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April 23, 1958

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TITLE

ANALYSES AND CORRELATIONS OF HAPO RUPTURE
EXPERIENCE WITH NATURAL URANIUM MATERIAL.

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ANALYSIS AND EVALUATION OF RADIO PICTURE EXPERIENCE
WITH NATURAL SCIENCE MATERIAL

G. F. Bloom and
J. J. Reef

April 23, 1958

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RICHLAND, WASHINGTON

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I INTRODUCTION

One of the major factors restricting reactor power levels is the incidence of ruptured slugs. The primary purpose in studying ruptures is to determine how reactor operating variables affect rupture rates. With this knowledge reactor operating conditions may be adjusted or controlled in the manner that will optimize reactor production. In addition, knowledge of rupture rate relationships are useful in fuel element development and in overall economic studies of existing and proposed reactors and reactor processes.

This report is a compendium of various types of rupture information largely developed during the past eighteen months. Plant rupture experience for CY-1957 is reviewed; ruptures are correlated with reactor variables for solid natural uranium material. Data are presented; a comparison between solid and cored natural uranium material rupture rates is made; the basis for current discharging practice of rupture-prone metal lots is discussed.

II SUMMARY

During CY-1957, ruptures were sustained in two hundred charges. One hundred and sixty-five of this total were in eight-inch solid natural uranium 1245 alloy jacketed slugs (normal production material). In CY-1956 the total number of ruptures was one hundred and seventy-six; one hundred and thirty-five were on normal production material. Although rupture incidence was higher in CY-1957 than in CY-1956, the total plant production efficiency loss due to ruptures was at essentially the same level during both years.

Ruptures in solid material fall into two major categories: those resulting primarily from corrosion penetration of the jacket, and those caused by mechanical failure or deformation of the uranium core. Corrosion (or side) rupture rates were found to correlate with exposure, average power, and average outlet temperature. Split rupture rates (split ruptures are caused by core mechanical failure) correlated with exposure, but could not be described using average power and/or outlet water temperature data. It was concluded that the incidence of split ruptures was primarily dependent on short-term or transient power effects, rather than on average power. Preliminary data have indicated that solid slugs may be operated at high powers, even in the beta phase, with tolerable split rupture rates.

The side rupture rate of eight-inch cored natural uranium material was significantly (Note 1) higher (statistically significant) than that of solid material. At the K Reactors, the observed rupture rates for the two types of material differed approximately by a factor of three.

Note 1: Statistical significance, as used in this report, is the five per cent level of significance.

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Rupture experience indicated that some lots of material were more rupture prone than others. Normally, the occurrence of two ruptures in a given lot provides sufficient indication of poor rupture performance to justify discharging the remaining tubes of material.

III DISCUSSION

A. Rupture Experience - CY-1957

This section briefly summarizes some of the most significant items related to the plant's rupture experience in CY-1957. Some comparisons are made with CY-1956 experience. Most of the items discussed herein are covered in more detail in other sections of this report and, where applicable, charts are presented. The data presented are those on record with the Process Analysis Operation.

(Note 2)
During CY-1957 the total number of ruptures was two hundred; this included normal production material, cored, enriched, dingot, and other test material. One hundred and sixty-five were in normal production material, i.e., eight-inch solid natural uranium slugs canned in 1245 alloy aluminum jackets. In CY-1956 the total number of ruptures was one hundred seventy-six; one hundred thirty-five were in normal production material.

Although rupture incidence during CY-1957 was nearly fourteen per cent greater than in CY-1956, the total plant production efficiency loss due to ruptures remained essentially constant: 3.4 per cent in CY-1956 and 3.5 per cent in CY-1957. Examination of Figure 1 shows that significant reductions in average rupture removal time were accomplished at five of the eight reactors. Table I shows that there was a slight reduction in the fraction of stuck rupture charges in CY-1957 when compared with CY-1956 experience.

TABLE I
PERCENTAGE OF STUCK RUPTURES
BY REACTOR - CY-1956 & CY-1957

Reactor	Per Cent Stuck*	
	CY-1956	CY-1957
B	82	76
C	57	35
D	58	43
DR	61	48
F	55	42
H	28	52
KE	25	29
KW	30	0
All Reactors	45	41

* Excludes bee metal ruptures. A non-stuck rupture is discharged with the charging machine with normal forces.

Note 2: The term rupture, as used in this report, is synonymous with rupture charge. A rupture charge is defined as a charge containing one or more ruptured pieces.

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FIGURE - 1
AVERAGE RUPTURE REMOVAL TIME AT THE VARIOUS REACTORS
(All Ruptures)

CY 1956
CY 1957

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The indicated decrease in average production efficiency loss per rupture can be attributed to several factors. Because of the many subtle interrelationship types involved, however, it was difficult to accurately estimate the contribution of individual factors. One of the important factors undoubtedly was improved rupture detection and removal performance. The gamma monitoring rupture detection systems were in use during most of the year at all reactors other than KE and KW. The increased sensitivity of this system compared with the beta monitoring system previously used, permitted earlier detection and discharge of ruptures.

Another significant factor pertains to types of failures, and their time of occurrence. For example, about the rupture in five occurred in "rushes" or "outbreaks", as well as groups of failures occurred nearly simultaneously. These failures were usually related to short periods of overloaded and/or relatively high tube power operation (this subject is more thoroughly discussed in other sections of this report). On the average, rupture removal time for "outbreak" failures was significantly less than for ruptures which occurred singly. This is reflected in Figure 2. The most significant reductions in rupture removal time were for split and unclassified ruptures. These were the types which usually were sustained during an "outbreak".

Limiting the discharge to solid natural uranium material, (See Figure 3) the majority of the ruptures in CY-1956 were corrosion induced. In CY-1957 there were approximately equal numbers of corrosion (side) failures and core (split) failures. Most of the split type failures were accompanied with rupture "outbreak". Of the corrosion failures, the side hot-spot type was predominant both years. In CY-1956, side hot-spot failures represented about 65 per cent of the total side failures. In CY-1957 this was increased to about 85 per cent, probably because of the higher specific power and outlet water temperatures that were attained. (Ref. p. 12)

The number of Doo metal (uranium-uranium alloy) ruptures in CY-1957 was ten, as opposed to seven in CY-1956. The increase was not significant.

Fourteen ruptures were sustained in enriched uranium material in CY-1957. Five of the ruptures, four solid and one $\frac{1}{2}$ -inch cored, occurred in 0.94 per cent enriched E-metal charges being irradiated, in lieu of Doo metal, to support plutonium requirements. The remaining E-metal ruptures were in charges being irradiated under Production Tests.

Eight ruptures were sustained in the large scale CY-1957 irradiations of $\frac{1}{2}$ -inch cored natural uranium.

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FIGURE - 2
AVERAGE RUPTURE REMOVAL TIME BY TYPE OF FAILURE
(All Ruptures - All Reactors)

CY 1956
CY 1957

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FIGURE - 3
DISTRIBUTION OF RUPTURES BY TYPE OF FAILURE FOR
8 INCH SOLID NATURAL URANIUM MATERIAL

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Sample 2011-01-01-01, dated 11/21/11, by two major categories of those contributing to the study: from respondents' perception of the diet, and from respondents' medical condition. Failure or deformation of the uranium rods.

For the purpose of subdividing into three size fractions. The first size fraction, and that is the most susceptible type, is the side hot-spot failures. Side hot-spot failures are attributed to localized high flag jacket temperatures, "hot spot", resulting accelerated corrosion rates and, finally, restriction of the flag jacket and bond. In the case of 3245 alloy jacketed material, metalurgical examinations of several side hot-spot failures showed the jacket to have been internally cracked. The "hot-spot" is normally fairly opposite from the rib mark, i.e. on top of the flag. The high surface-temperature region is often elliptically shaped and is readily defined by film patterns on the flag. Swelling and blistering of the flag, to a varying degree, is quite common. Presence of the internal sleeve adherent to which oxidation is progressing is probably excluded because the side hot-spot is a surface condition and the side-rib crack condition, the latter being the most prevalent type of corrosion failure.

The two other failure types are stable film failure. The failure probably resulted from a localized corrosion attack on some other unknown material. The exposing of a weld on behalf of the jacket and/or local corrosion of possible exposed film parts in essential jacket areas, resulting in a degradation of the film reflectance or film-other failure, during an approximately six month period in the latter part of 1971 and in 1972 may also have been characterized by the peaks in occurrence at or near the (top or base) end of the plate. Most of the on-board side failures were observed during a period when the danger of corrosion with temperatures and exposure may have existed. The error in the latter end of the base end. The effect would be to increase the probability of exposure penetration at the other end.

The side reduced split-type failures have been non-existent for the past year and one-half. This type of failure apparently resulted from accelerated corrosion at the position of the lug jacket lying between an unadvised gap, the probe, and ribs. This corrosion was attributed to a gap between the probe and ribs from corrosion and wear, which resulted in a water leak, an oxygen flow and abnormally high coolant temperature, and other conditions.

Core failures have been caused by the accelerated cleavage of the uranium slug and the accelerated growth of the uranium. The failures have been classified as split-type. If a failure occurs in the plane along the axis of the slug, the failure is called split-longitudinal. Cores that are broken perpendicular to the axis or are shattered into several pieces are called split-transverse, split-diagonal, or split-compound type failures.

Uranium growth in the probe, caused by slugs failing at the cap end. The cap is completely pushed off. However, because corrosion penetration of the jacket at or near weld end may result in a failure of similar appearance, the mechanism of any particular cap failure cannot be determined without detailed metallurgical examination.

The foregoing descriptions of the data for the classification of rupture failures are of a general nature. The mechanisms causing these failures, and the conditions and variables thereto related, are more adequately covered in the section on rupture rate correlations.

C. Rupture Rate Correlations:

- 1) Data Sources: a) The power, rupture rate, for solid natural uranium material is directly correlated with exposure. The power was also correlated with the rupture rate, but less reliably. b) The following tables present rupture rate correlations for side failures and split failures as functions of average power, average fuel element temperature, and exposure. The results are not related to some extent.

The data for the B, C, D, E, F, G, H, and I Reactor correlations were limited to data obtained subsequent to the latest significant change in water quality, which occurred in the spring of 1956, and continued through November, 1957. March 1, 1956 was selected as the beginning date for the B, D, DR, and H Reactor data. Reactor data were for material charged since

(1) HW-45070, Water Treatment History at Stafford Reactors Through August 20, 1956, RE Richman, August 2, 1956, Secret.

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November 1, 1956. This was done to eliminate anomalous data that might reasonably be related to the F Reactor tube corrosion problem. C Reactor data were for tubes charged subsequent to April 20, 1956. Ruptures that occurred in December, 1957, were included in these analyses but no changes in the overall populations were made. Any errors that would be introduced by this step are insignificant. Ruptures attributed to charging-machine damage were excluded, as were cap-end side failures. The K Reactor rupture rate correlations were based on CY-1957 irradiations of material charged subsequent to September 30, 1956.

The data for the rupture rate correlations were developed using the Process Analysis Operation's Reactor Fuel Data (RFD) program on the 702 Electronic Data Processing Machine.

Many of the other correlations presented, particularly those pertaining to split-type failures, are based on HAPO experience for CY-1955 through CY-1957.

- 2) Side Failures - Using the data from the B, C, D, DR, F and H Reactors, a detailed analysis was performed to determine whether or not average tube power and/or average tube outlet temperature significantly affected the combined side-other and side hot-spot rupture rate. This approach was taken because: (1) the "gray" zone that exists between side hot-spot and side-other failures is not well defined, (2) the data were insufficient for studying the side-other rupture rate, and (3) combination of the data permitted studying the temperature and power effects over the widest possible range. Examination of Figure 4 shows that at the higher tube power levels, most side failures would be of the hot-spot type. In the power and temperature regions of interest, then, the correlations would essentially be describing the side hot-spot rupture rate. The data were broken down into four power and three temperature categories. Because of the differences in tube geometry, the data from the B, D, DR, F, and H Reactors were treated separately from the C Reactor data.

The rupture rates for the various power-temperature categories were estimated⁽²⁾ and were fitted to two models. One model was of the form:

(1) $RR = 1 - \exp(-a_1 E^{1/2} P^{1/2} T^{1/3})$, which in the region of interest, below rupture rates of 0.10 can be expressed approximately as:

(2) $RR = a_2 E^{1/2} P^{1/2} T^{1/3}$ (Model I)

(2) HW-49661, Suggested Method For Estimating Rupture Rates, JL Jaech, 4-15-57, (Secret).

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FIGURE - 4

TYPE OF SIDE FAILURE BY POWER CLASS

□ Side Hot Spot
▨ Side Other

B, C, D, DR, F & H Reactors
[Approximately May, 1956]
[Through December, 1957]

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The second model used in the analysis was of the form:

$$(3) \quad RR = \exp (a_0 / a_1 E^{a_2} P^{a_3} T^{b_3}) \quad (\text{Model II})$$

Where RR = tube rupture rate

E = tube exposure

P = tube power

T = tube outlet temperature

a_0, a_1, a_2, a_3 = constants

b_0, b_1, b_2, b_3 = constants

Both average power and average outlet temperature were found to have a significant effect on the tube rupture rate, but no significant interaction between power and temperature was found. This lack of interaction means that raising tube power by K kw has the same relative effect on tubes operating at different outlet temperatures; or that raising outlet temperature by $K^\circ\text{C}$ has the same relative effect on tubes operating at different powers.

In the two models, the constants a_1, a_2, a_3 and b_1, b_2, b_3 did not differ significantly between the C1 and C2 Reactors. This means that the relative power and temperature effects were essentially independent of which reactor was involved.

The quantified versions of Model I and Model II, are as follows:

$$\text{Model I: C1 Reactor: } RR = 4.3 \times 10^{-43} E^{3.7} P^{3.7}$$

$$\text{C2 Reactor: } RR = 4.1 \times 10^{-42} E^{3.5} P^{3.7}$$

$$\text{Model II: C1 Reactor: } RR = \exp (-27.74 / .0088E + .0040 P + .087T)$$

$$\text{C2 Reactor: } RR = \exp (-27.74 / .0088E + .0040 P + .087T)$$

The differences between the C1 and C2 Reactors are reflected in different values of a_0 and a_1 respectively. The resulting rupture rate curves developed from the data with a high degree of confidence ($> 99.9\%$). Using Model I, the tube rupture rate at C2 Reactor was 7.1 times that of the C1 Reactor; for Model II the difference was a factor of 7.2.

The average standard deviation between the observed rupture rates (Figures 1, 6 and 7) and the calculated values using either model, is about a factor of two. Since rupture data are basically quite varying, there is little to choose between either model from a data fitting standpoint. Either model should adequately describe the effect of tube exposure, or power, or temperature

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FIGURE - 5
SIDE HOT SPOT RUPTURE RATE
B, D, DR, F, H REACTORS

[Approximately - May, 1956]
[Through - December, 1957]

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FIGURE - 6
SIDE HOT-SPOT RUPTURE RATE
C REACTOR

(Approximately June, 1956 Through December, 1957)

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FIGURE - 7
SIDE HOT-SPOT RUPTURE RATE
KE, KW, REACTORS
SOLID & CORED
(CY 1957)

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within the range of immediate interest, i.e. for rupture rates less than 0.10. From Model I, on a relative basis, the side rupture rate for standard length charges doubles for each 15 per cent increase in exposure, for each 23 per cent increase in tube power and for each eight per cent increase in outlet temperature. The corresponding Model II doubling factors were 80 MWD/T, 1.75 kw/tube and 39°C outlet temperature.

Figure 5, 6, and 7 are plots of the side hot-spot rupture rates versus exposure for various power-temperature groups. The difference between the S and old reactors is readily discerned. For example, in the 850 - 950 kw/tube power class with an average outlet temperature of 91°C, the rupture rate at 500 MWD/T at C Reactor was approximately 0.01. At the old reactors the rupture rate in the same power class and at a higher outlet temperature, 102°C, was approximately 0.002 at 500 MWD/T. It is interesting to note that for equivalent maximum specific slug power, outlet temperature and exposure conditions, there was no significant difference between the side hot-spot rupture rates for solid material at the old and K Reactors.

There are many factors that combine to cause side hot-spot ruptures. The ultimate result is to produce areas of non-uniform heat and/or non-uniform coolant distribution where accelerated corrosion rates cause penetration of the jacket and bond. Variations in these factors probably account for the observed differences in apparent rupture performance between the reactors. The factors that affect the side hot-spot rupture rate can be grouped into two broad categories: (1) factors related to reactor environment, and (2) factors inherent in the fuel elements themselves.

The irradiation conditions of power, temperature, and exposure fall into the first category, and their effects were quantified in foregoing paragraphs. Also included in this first category is slug alignment, or more objectively, slug misalignment. Misalignment broadly refers to slug cocking, column bowing, misaligned or twisted process tubes, or other factors that are mechanical in nature. There are several possible causes of slug cocking but these will not be fully discussed herein. One possible cause, recently reported by Mollerus⁽³⁾, is misaligned inlet nozzles. In theory, with a nozzle misaligned so that the ribs of the process tube are higher in elevation than the slug bearing surfaces of the inlet nozzle, the slugs effectively "jump" upward onto the process tube ribs while being charged. This causes cocked slugs. The preliminary laboratory tests have confirmed the

(3) Letter, Effect of Nozzle Misalignment on Cocked Slugs, PJ Mollerus, to Ed Smithers, dated January 3, 1972.

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theory and is in accord with a mechanism in which the increased, the severity of the cracking increases. There have been numerous examples of side hot-spot failures that probably were due to soaked fibers. A recent failure of a wire was attributed to a delamination which began at the end of the wire and spread outwards. It was noted that hot-spot was caused by a crack or misaligned joint in the wire. However, if such a joint were one of the type of joint shown, it would be the same as the one in the wire. The joint would be a joint in the wire and would be a joint in the wire. The joint would be a joint in the wire and would be a joint in the wire.

Comparison of the side hot-spot failure rates, some dimensional stability, and the hot-spot failure rates are examples of the second category of factors that influence side hot-spot rupture rates.

Recent experience has shown that the Alcon wire is susceptible to intergranular attack which is a long known factor in determining rupture performance. The glass experience in late CY-1957 with solid metal wire and components supplied by the Foster-Douglas, an Alcon wire supplier, demonstrated this point. Based on the DR Rupture performance, the side hot-spot rupture rate for the subject material was 10.2 percent per year at 10.3 plus or minus a factor of 0.2 times that of the Alcon component. The irradiation experience at the 10.2 percent per year was in qualitative agreement. One of the differences between the two types of material was in the composition of the aluminum. The Foster-Douglas wire contained a total of 0.3 percent iron. The difference in jacket iron content, though slight, was the apparent cause of the poor rupture performance of this material. Laboratory work by Geddes and Wilson (5) and Dillon (6) have shown that this surface failure to intergranular attack improves as the iron content increases (in the range of 0.2 - 1.5 percent iron).

Further studies of this type are needed to give some indication of the extent to which the Alcon wire is susceptible to intergranular attack. High correlation of this failure mode is sometimes reported, particularly for the solid metal wire. It should be stressed, however, that this failure mode can be demonstrated.

- (1) "The Alcon Wire", Alcon Wire Company, 13 November 1957, and "The Alcon Wire", Alcon Wire Company, 13 November 1957.
- (2) "The Alcon Wire", Alcon Wire Company, 13 November 1957, and "The Alcon Wire", Alcon Wire Company, 13 November 1957.
- (3) "The Alcon Wire", Alcon Wire Company, 13 November 1957, and "The Alcon Wire", Alcon Wire Company, 13 November 1957.
- (4) "The Alcon Wire", Alcon Wire Company, 13 November 1957, and "The Alcon Wire", Alcon Wire Company, 13 November 1957.
- (5) "The Alcon Wire", Alcon Wire Company, 13 November 1957, and "The Alcon Wire", Alcon Wire Company, 13 November 1957.
- (6) "The Alcon Wire", Alcon Wire Company, 13 November 1957, and "The Alcon Wire", Alcon Wire Company, 13 November 1957.

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The occurrence of multiple failures on some lots of material suggest that there may be differences in rupture resistance even between lots that lacked ruptures. The correlations in support of this conclusion, were based on irradiation data and are discussed in another section of this report (Interpreting of Rupture Data).

In summary, the important results of the rupture rate correlations were:

- (1) Average power, average outlet temperature, and exposure significantly affect the rupture rate.
- (2) Some possible causative factors for hot-spot failures, e.g., weld segment and bond quality, are hypothesized, but analyses of irradiation experience have not established the relative significance of these factors.
- 3) Split Failures - Split failure rate correlated with the older reactors show that the split rupture rate increased, in an exponential manner, with exposure. Figures 8 and 9 are plots of the split rupture rate at the old and new reactors. The graphs show that average operating data, specific to average power and average outlet temperature, could not be used to describe split rupture rate. (Note: Inspection of the graphs show that split rupture rate for low power and high power tubes are about the same at low exposure. Further inspection shows that the split rupture rate at reactor was significantly higher than at the older reactors. The approximate ten-fold difference, however, is not due to higher power; average power conditions were not dissimilar.

A correlation with exposure could be expected. Split ruptures are caused by the time, under irradiation, in the sodium core. The failure occurs when the stress in the wire exceeds the ultimate strength. The properties of the wire are known to deteriorate with time; with increasing temperature, yield strength increases, and ductility decreases.

It is of interest to note that the data in Figures 8 and 9 indicate that split rupture rates were not significantly different during the past three years. The number of split failures was divided primarily by change in power and exposure levels.

Because the split rupture rate could not be described using average operating data, attempts were made to correlate splits with short-term effects. For a three year period, 11-1954 through 11-1957, the number of days that the reactors were operated was divided into the

Note 3: Figure 8 and 9 correlate the split rupture rate with exposure. The data in these figures will not alter the conclusion of time of life dependence on average power or temperature.

(C) Reactor and Temperature - The data for 11-1954 through 11-1957, show that the

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FIGURE - 8
SPLIT RUPTURE RATE
B, D, DR, F, H REACTORS
(EXCLUDES OUTBREAKS)

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fraction of operating days which occurred within consecutive twenty-four hour periods after reactor startup. This frequency distribution of opportunity-days-for-rupture is shown in Figure 10. Almost a fifth of the time the reactors were operating was on dry zero, i.e., less than two to four hours after startup. All other things being equal, a fifth of the ruptures could be expected to occur during this period.

Split and side failures were broken down in the same manner and their respective frequency distributions were superimposed on the same chart. It was obvious that the split failure curve differed from the dry-operated curve. Approximately two-thirds of all split failures occurred less than twenty-four hours after startup. (Table 4). From a statistical standpoint, the probability of this distribution occurring to chance alone is virtually nil. In the positive sense, the observed difference between the two distributions was highly significant. The difference between the two distributions remained highly significant even when "outbreak" ruptures were excluded.

This correlation suggested that transient or delta conditions were highly important, because flux distortion, and the resulting variations in slug power, would be expected to be greatest during reactor startups and during the non-equilibrium rise to power.

The plant rupture "outbreak" experience, where split ruptures were preponderant, also suggested a strong interrelationship between split failure rates and transient power effects. In CY-1957 nearly sixty per cent of the confirmed split failures in standard charges of eight-inch solid material were definitely associated with short periods of distorted high-tube-power operation. Large scale rupture "outbreaks" attributed to this cause were experienced at the C, H, and F Reactors. On a smaller scale, some ruptures at B Reactor, and again at C Reactor, were possibly similarly induced. In at least one of the outbreaks (K Reactor in August, 1957) uranium core temperatures exceeded the alpha-beta transformation temperature. This was confirmed by metallographic examination of one of the ruptures. Transformation, however, is not a requisite for split failure and indeed, metallographic examination of two ruptures that were part of the C Reactor outbreak of March, 1957 did not reveal evidence of transformation.

Note 4: For side failures, there is essentially a one-for-one relationship between the respective frequency distributions. The distributions did not differ significantly. This could indicate that side failure rates would correlate with average or long-term reactor conditions.

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FIGURE -10

RUPTURE OCCURENCE COMPARED WITH TIME
AFTER STARTUP - ALL REACTORS 1955, '56, '57

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Two significant factors were common in all of the outbreaks:
 (1) the slugs were subjected to power conditions that, in all probability, were 15 - 20 per cent higher than they had previously experienced; and (2) the outbreaks were successfully quelled by discharging material in the affected reactor areas back to an exposure level of 250 - 300 IWD/T.

If short-term variations in power induced the split failures, the failures would not be expected to be distributed randomly throughout the reactor. Because the variations in front-to-rear flux distribution are most severe in the locations nearest the horizontal control rods, a location preference would be expected.

The data from Table II, show that split type ruptures, at least the longitudinal variety, were distributed non-uniformly through the various lattice units. The largest fraction of split ruptures occurred in the lattice units nearest the horizontal rod banks.

TABLE II

PROXIMITY OF SPLIT TYPE FAILURES
TO HORIZONTAL CONTROL ROD BANKS

ALL REACTORS . JANUARY, 1955 THROUGH MARCH, 1958

<u>Distance From HCR Bank</u> <u>(lattice units)</u>	<u>Number of Failures*</u>	
	<u>Split-Longitudinal</u>	<u>Split-Transverse and/or Split-Compound</u>
1	43 (18)**	5 (5)
2	14 (8)	5 (5)
3	15 (11)	7 (7)
4 or more	12 (5)	1 (1)

* Failures in "Run-To-Rupture" charges or in Doe metal charges were excluded because their locations were biased.

** Totals in parentheses exclude "outbreak" ruptures.

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To test the significance of the distributions of Table II, it was assumed that over a long period of time, the throughput in the various lattice units would be expected to be approximately equal. Furthermore, by carefully considering the axial zones of the reactors, the exposure distributions of the throughput in the various lattice units would also be comparable. On the basis of these assumptions, approximately equal numbers of split types ruptures should have been distributed in the various lattice unit defined locations. The preferred location of the split-longitudinal failures, including those from 'outbreaks', in the first lattice unit from the rod banks was highly significant. The probability of the observed distribution occurring due to chance is extremely small ($< .0001$). Limiting the data to non-outbreak splits, statistically significant preference for the first lattice unit was also observed. The probability of the distribution occurring due to chance was 0.03. In actuality, there probably were departures from the exposure and throughput densities that were assumed. The results of the analysis could not be repudiated, however, unless the assumptions were grossly incorrect.

Split ruptures were broken down into longitudinal and transverse or compound failures. Frequency distributions with exposure were plotted (Figure 11). The plot shows: (1) that there were virtually no splits at very low exposures; (2) that nearly all of the splits at moderate exposures were longitudinal; and (3) almost all transverse or compound splits were at high exposures. Qualitatively, possible explanation of this experience is as follows: The ultimate strength of uranium is reduced by irradiation. Uranium also becomes more brittle as exposure is increased. At low exposures, when the uranium had lost little of its original strength, there were no ruptures. As exposure reached the region where the ultimate strength had been reduced to a critical level but the metal still retained most of its ductility, virtually all of the failures encountered were longitudinal splits. As the time the uranium had become completely brittle, transverse or compound splits began to appear in significant numbers.

During full power, the center of each dried fuel element is subjected to axial compressive stresses and the outer edge of the core is in tension. When the circumferential stress exceeds the strength of the uranium, longitudinal cracks develop along the surface of the cylinder. Shutdown reverses these stresses, placing the surface in compression both axially and circumferentially, and the center of the cylinder in axial tension. Stress exceeding the ultimate strength results in a crack perpendicular or transverse to the axis. Pre-irradiation strength tests have qualitatively confirmed that a large number of slugs probably have failed in transverse or axial produced during rapid shutdowns. Assuming that a pre-irradiation exposure

FIGURE -11
DISTRIBUTION OF SPLIT FAILURES BY EXPOSURE
Includes All Failures - All Reactors - 1955, '56, '57

□ Longitudinal
▨ Transverse and Compound

condition ($< 600 \text{ kW/T}$ for virtually all solid material) that the great majority of split failures were longitudinal, it would appear that the fracture-or-shutdown mechanism was rarely causing ruptures.

Data from HW Reactor have indicated that tolerable split rupture rates can be expected with solid slugs operating in the beta phase, if this is their normal condition. Radiometallurgical examination of the highest power slug from a relatively high power tube of solid natural uranium piece disclosed a total exposure - no rupture was sustained - revealed that the uranium had undergone transformation. Based on limited flux distribution data, it was estimated that of the order of one thousand tubes of solid metal, with one or more slugs operating in the beta phase, have been predicted to go 1 exposure without incident. Although these data must be considered preliminary, they do indicate the possibility, and even the feasibility, of beta phase operation with solid slugs. Current irradiations of solid metal, with specific slug powers approximately two to three times higher than for solid natural uranium slugs, have also provided a reasonable amount of probable beta phase operational experience. Currently, there are two additional high power slugs from HW Reactor awaiting radiometallurgical examination. These examinations will provide additional data for more firmly defining the extent of solid slug beta phase irradiations.

Wood⁽¹¹⁾ has developed a mathematical model that appears to qualitatively predict most of the significant observations about uranium cleavage. It predicts that there should be many slugs with internal transverse cracks, and it also predicts that solid slugs may be operated at high power as long as the rate of rise is kept sufficiently low. Reactor data, particularly those related to some of the rupture outbreaks, are being studied in an effort to better understand the cleavage failure mechanism.

Summarizing, the significant conclusions based on these correlations and observations were:

- (1) The split rupture rate was shown to correlate with exposure.
- (2) The split rupture rate, unlike the side failure rate, could not be described by other average operating data, such as average power and average temperature.
- (3) Short-term or delta power conditions are primary causal factors in producing split ruptures. Longitudinal splits, which are the most common type of split rupture, are more likely to be caused by startup power conditions than by scram or shutdowns.
- (4) The prediction of longitudinal split failure in solid slug is covered by projecting them to power conditions that are somewhat higher than the maximum power experienced during the tube exposure levels. It was noted that about 1000 kW/T . It has been suggested that solid slug may be operated at high powers, even in the beta phase, with tolerable split rupture rates as long as this was their normal condition.

(11) HW-50549, Form For Analysis of Failures, by Wood, 5-22-57, (No. ident. document).

D. Performance Of Cored Natural Uranium Material

During CY-1957, eight ruptures were sustained in the large scale irradiations of 4-inch cored natural uranium 1245-alloy-jacketed slugs. Seven of these failures occurred at KE Reactor; the analyses to follow were limited to this experience. The eighth rupture occurred at H Reactor, as did a ninth rupture in January, 1958. The H Reactor experience did not differ significantly from that at KE Reactor.

The side hot-spot rupture rate for cored material at KE Reactor is shown on Figure 7, as is the side hot-spot rupture rate for solid material for both K Reactors. The number of ruptures was insufficient for quantifying the effects of average power and outlet temperature. A comparison of the observed rupture rates, shows that the cored material had a statistically significantly higher failure rate. The observed difference was approximately three-fold.

All of the KE Reactor cored ruptures occurred during the first six months of CY-1957, when their goal exposure was nominally 600 MWD/T. In irradiations during the last six months, approximately 1200 tubes were discharged at a nominal 500 MWD/T without incident. Only five of the cored failures were visually examined at the reactor. Four of these failures; one initially classed as a side hot-spot failure, one as a cap failure, and two unclassified, were subsequently re-examined in the Radiometallurgy laboratory. These examinations indicated that all of the failures were probably caused by an intergranular corrosion mechanism. Side hot-spot rupture rates were, therefore, the most logical basis for comparing the solid and cored rupture experience.

During the August, 1957 rupture outbreak at KE Reactor there were no ruptures sustained in the cored material. This experience qualitatively demonstrated the relatively improved resistance of the hollow slug design to cleavage failure.

E. Rupture Prone Lots

Rupture experience has indicated that some lots of material were more rupture prone than others, in that they sustain multiple rather than single failures before reaching goal exposure.

In April, 1957, an analysis of single and multiple failure lots for a two year period (CY-1955 and CY-1956) at the older reactors was performed. The data for C Reactor were treated separately from the other reactors. Side failures caused by reduced process tube rib height were excluded. The results of the analysis showed that the exposures at first failure for multiple failure lots were lower, on the average, than the exposure at failure for single failure lots. The difference between the two groups was statistically significant for the B, D, DR, F, and H Reactor data. The C Reactor data alone did not indicate a statistically

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significant difference. The tendency, however, was in the same direction as at the other reactors; the lack of significance was due to the smaller number of ruptures observed.

In view of the basic differences between split and side failures that have since been proven, the data were re-examined to determine if the exclusion of lots which sustained split ruptures would invalidate the original findings. Rupture experience for CY-1957 was combined with that for CY-1955 and CY-1956 in this most recent study. The data were limited to the older reactors because there were no multiple side failure lots at the K Reactors. The results of this study showed that multiple and single failure lots, limited to lots that sustained only side failures, differed with respect to exposure at first failure. The exposure at first failure was lowest for multiple failure lots. The difference in exposure was statistically significant.

The differences between multiple and single failure lots were not sufficient to justify discharging a lot at the initial rupture occurred below a given exposure. The large number of ruptures that occurred subsequent to initial ruptures, however, would give support to such a plan. Referring to CY-1955 and CY-1956 experience, at the B, D, DR, F, and H Reactors, the initial twenty-nine ruptures in multiple failure lots were followed by fifty-four additional ones. This was an average of about three failures per multiple failure lot.

The underlying reasons for the performance variations are not adequately understood. Lot designations are used to describe groups of slugs whose fabrication histories are approximately comparable. Theoretically, this permits consideration of the numerous fabrication variables in analyzing rupture performance. Because material from a given lot is normally charged and irradiated under similar conditions, the occurrence of multiple failures in a lot may be due to either abnormal reactor conditions or possible slug interior ties. The occurrence of two ruptures in a lot is, nonetheless, a good measure of rupture proneness.

These studies provide the justification for the current practice of discharging a lot after two failures have been sustained.

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