truly hot-spot failures improperly classified.

Four ruptures in bumper fuel elements have been classified as side-other failures. Based on radiometallurgical examination results, two were attributed to corrosion penetration of the jacket and two were caused by mechanical damage. The charges that sustained the corrosion failures were irradiated under conditions grossly different

(16) HW-66830, "PITA-IP-1Z-I, Evaluation of Aluminum Components from Alternate Vendors," R. D. Shimer, September 20, 1960 (1961)

* Appendix A.

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from those experienced by normal production material. These were production test irradiations in new (high R value) process tubes, without water-mixer pieces, and were irradiated to high exposure (960 MWD/T). Jacket penetration due to corrosion was the expected mode of failure under those conditions. The chance of incurring corrosion failures in these charges was an estimated one to two orders of magnitude higher than normal.

Ruptures classified as hole failures are believed to result, in the majority of cases, from water penetration through "defective" end closures; a second mechanism, non-uniform corrosion probably caused failures in two high exposure columns of enriched bumper fuel. Ruptures classified as end failures can result from end closure defects, undetected mechanical damage prior to or during charging, or uranium distortion to name a few possibilities. Few failures of this classification have been metallographically examined; the tendency is to judge the controlling mechanisms to be either end closure oriented or uranium oriented. It is not unusual for individual fuel element lots to incur one rupture classified as a hole failure and a second classified as an end failure, or vice versa, lending some weight to the former hypothesis.

The mechanism(s) producing ruptures classified as cleavage (split) failures are perhaps the least understood of any, at this time. It is not clear whether cleavage actually causes failure, or is primarily an end result. Cracks are known to exist in unirradiated natural and enriched uranium; in dingot uranium they are probably predominantly transversely oriented.⁽¹⁷⁾ Various failure mechanisms that logically can produce the visual appearance of split ruptures can be hypothesized. For example, braze penetration during canning into cracks extending to the core surface might be conducive to stresses that would ultimately cause the cracks to propagate through the jacket during irradiation; a second mechanism(s) involves water entry and corrosion product buildup exerting sufficient force to fail an already weakened fuel element. The presence of the cracks, in the former case, could be said to be definitely controlling the failure rate. In the latter case, the absence of the cracks might preclude the occurrence of a split rupture, but a rupture of some classification would be sustained nonetheless -- a hole failure, for example.

There is reason for suspecting that the SRP "grain-boundary tearing" phenomenon occurs in some HAP0 I&E fuel elements under current operating conditions. Since the voids thus formed would probably be jagged, one can hypothesize the presence of stress risers, probably concentrated near the adiabatic radius of the fuel element, causing cleavage failures. Some aspects of this "grain-boundary tearing" hypothesis, might logically explain behavior patterns observed in cleavage failures in solid fuel elements.

(17) HW-73149, "Status of Alloyed Dingot Program at HAP0," E. A. Weakley, April 1, 1962 (Secret).

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Cleavage failures could be produced simply because some pieces, though sound, are less ductile than others and are incapable of withstanding normal reactor environment. Clearly, a transverse cleavage failure at the end of the fuel element could easily be classified as an end failure.

It is significant to note that the condition of the braze is of potential importance in any or all of the failure mechanisms hypothesized above. Closure integrity is probably a function of the welding and brazing processes. Porous or unbonded areas influence heat dissipation patterns that affect surface temperatures, core temperatures and probably warp; and have little value as secondary corrosion barriers.

Two conclusions follow from the above discussion:

- (1) The correlation between rupture classification and failure mechanism(s), other than for side-hot spot ruptures, is poor.
- (2) Except for side-hot spot ruptures, and some unknown proportion of side-other ruptures, it appears reasonable to postulate that the rupture rates of bumper and non-bumper fuel elements are controlled by essentially identical failure mechanisms.

2. Basic Performance Statistic (q)

The basic data used in analyzing the rupture performance are summarized in Tables I through IV.* Rupture index (ΔRI) is a measure of the severity of service, i.e., reactor rupture producing climate.⁽¹⁸⁾ The statistic q , which is defined simply as the number of ruptures per unit charge in rupture index ($R/\Delta RI$) is a measure of the fuel performance level. Comparison of q 's, under the conditions of this test, is effectively a comparison of intrinsic fuel "qualities" since unmeasured reactor parameters that might affect the rupture rate have been equalized, through charging procedures, for both test and control material.

3. Sequential Test Data (Non-Bumper)

Analyses based on the rupture data accumulated through April, 1962 indicate:

- (1) The ratio of dingot to ingot quality (q_d/q_i) estimated from the over-all non-bumper fuel rupture experience is 2.6:1. The true ratio, with 95% confidence, lies in the interval 1.2:1 to 5.7:1.

(18) HW-65550, "Use of Control Charts for Analysis of Plant Rupture Experience," R. R. Bloomstrand, June 9, 1960 (Secret)

* Appendix A.

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- (2) The level of "quality" (q) within the test (dingot) and within the control (ingot) groups did not change significantly over the testing period. This implies that the ratio q_d/q_i in the non-bumper fuel was constant over the testing period. The observed experience is quite consistent, for example, with the hypothesis that q_d/q_i was constant and equal to two.
- (3) The non-bumper test and control groups exhibited statistically significant differences in the distribution of types of failure. Irrespective of the true disposition of unknown and unclassified failures, the test material incurred a higher proportion of non-side failures than did the control group. However, there was no evidence that the proportion of non-side failures, for either group, was changing during the course of the testing.
- (4) No significant differences in rupture performance, other than those ascribed to "ingot" versus "dingot", were observed between the OIIN and OIIIN products.

4. Comparison of Ingot and Dingot Performance Excluding Side-Hot Spot Failures

If rupture performance, excluding side-hot spot failures, from both the bumper and non-bumper phases of the testing program are compared, the following conclusions are indicated by the data:

- (1) Within the ingot and dingot groups there were no statistically significant differences observed between bumper and non-bumper fuel elements with respect to rupture resistance. This is based on statistically conservative disposition of unknown, unclassified, and side-other failures, i.e., treatment of the above categories so as to amplify, if anything, the possible existence of a difference.
- (2) Based on statistically conservative disposition of unknown, unclassified, and side-other failures (none of the three ingot non-bumper side-other failures were assumed to be truly side-hot spot failures), the rupture resistance of dingot material is probably less -- the difference was significant at the eight per cent level -- than that of ingot material.
- (3) The dingot material is more susceptible to ruptures classified as cleavage (split) failures. There is some question as to how technically meaningful this statement is, because there is no reasonable assurance that the mechanism(s) controlling the various non-side hot spot categories are sufficiently independent of one another to warrant comparing only split rupture performance.

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5. Enlarged Control Group

During the test period only about forty per cent of the total non-bumper OIIN and OIIIN ingot irradiations were used as "controls." The rupture performance of the X-8001 clad ingot "controls" and the "remaining" X-8001 clad material was equivalent in all measurable respects (based on irradiation and rupture data from March, 1960 through April, 1962). A total of twenty-six* ruptures were sustained; ten in the ingot "controls" and sixteen in the "remainder." Based on the rupture index data, the expected rupture distribution would be 9.3 and 15.7, respectively. It is clear from the data of Table IV, that the two ingot groups did not behave differently with respect to distribution of failure types. Comparing dingot performance with this objectively enlarged ingot "control" group yields results consistent with those stated in the preceding section.

6. Additional Comments on Constant Quality Observations

The absence of detectable shifts in "quality" of the ingot material or even in the dingot material for that matter, during the testing period seems to be at variance with the quality improvement trend that has been monitored and evaluated, based on over-all plant rupture experience, for the past two to three years. It should be recalled, that during the latter stages of the ingot-dingot testing program a high proportion of the fuel elements irradiated were clad in "test" components. This "test" material was shown to be less rupture resistant, by a factor of about three, than "normal" material of the same vintage. While the presence of this "poorer" quality material would not bias the comparison between ingot and dingot uranium, it would reduce the observed "quality" levels for both groups and tend to mask "quality" improvements gained through process improvement.

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RRB:vb

*Excludes second failures in multiple failure lots.

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APPENDIX A

COMPARISONS OF INGOT AND DINGOT

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(00) TFC - ($\sqrt{MILS}$)

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FIG. 6
TOTAL BOND COUNT
TIME

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FIGURE 7
SEQUENTIAL TEST
DINGOT NON - BUMPER MATERIAL

TABLE I

RUPTURE HISTORY FOR TEST AND CONTROL MATERIALS

<u>Tube Number</u>	<u>Lot Number</u>	<u>Month & Year</u>		<u>Exposure (MWD/T)</u>	<u>Rupture Classification</u>	<u>Type Uranium</u>
		<u>Canned</u>	<u>Failed</u>			
3563-D	CL-892-D	11/59	3/60	548	Side other	Ingot
1463-D	VL-009-D	11/59	3/60	560	Unclassified	Dingot
1366-D(1)	VL-012-D	3/60	5/60	278	Side hot-spot	Dingot
2665-D	KL-845-D	5/60	7/60	473	Side other	Ingot
1960-D	VL-037-D	5/60	9/60	640	Side hot-spot	Dingot
1559-B	KL-559-D	8/60	12/60	603	Side other	Ingot
1366-D(1)	CL-951-A	10/60	1/61	475	Side hot-spot	Ingot
1686-B	VL-035-D	9/60	2/61	774	Side hot-spot	Dingot
3764-B	KL-587-H	12/60	3/61	517	Unclassified	Ingot
3272-B	ML-005-H	12/60	4/61	623	Side hot-spot	Ingot
0893-D	OL-010-D(2)	9/60	4/61	745	Split	Dingot
1065-B	ML-001-A	12/60	4/61	639	Side hot-spot	Ingot
1989-H	KL-608-A	12/60	4/61	542	Side hot-spot	Ingot
0460-D	OL-010-D(2)	9/60	4/61	760	Hole	Dingot
2370-B	LZ-500-A(2)	2/61	5/61	491	Side hot-spot	Dingot
1959-B	LZ-500-A(2)	2/61	5/61	450	Unclassified	Dingot
2986-DR	UZ-014-A	3/61	6/61	305	Split	Dingot
0967-B	VZ-006-B	3/61	6/61	252	End (male)	Dingot
2264-F	UZ-015-H(2)	4/61	6/61	208	End (female)	Dingot
2485-F	UZ-015-H(2)	4/61	7/61	419	Split	Dingot
1163-D	KZ-064-E	3/61	8/61	795	Hole	Ingot(bumper)
2478-DR	PZ-010-A	3/61	8/61	786	Hole	Dingot
2762-D	KZ-024-B	3/61	10/61	758	Hole	Ingot(bumper)
2377-F	KZ-046-F	8/61	10/61	274	Split	Dingot
2369-F	PZ-019-H	6/61	10/61	337	Split	Dingot
3264-DR	HZ-036-H	7/61	12/61	780	Side hot-spot	Dingot
0867-DR	KZ-083-A	6/61	12/61	750	Side hot-spot	Ingot
2088-B	UZ-057-H	8/61	1/62	208	Split	Dingot
2773-D	HZ-043-E	8/61	1/62	253	Unclassified	Dingot(bumper)
2371-D	VZ-032-D	6/61	1/62	976	Split	Dingot(bumper)
2378-B	UZ-060-B	10/61	3/62	289	End (female)	Dingot
1078-DR	KZ-152-H	10/61	3/62	469	Side hot-spot	Ingot
1372-H	KZ-135-D	10/61	3/62	263	End (male)	Ingot(bumper)
1684-D	HZ-065-0(2)	3/62	4/62	79	Hole	Dingot(bumper)
1064-DR	HZ-068-A	3/62	4/62	121	Hole	Dingot
3879-DR	UZ-082-A(2)	3/62	4/62	221	Unknown	Dingot

(1) Same channel, different process tube.

(2) Multiple failure lot.

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TABLE II
SEVERITY OF SERVICE HISTORY
BY MONTH FOR TEST AND CONTROL MATERIALS

<u>Month and Year</u>	<u>Adjusted Rupture Index⁽¹⁾</u>			
	<u>Non-Bumper</u>		<u>Bumper</u>	
	<u>Test</u>	<u>Control</u>	<u>Test</u>	<u>Control</u>
June 1960	2.64 ⁽²⁾	8.25 ⁽²⁾		
July	1.76	2.04		
Aug	3.28	6.20		
Sep	2.78	4.59		
Oct	2.58	3.94		
Nov	3.21	2.88		
Dec 1960	10.02	9.13		
Jan 1961	6.44	7.07		
Feb	4.47	7.82		
Mar	8.28	7.24		
Apr	13.31	15.21		
May	1.88	8.19	2.36 ⁽³⁾	11.75 ⁽³⁾
Jun	2.70	4.18	3.94	3.75
Jul	3.71	4.33	4.61	2.98
Aug	4.30	6.00	4.90	5.93
Sep	4.47	5.80	2.77	4.51
Oct	3.77	1.34	3.84	4.57
Nov	6.04	3.81	3.88	4.93
Dec 1961	8.60	13.58	6.72	6.14
Jan 1962	2.98	4.96	8.74	4.90
Feb	1.53	2.81	9.32	3.37
Mar	2.72	2.89	4.54	3.30

(1) Adjusted to equivalent values for 34 piece O-III-N columns.

(2) Accumulated through June 1960 since initiation of charging.

(3) Accumulated through May 1961 since initiation of charging.

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TABLE III
SEVERITY OF SERVICE AND RUPTURE HISTORY OF
ALL X-8001 CIAD OIIN AND OIIN INGOT MATERIAL⁽¹⁾

<u>Time Period</u>	<u>Adjusted Rupture Index</u> ⁽²⁾	<u>Number of Ruptures</u> ⁽³⁾
Mar 1960 to June 1960	38.96	4 (1)
Jul 1960 to Sept 1960	47.84	3 (1)
Oct 1960 to Dec 1960	48.92	8 (1)
Jan 1961 to Mar 1961	67.39	5 (2)
Apr 1961 to June 1961	56.73	3 (3)
Jul 1961 to Sept 1961	26.36	0 (0)
Oct 1961 to Dec 1961	33.48	1 (1)
Jan 1962 to Mar 1962	<u>14.60</u>	2 (1)
Total	334.28	

(1) Includes ruptures from lots where uranium identification is unknown.

(2) Adjusted to equivalent values for 34-piece OIIN columns.

(3) Excludes second failures in multiple failure lots. Numbers in parenthesis are "control" ruptures from sequential test.

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TABLE IV
DISTRIBUTION OF RUPTURES BY TYPE OF FAILURE
MARCH, 1960 THROUGH APRIL, 1962

Failure Classification	Non-Bumper Fuel Ruptures*				
	Ingot Material			Dingot Material	
	"Controls"	Remainder	Total		
Side-Hot Spot	6	4	10	5	(5)
Side-Other	3	3	6	0	(0)
Hole	0	0	0	3	(2)
End	0	1	1	3	(3)
Cleavage (Split)	0	1	1	6	(5)
Unknown or Unclassified	<u>1</u>	<u>7</u>	<u>8</u>	<u>3</u>	<u>(2)</u>
Total	10	16	26	20	(17)

Bumper Fuel Ruptures

Ingot Material -	2 Hole failures 1 End failure	Total 3
Dingot Material -	1 Hole failure 1 Split 1 Unclassified	Total 3

* The ingot numbers exclude second failures from multiple failure lots. For dingot, the totals that exclude second failures are in parenthesis.

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APPENDIX B

DIMENSIONAL DATA - INGOT AND DINGOT MATERIAL

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TABLE B-I
DIMENSIONAL DATA - INGOT MATERIAL

Tube Number	Lot Number	Canning Date (HAPO)	Warp		TFC		o-e		ΔOD2		ΔOD3	
			$\bar{x}$	σ^2	$\bar{x}$	σ^2	$\bar{x}$	σ^2	$\bar{x}$	σ^2	$\bar{x}$	σ^2
3874-B	KL-355-D	5510	0.61	--	0.21	--	-1.09	--	-0.50	--	-3.55	--
2176-D	KL-374-D	5517	0.36	--	-0.04	--	-5.84	--	-1.01	--	-4.42	--
3884-B	KL-370-D	5538	0.20	--	-0.28	--	-0.05	--	-0.55	--	-2.57	--
2574-B	KL-391-D	5568	-0.25	--	-0.48	--	1.00	--	-3.67	--	-2.89	--
2671-D	KL-415-D	5579	-0.498	1.167	0.325	0.535	3.38	8.61	5.97	17.32	3.97	2.91
0772-D	KL-407-D	5580	-0.49	--	0.06	--	0.37	--	2.16	--	1.69	--
4074-B	KL-424-D	5588	-0.21	--	-0.90	--	-2.06	--	-5.26	--	-1.77	--
2784-B	KL-433-D	5609	-0.49	--	-0.92	--	-0.15	--	-5.66	--	-2.56	--
2866-B	KL-436-D	5609	-0.87	--	-0.98	--	-1.25	--	-1.48	--	-2.86	--
1164-B	KL-442-D	5637	-0.29	--	-0.64	--	-2.28	--	-3.56	--	-2.17	--
2184-B	KL-443-D	5638	0.080	1.415	-0.367	0.663	-2.91	10.13	-4.67	19.59	-3.08	20.26
2364-D	KL-461-D	5665	0.37	--	0.87	--	4.49	--	6.36	--	3.14	--
4284-DR	KL-472-D	5666	0.40	--	0.73	--	5.11	--	6.04	--	4.05	--
4089-F	KL-473-D	5698	0.32	--	0.13	--	-2.05	--	3.54	--	0.72	--
2260-DR	KL-485-D	5701	0.519	1.240	0.905	0.286	4.21	6.60	5.17	22.31	3.19	12.54
4274-B	KL-484-D	5702	0.15	--	0.13	--	-0.14	--	1.48	--	-0.79	--
1861-DR	KL-481-D	5706	0.376	1.202	0.767	0.484	3.43	9.45	6.06	11.94	2.46	4.06
0865-F	KL-496-D	5721	0.113	0.707	-0.059	0.642	-1.21	30.04	1.73	9.55	-0.07	20.74
1386-F	KL-512-D	5721	0.148	1.226	0.024	0.770	-1.43	13.50	0.34	13.61	-2.28	9.20
3474-B	KL-513-D	5722	-0.012	0.630	0.703	0.289	6.26	12.23	6.42	10.62	6.30	14.73
2277-B	KL-491-D	5728	0.905	1.049	1.258	0.608	5.92	12.49	5.91	16.06	6.41	8.00
2277-B	KL-520-C	5734	0.25	--	0.61	--	4.74	--	3.04	--	4.85	--
2277-B	KL-516-C	5735	-0.09	--	0.42	--	4.56	--	4.68	--	4.78	--
2277-B	KL-527-D	5755	0.10	--	0.26	--	0.27	--	3.17	--	-1.87	--
2277-B	KL-528-C	5758	-0.19	--	0.27	--	0.31	--	4.26	--	2.31	--
2277-B	KL-530-C	5758	0.339	1.177	0.108	0.553	-6.81	6.06	6.01	26.36	3.19	29.93
2277-B	KL-518-D	5762	-0.062	0.977	0.348	0.420	1.85	2.28	4.23	3.62	3.29	4.31
2277-B	KL-556-D	5786	-0.336	1.074	0.219	0.646	0.08	9.04	4.22	26.56	1.24	4.04
2277-B	KL-549-D	5787	-0.45	--	-0.21	--	0.49	--	3.22	--	0.63	--
2277-B	KL-573-D	5810	-0.07	--	-0.30	--	-1.58	--	0.95	--	-1.96	--
2277-B	KL-533-D	5817	-0.435	1.232	-0.356	1.166	-0.82	6.57	1.64	10.72	-2.17	6.09
2277-B	KL-535-D	5818	-0.054	1.418	-0.155	1.143	-0.41	6.84	0.99	16.20	-2.13	11.39
0873-B	KL-559-D	5818	0.049	0.790	0.019	0.413	-1.34	9.09	1.51	18.86	1.35	16.77
0871-B	KL-589-D	5845	-0.33	--	-0.38	--	-1.93	--	1.69	--	-0.45	--
2663-F	KL-595-A	5847	-0.04	--	0.06	--	2.06	--	1.16	--	0.14	--
2673-H	KL-550-H	5848	0.29	--	0.42	--	2.99	--	0.89	--	0.56	--
0668-H	KL-567-A	5848	0.064	0.880	0.411	0.555	3.62	31.57	2.33	32.60	0.60	15.11

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TABLE B-I (Cont'd)

Tube Number	Lot Number	Canning Date (HAPO)	o-e									
			Warp		TFC		ΔOD_1		ΔOD_2		ΔOD_3	
			$\bar{x}$	σ^2	$\bar{x}$	σ^2	$\bar{x}$	σ^2	$\bar{x}$	σ^2	$\bar{x}$	σ^2
2065-F	KL-581-A	5849	-0.427	1.177	-0.375	0.846	-0.96	7.81	1.46	33.98	-3.29	19.41
2263-B	KL-566-A	5852	-0.412	1.128	-0.085	0.585	-0.70	7.15	1.58	11.47	-1.78	8.04
2183-B	KL-604-A	5884	-0.349	1.085	-0.338	0.419	0.19	6.24	2.33	15.94	-0.47	4.13
2687-D	KZ-004-A	5890	-0.284	0.809	0.454	0.932	1.00	56.34	-1.52	73.99	3.48	43.44
1075-H	KL-608-A	5911	-0.664	0.767	-0.400	0.692	1.02	7.39	2.72	12.46	-0.44	3.27
2580-F	KL-584-A	5912	-0.28	--	0.15	--	3.21	--	3.40	--	1.45	--
1067-H	KL-616-H	5919	-0.39	--	-0.26	--	0.34	--	-0.49	--	-1.39	--
3789-H	KL-571-H	5944	-0.56	--	-0.34	--	1.66	--	-0.25	--	-1.99	--
1485-B	KZ-030-A	5980	-0.455	0.783	-0.050	0.330	1.43	7.68	3.95	15.53	0.10	5.73
1487-F	KZ-025-B	5981	-0.432	1.025	0.038	0.788	5.22	19.96	1.07	8.90	1.58	12.51
1880-D	KZ-045-D	5996	-0.573	1.061	0.477	0.794	5.29	19.64	-0.84	31.93	6.27	23.07
1570-DR	KZ-035-DR	6014	-0.471	--	0.175	--	5.76	--	1.81	--	4.12	--
2576-DR	KZ-039-B	6014	-0.22	--	0.18	--	2.55	--	2.10	--	1.37	--
2469-D	KZ-024-B	6016	-0.74	--	-0.26	--	3.79	--	-0.41	--	4.55	--
3364-D	KZ-060-D	6017	-0.140	1.205	0.128	0.575	1.64	7.53	3.82	34.60	0.28	6.75
3084-DR	KZ-061-B	6020	-0.22	--	0.34	--	5.86	--	1.65	--	4.32	--
3465-D	KZ-062-E	6020	-0.425	0.799	0.212	0.471	1.45	12.22	2.52	13.58	-0.80	9.07
1367-DR	KZ-054-A	6021	-0.257	--	0.144	--	2.70	--	1.60	--	1.63	--
1383-DR	KZ-052-B	6022	-0.374	--	0.368	--	5.03	--	3.33	--	4.17	--
1465-DR	LZ-004-A	6023	-0.472	--	0.199	--	2.45	--	3.66	--	16.27	--
2768-F	KZ-043-B	6050	-0.298	0.953	0.569	0.765	1.75	36.18	1.99	13.91	4.78	31.23
2768-B	KZ-058-A	6052	-0.714	1.084	-0.303	0.736	0.30	20.47	1.67	7.47	-2.95	4.77
1464-B	KZ-049-A	6057	-0.479	1.200	-0.307	0.434	-0.77	10.27	1.79	3.76	1.33	4.62
2670-DR	KZ-072-A	6071	-0.178	--	0.053	--	-1.33	--	0.47	--	-1.97	--
1384-B	KZ-075-B	6106	-0.427	0.697	-0.104	0.352	2.77	9.88	2.72	8.36	0.81	6.13

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TABLE B-II
DIMENSIONAL DATA - DINGOT MATERIAL

Tube Number	Lot Number	Canning Date (HAPO)	o-e									
			Warp		TFC		ΔOD_1		ΔOD_2		ΔOD_3	
			$\bar{x}$	σ^2	$\bar{x}$	σ^2	$\bar{x}$	σ^2	$\bar{x}$	σ^2	$\bar{x}$	σ^2
1559-D	VL-009-D	5544	-0.219	1.640	0.408	0.639	0.24	7.52	5.32	21.95	-0.61	3.27
2468-D	VL-012-D	5638	0.145	1.311	0.651	0.372	3.00	5.09	7.52	19.28	4.45	3.37
3570-DR	VL-025-D	5701	0.029	1.367	0.748	0.556	4.71	15.06	7.00	24.57	5.22	21.60
0686-D	VL-030-D	5705	0.261	2.037	1.218	0.671	4.52	10.55	12.91	41.52	6.45	11.61
2683-D	VL-034-D	5723	-0.157	1.066	0.339	0.377	3.13	8.21	5.39	18.92	3.16	4.62
0566-D	VL-037-D	5723	0.248	1.136	0.725	0.896	3.26	11.41	8.65	29.86	5.08	7.16
1074-D	VL-024-D	5727	0.478	1.153	-0.252	1.135	-1.79	14.10	-2.92	21.90	-3.13	33.43
1776-D	VL-038-D	5763	-0.681	0.864	0.582	0.367	6.24	7.12	9.16	23.51	5.84	4.59
1777-D	VL-040-D	5764	-0.837	1.146	0.886	0.261	6.83	14.79	11.60	21.71	6.86	17.86
3583-DR	OL-003-D	5819	-0.241	1.590	0.427	0.737	3.04	14.03	5.39	23.51	3.58	8.39
3061-DR	OL-005-D	5820	-0.003	0.931	0.804	0.316	4.86	14.75	8.90	19.29	4.66	4.99
3772-D	OL-010-D	5821	-0.430	1.062	0.668	0.278	4.61	13.89	9.00	17.25	6.72	7.41
2756-DR	VL-057-A	5853	-0.181	0.966	0.446	0.435	-0.73	10.25	6.41	19.00	0.27	3.90
1263-DR	VL-058-A	5854	-0.242	0.925	0.078	0.350	-0.41	5.65	4.38	10.89	-1.22	5.56
2991-DR	OL-016-A	5855	-0.070	1.405	0.097	0.537	-2.95	21.10	1.72	22.03	-0.86	8.99
1586-DR	VL-056-A	5856	-0.528	1.102	-0.124	0.598	-0.85	10.02	4.82	25.37	-0.40	5.85
1080-D	OL-018-A	5887	-0.272	1.274	-0.174	0.504	-0.51	6.61	1.21	9.09	-2.19	11.00
3664-B	UL-012-A	5888	-0.067	1.190	0.576	0.431	0.90	24.63	4.48	22.61	-2.77	13.95
2387-B	PL-002-A	5911	-0.244	1.182	-0.160	0.317	0.50	6.54	3.29	16.54	-0.75	5.28
3578-F	LZ-500-A	5982	-0.126	1.295	-0.235	0.767	-1.35	5.85	2.06	21.66	-2.49	7.74
3486-D	UZ-011-D	6023	-0.338	1.458	0.514	0.725	3.27	18.26	5.48	29.24	3.72	37.66
1477-DR	PZ-010-A	6024	-0.278	--	0.485	--	6.30	--	3.73	--	4.09	--
3486-F	UZ-014-A	6027	-0.245	0.754	0.551	0.435	4.84	17.16	4.99	9.53	5.25	14.00
2768-D	PZ-012-D	6027	-0.201	1.271	0.289	0.441	-0.38	7.21	5.28	21.47	1.04	7.84
3463-B	VZ-006-B	6055	-0.637	0.780	-0.086	0.534	2.28	6.58	3.37	9.88	-1.76	5.69
1485-B	PZ-015-B	6055	-0.683	0.588	0.112	0.329	5.30	16.96	2.85	10.43	3.28	31.14
2769-B	PZ-018-A	6057	0.198	0.894	0.351	0.717	4.39	21.55	2.59	17.97	2.69	15.81
3566-F	UZ-026-A	6107	0.220	--	0.405	--	2.23	--	-0.19	--	1.07	--
3576-F	UZ-025-A	6107	-0.473	--	0.380	--	5.52	--	3.88	--	5.98	--
1277-F	LZ-504-B	6111	-0.067	1.319	0.208	1.075	3.25	20.37	1.84	13.92	2.95	23.34

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