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REVISED MODEL TO DESCRIBE SIDE RUPTURE
DATA

AUTHOR

J. L. JAECH

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REVISED MODEL TO DESCRIBE SIDE RUPTURE DATA

Introduction

It has been noted on occasion that the side rupture rate at lower exposures is higher than one would expect in order to be consistent with the mathematical model (Weibull curve) used to describe the rupture data. This has apparently been due to a few ruptures occurring at exposures lower than one would anticipate on the basis of the model.

Restricting ourselves to fuel elements irradiated under similar conditions of power and temperature, it is difficult to assert that these ruptures are anomalous with respect to the model used since there are so few ruptures involved. For this reason, some means of combining data was called for in order to see whether or not at least some of these low exposure ruptures were inconsistent with the model, and, if so, to revise the model in order to better describe side rupture performance.

In this report, the results of an analysis of side failure data for failures covered in a previous report⁽¹⁾ are given. Also included is a discussion of possible implications derived from recognition of the existence of this revised model.

Discussion

For the old reactors, the data used are given below. In the last column, an adjusted exposure is given, where the adjustment was made to a base power of 800 and a base temperature of 90, assuming that the exponents for power, temperature, and exposure are 3.3, 8.7, and 5 respectively. The effect of using an exponent different from 5 to adjust exposures will be discussed later.

(1)

HW-55219 RD, "Effects of Exposure, Power, and Temperature on Rupture Rates," J. L. Jaech 3/4/58.

[redacted]

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TABLE I (Old Reactors)

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<u>T</u>	<u>P</u>	<u>E</u>	<u>Adjusted E</u>	<u>Type</u>	<u>Comments</u>
81	408	348	175 187	side other	Poss. reduced rib
87	400	375	224 225	"	can end
90	545	613	476 476	hot spot	- - - - -
93	539	417	324 340	side other	tube also contained split
94	521	165	133	"	can end (?)
102	504	320	296	not available	Hi carbon
90	573	657	580 587	hot spot	- - - - -
95	562	716	683	side other	- - - - -
95	570	670	636	"	- - - - -
95	556	466	447	"	- - - - -
96	585	526	495	"	- - - - -
99	567	655	636	"	can end
89	576	516	409	"	- - - - -
85	615	138	97	"	Poss. charge damage
94	600	334	279	"	can end
95	600	761	730 691	hot spot	- - - - -
81	623	471	334	cap	(Inadvertently included)
97	619	293	259	side other	can end
97	699	605	652	side other	- - - - -
88	691	269	237	not available	- - - - -
90	698	435	404 390	hot spot	- - - - -
95	655	302	339	side other	can end
99	702	625	652	"	- - - - -
88	722	454	410	hot spot	- - - - -
98	720	505	548	side other	- - - - -
101	717	515	597	"	- - - - -
97	731	446	443	hot spot	- - - - -

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TABLE I continued

<u>T</u>	<u>P</u>	<u>E</u>	<u>Adjusted E</u>	<u>Type</u>	<u>Comment</u>
104	739	542	597	side other	- - - - -
94	743	325	309	hot spot	- - - - -
102	710	524	597	"	- - - - -
94	775	475	494	"	- - - - -
89	774	375	354	"	- - - - -
100	786	416	528	"	- - - - -
100	769	315	404	not available	- - - - -
99	763	226	256	hot spot	incident
97	753	333	370	"	"
98	775	340	370	hot spot	- - - - -
106	773	426	574	side other	- - - - -
84	778	526	447	"	- - - - -
93	809	247	234	hot spot	- - - - -
105	882	497	694	"	- - - - -
104	885	268	370	"	- - - - -
100	851	473	638	"	- - - - -
106	889	340	475	hot spot	- - - - -
103	894	387	504	"	- - - - -
100	880	514	706	"	- - - - -
98	911	511	647	"	- - - - -

Exposures at discharge for the non-rupture tubes were adjusted in a similar manner.
The data are summarized below.

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TABLE II (Old reactors)

<u>Adjusted Exposure</u>	<u>Ruptures</u>	<u>N</u>	<u>L</u>	<u>Instantaneous Rupture Rate</u>	<u>Cumulative</u>
50-100	1	29307	513	.0000344	.0000344
100-150	1	28794	1054	.0000354	.0000698
150-200	1	27740	1678	.0000372	.000107
200-250	3	26062	1606	.0001188	.000226
250-300	4	24455	1996	.0001705	.000396
300-350	4	22458	2111	.000187	.000583
350-400	4	20345	2403	.000209	.000792
400-450	7	17937	3743	.000436	.00123
450-500	4	14189	5069	.000344	.00157
500-550	3	9115	3340	.000404	.00198
550-600	5	5769	3042	.00118	.00315
600-650	4	2725	1360	.00196	.00512
650-700	4	1362	748	.00407	.00919
700-750	2	610	329	.00454	.0137
750-800	0	279	204	- - - - -	.0137

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Now, using the Weibull model, the relationship between cumulative rupture rate and adjusted exposure X is

$$F(X) = 1 - \exp \left(- \frac{X^a}{b} \right)$$

It can be shown that if the instantaneous rupture rate is divided by the probability that a tube did not contain a rupture up to the beginning of the interval [i.e., $1 - F(X)$], the result, which we will call $\rho(X)$ is theoretically equal to

$$\rho(X) = a/b X^{a-1} \text{ dx, under this model.}$$

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This states that the logarithm of $\rho(X)$ should be linearly dependent on the logarithm of the adjusted exposure X , with the slope being $(a-1)$. Thus, by plotting logarithms of $\rho(X)$ vs. logarithm of X , one can check the validity of the Weibull assumption by noting how the plotted points are grouped about a straight line. Further, since the successive points are statistically independent, one can get a good estimate of the parameter a with confidence limits by the usual least squares approach (possibly weighting points).

This was done for the data in table II, and the results are shown in figure (1). It is fairly evident that curvature is indicated by the plotted points, a result inconsistent with the Weibull model. However, if one restricts himself to the last 7 or 8 points, a straight line relationship is indicated. This is explained as being due to the existence of some ruptures occurring at low adjusted exposure which were anomalous as far as this model is concerned. That is, over and above the Weibull rupture curve, there apparently exists another contribution to the over-all rupture rate, this contribution being due to ruptures occurring at lower adjusted exposures, say $< 350 \text{ MWD/T}$ for tubes operating at $P = 800$, $T = 90$.

If that section of the curve consisting of the last 8 points is fitted with a straight line, it turns out that the estimate of the parameter a is 5.9 with a standard deviation associated with the estimate of 0.7. Clearly, this does not represent a significant departure from the presently accepted value of 5.

In back extrapolating this curve, one can determine how many of the lower exposure ruptures are inconsistent with this model. It turns out that for those exposure classes below 350, one would expect 3.6 ruptures based on the experience beyond 350. Fourteen ruptures were observed, which indicates that 10-11 of these were anomalous. If we summarize the data from table I as is done below, the explanation for these ruptures is apparently obvious.

TABLE III (old reactors)

	< 350	> 350
hot spots	3	19
side other	8	13
cap	1	0
not available	2	1
with comments	10	2
	(1 hot spot 8 side other 1 not available)	(1 hot spot, 1 side other)

Observe that there were 8 side other failures at lower exposures, all of which had comments associated with them. By throwing out these 8 failures, plus the cap failure and the one not available failure having a comment, the residual data are described very well by the Weibull model. Note that these residual data are essentially all hot spots plus those side other failures that occurred at exposures beyond 350.

Figure (2) portrays how this revised model explains the over-all rupture data. The combined curve, consisting of the actual observed rupture rate curve is made up of normal ruptures, predictable on the basis of reactor operating data, plus some ruptures

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occurring at lower exposures and labelled "oddballs" for want of a better name. These may be due to either 300 area or 100 area difficulties, such as a batch of fuel elements of unusually low quality, or charging machine damage. Observe that at low exposures, these essentially contribute to all of the ruptures observed, whereas at the higher exposures, they have very little effect on the over-all rupture rate because of the increasing number of ruptures predictably occurring at the more extreme reactor conditions.

A similar analysis was made of C reactor data as given in table IV below:

TABLE IV (C reactor)

<u>T</u>	<u>P</u>	<u>E</u>	<u>Adjusted E</u>	<u>Type</u>	<u>(No comments given)</u>
89	667	121	108	Not available	
88	696	394	324	"	
86	733	295	237	hot spot	
82	797	409	362	"	
78	775	212	171	"	
88	760	281	259	Unclassified	
87	792	402	401	hot spot	
90	801	428	442	"	
86	823	410	401	"	
87	849	350	354	hot spot	
84	813	249	191	Not available	
83	841	342	277	hot spot	
92	835	174	182	"	
88	885	271	270	"	
95	881	206	277	"	
90	887	212	253	"	
91	893	220	253	"	
90	861	440	477	"	
86	890	306	319	"	
95	864	215	277	Not available	
86	883	159	172	hot spot	
82	858	374	345	"	

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TABLE IV Continued

<u>T</u>	<u>P</u>	<u>E</u>	<u>Adjusted E</u>	<u>Type</u>
96	884	503	647	hot spot
91	878	279	309	"
86	858	334	319	"
94	878	391	421	Not available
89	895	410	417	hot spot
93	874	455	533	"
94	854	688	758	"

After adjusting the discharge data to the same base conditions, table V results.

TABLE V (C reactor)

<u>Adjusted Exposure Interval</u>	<u>Rupture</u>	<u>N</u>	<u>L</u>	<u>Instantaneous Rupture Rate</u>	<u>Cumulative</u>
100-150	1	8749	196	.000116	.000116
150	4	8552	462	.000481	.000597
200	1	8086	880	.000131	.000728
250	7	7205	1653	.001097	.00182
300	5	5545	1276	.001019	.00284
350	2	4264	1373	.000559	.00340
400	5	2889	1397	.002282	.00567
450-550	2	1487	1127	.002165	.00782
550-650	1	358	303	.004854	.0126
650-800	1	54	34	.02703	.0393

Again fitting the model $\rho(X) = a/b X^{a-1} dx$, the points in figure (3) were plotted. Although the degree of curvature is not as striking as it was for the old reactors, it is still existent as is seen by fitting the last 5 points corresponding, somewhat arbitrarily, to adjusted exposures beyond 350. When back extrapolating this line,

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all of the first 5 points are above it, indicating that curvature exists.

The estimate of the $\underline{a}$ parameter using these data is $\hat{a} = 4.4$, and the standard deviation associated with this is 1.2. As for the old reactors, this does not represent a significant difference from the accepted value of 5 in current use.

Eighteen ruptures occurred in the C reactor at exposures < 350 . Using the estimate of how many are expected based on data beyond 350, namely, 5.2, this would mean that about 13 of these 18 ruptures were anomalous. Unfortunately, the explanation for this is not as obvious as it was for the old reactors since none of the ruptures had comments associated with them, and further, none of the ruptures were classified as side other. However, it still appears that some of those lower exposure failures called hot spots were anomalous in view of performance at higher exposures.

Note the otherwise good agreement between results from C reactor and the old reactors. In the old reactors, 10.4 of the 14 ruptures occurring before 350 are labelled anomalous under this model. This represents 74% of these "low exposure" failures. At the C reactor, 12.8 out of 18, or 71% are so designated.

In figure (4), the observed rupture rate data for C reactor are shown, together with the curves used to explain the data under this revised model.

Before discussing the possible implications arising from this model, we had better determine how great an effect one of the assumptions entering into this analysis had on the results. Recall that exposures were adjusted originally using the value of 5 for the exposure exponent. Clearly, one would suppose that this might be a critical factor in concluding that the $\underline{a}$ estimates were close to 5, namely, 5.9 and 4.4 respectively. To check on the importance of this assumption, data from the old reactors were also analyzed in which the exposures were first adjusted using $a = 10$ rather than $a = 5$. Fitting only the last 7 points as opposed to the last 8 since the break in the curve appeared to occur there for the $a = 10$ set of data, we find that the estimates of $\underline{a}$ were as follows:

	$\hat{a}$	standard deviation
Assuming $a = 5$	6.4	0.9
Assuming $a = 10$	5.6	0.8

Although the use of a larger value for $\underline{a}$ will tend to affect the final estimate, the degree to which this affects it is not very great. The point is that by choosing $a = 5$ in adjusting the exposure data, one does not automatically force the resulting estimate to be 5. The similarity between the two rupture rate curves is shown in figure (5).

Implications

This model implies that each tube of material normally has associated with it a set of reactor operating conditions under which the probability of incurring a failure is fairly well established. Ignoring for a moment the presence of factors over and above this, this essentially means that when the ruptures do occur in a predictable fashion, there is no more reason to suspect poor quality in one group of material

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than in another. That is, if 100 homogeneous groups of metal (which we hopefully call "lots") were irradiated under reactor conditions which predict that two ruptures will be sustained, the fact that two given lots sustained these ruptures, while the other 98 did not, cannot be considered unusual, and lot quality cannot really be suspect.

On the other hand, there are a number of ruptures that occur at lower adjusted exposures, or less stringent operating conditions, this number being somewhat larger than one would expect. If it is determined that unusual reactor conditions were not causative in a given case (e.g., charging damage, twisted tube, etc.) then there is reason to suspect that the rupture occurred because of unusually poor quality in some respect.

What this essentially means is that any program to eliminate ruptures based on 300 area data, however refined it may be, cannot hope to eliminate them entirely, but only to reduce the number of ruptures occurring at low exposures. Further, any attempts to tie in 300 area data with rupture data must be restricted to "low adjusted exposure" failures. (Multiple failure lots are in general included in this class since experience shows that the first failure usually can be classified a low exposure failure.) Of course, in taking all low adjusted exposure failures, one also includes some consistent with the model. This is a difficulty which cannot be avoided except possibly in retrospect after looking at 300 area data. Since the percentage of these normal failures is not too predominant, the effect of including them should not be so large as to mask any possible 300 area - 100 area tie-in. In order to reduce the number of failures occurring under more stringent operating conditions, it will be necessary to essentially "shift over" the whole curve of fuel element quality, and not hope to cull out potential higher exposure ruptures based on 300 area data.

R. Jaech
J. L. Jaech
OPERATIONS RESEARCH & SYNTHESIS

JLJ:ewk

Figure (1)

"old" Reactors

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ln P

K&E 10X10 TO THE CM. 358-14
KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure (2)

"old" Reactors

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SEMI LOGARITHMIC 358.81
REACTOR RESEARCH
4 Cycles X 10 DIVISIONS

Figure (3)

"C" Reactor

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$\ln P - \ln QX$

KE 10 X 10 TO THE CM. 358-14
KEUFFEL & ESSER CO. MAINTENANCE

figure (4)

"C" Reactor

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SEMILOGARITHMIC 358-81
KODAK SAFETY FILM
4 CYCLES X 20 DIVISIONS

Figure (5)

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• ASSUMES $a=5$

• ASSUMES $a=10$

18881
35881
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1000000
100000
10000
1000
100
10
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