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HANFORD LABORATORIES

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DISTRIBUTION OF TIME BETWEEN UNSCHEDULED OUTAGES

by

J. L. Jaech
R. C. BurkeINTRODUCTION

A study is in progress in which reactor operations will be simulated on the computer, the primary purpose being to evaluate the costs associated with various administrative alternatives which may be followed in conducting the overall operation, in addition to defining how operational costs are affected by such things as changes in fuel quality. The problem is complicated by the fact that the operation of the reactors is largely affected by random occurrences; no one can predict exactly when a tube will leak, or when a rupture will occur. Therefore, basic to the study is a probabilistic function, or set of functions, which govern the random aspects of reactor outages, and which can be used in the simulation study to generate reactor outages.

This report is concerned with the derivation of such probabilistic functions. Although derived specifically for the simulation study, they are deemed of sufficient interest to warrant a separate report. Similar documents will be issued from time to time as the study progresses, and as results are found which are considered worthy of reporting prior to completion of the study.

SUMMARY

Expressions are found for use in the Reactor Simulation Study which govern the occurrence of unscheduled reactor outages. These are as follows:

Old Reactors

- (1) All unscheduled outages:

$$\text{Pr (operating } t \text{ hours without an outage)} = .2e^{-.50t} + .8e^{-.0071t}$$

- (2) Eliminating "quickies" which occur during startup:

$$\text{Pr (operating } t \text{ hours without an outage)} = e^{-.0071t}$$

- (3) Pr (operating an additional H hours/given there have been t hours of operation)

$$= \frac{.2e^{-.50(t+H)} + .8e^{-.0071(t+H)}}{.2e^{-.50t} + .8e^{-.0071t}}$$

$$\approx e^{-.0071H} \quad \text{for } t > 12 \text{ hours}$$

K Reactors

In (1), (2), and (3) replace: .2 by .4, .8 by .6, .50 by .35 and .0071 by .0049.

SOURCE DATA

The data appended as Table I in the form of an electronic data processing listing are based on source data supplied by D. L. DeNeal, Special Production Reports and Statistics, IPD. After review of the source data supplied during the initial phase of the study, considerable effort was expended by Mr. DeNeal to establish new functional outage definitions for use in compiling a comprehensive source file of reactor statistics beginning with January of 1961. This basic file, stored on magnetic tape, contains the date, time, and outage cause for each outage. In addition, beginning with April of 1961, the amount of time allocated to each recovery function performed during an outage is available.

In Table I, "lapse" times, measured from the beginning of a reactor operation up to the beginning of an outage, are given for each reactor, expressed to the nearest tenth of an hour. Those values which are asterisked relate to scheduled outages and are not used in this analysis which is concerned solely with the randomly occurring outages. In the simulation study, scheduled outages will be handled separately.

DERIVATION OF PROBABILISTIC FUNCTIONS

Two previous reports have been issued presenting the probabilities of incurring unscheduled outages. (1), (2). In the first reference, a very simple model was used based on sketchy data, the idea being to indicate the type of result applicable rather than presenting a firm probabilistic function. In reference (2), a complicated model was developed which assumed an increasing potential of incurring an unscheduled outage, due to increased rupture potential, as a function of time since start-up. Parameters of the model were estimated based on data from 144 outages. In both developments, possible differences between reactors were ignored, as were "quickie" outages.

Although the form of the model given in (2) is more appealing in that it ties in with the existing rupture model, it is a complicated model to work with. Therefore, in up-dating the model, an attempt was first made to use a simpler model and test its adequacy before resorting to the more complicated one given in (2). With so much data available (687 unscheduled outages), if a simpler model can be found which agrees with the observed data, it is clear that the use of a more complicated model, at least for use in the simulation study, is not justified.

First, an analysis was made to determine what degree of separation between reactors must be maintained. A chi-square test of the hypothesis that reactors are identical in their outage pattern was rejected. Subsequent tests indicated that reactors 1-6 (the old reactors) were not significantly different from one another in their outage patterns, nor were reactors 7-8 (the K reactors). Therefore, two separate models were derived. The one for the 6 old reactors is based on 565 unscheduled outages, and the K reactor model is based on 132 unscheduled outages. These data are summarized in Table II of the appendix.

- (1) HW-64013, "Distribution of Time Between Unscheduled Outages", J. L. Jaech, 2-23-60, Unclassified.
- (2) HW-65842, "Probabilities of Incurring Unscheduled Outages", J. L. Jaech 6-27-60, Secret.

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By far the simplest model follows when it can be assumed that outage "potential" is constant with time. If this were so, and if the average number of outages per hour were denoted by λ , then

$$\begin{aligned} G(t) &= \text{Probability of surviving } t \text{ hours with no unscheduled outages} \\ &= e^{-\lambda t} \end{aligned}$$

With this model, a plot of $G(t)$ vs. t would be a straight line on semi-log paper. A plot of the data of Table II in this fashion does not yield a straight line, which indicates that this simplest model is inadequate. However, such a plot does consist of a number of straight line segments having different slopes. This would come from an underlying "mixed-exponential" distribution, which is descriptive of the following situation:

p_i = probability that outage occurs due to cause i

λ_i = average number of outages per hour due to cause i

Then

$$G(t) = \sum_{i=1}^k p_i e^{-\lambda_i t}, \quad \text{where} \quad \sum_{i=1}^k p_i = 1$$

There are a fairly large number of reasons why a reactor outage may occur such that, strictly speaking, k would be large. However, the plot of the observed data indicates that some of these outage causes may be combined to give a simpler model. Since simplicity and adequacy are more important for our application than theoretical exactness, we attempt first of all to fit the data for $k = 2$. When this is done by estimating the p_i and the λ_i , the following models are found:

$$\text{Reactors 1 - 6 : } G(t) = .2e^{-.50t} + .8e^{-.0071t}$$

$$\text{Reactors 7 - 8 : } G(t) = .4e^{-.35t} + .6e^{-.0049t}$$

This says that for reactors 1-6, about 20% of the unscheduled outages occur with a λ of .5 (one every two hours), and the remaining 80% with a λ of .0071 (one every 141 hours). The 20% with the λ of .5 are, for the most part, the "quickies" that occur during start-up. For the K reactors, the model says that there are proportionately more outages of this type, there being about 40% with a λ of .35 (one every three hours). The remaining 60% occur with a λ of .0049 (one every 204 hours).

In testing whether these models are adequate, chi-square tests are made as shown in Table III appended. The tests show that the models with $k=2$ do a good job of describing the data. Therefore, in spite of the fact that there are more than two causes why unscheduled outages may occur, the models developed here will be used as the random outage generator in the simulation study. Outage cause in this study can be determined by a simple supplementary random generator which will be used to answer the question, "Given that an unscheduled outage has occurred, what is the cause?".

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In figures (1) and (3), plots are made of the observed $G(t)$ vs t for reactors 1-6 and 7-8 respectively. The fitted curves are drawn in. (Lack of randomness of the points about these curves are no cause for alarm, since these are cumulative plots.) Figures (2) and (4) represent the same curves except that the "high λ " outages, occurring in the initial hours after start-up, are not included. The resulting curves are then of the simplest form:

$$G(t) = e^{-.0071t} \quad \text{for reactors 1 - 6}$$

$$G(t) = e^{-.0049t} \quad \text{for reactors 7 - 8}$$

These data, eliminating the outages occurring during start-up, are the data which were described in references (1) and (2).

CONDITIONAL PROBABILITIES OF OPERATING AN ADDITIONAL H HOURS

From a planning viewpoint, it is of interest to determine the conditional probability of operating an additional H hours given that the reactor has operated t hours without incurring an outage. This probability is represented as follows:

$$\Pr(H/t) = \frac{pe^{-\lambda_1(t+H)} + (1-p)e^{-\lambda_2(t+H)}}{pe^{-\lambda_1 t} + (1-p)e^{-\lambda_2 t}}$$

Since, in our application, λ_1 is large relative to λ_2 , once t exceeds about 12 hours, $e^{-\lambda_1 t}$ (and hence, $e^{-\lambda_1(t+H)}$) is very nearly zero. In this case,

$$\Pr(H/t) = e^{-\lambda_2 H}, \quad \text{which is constant for given } H. \quad \text{This says,}$$

in effect, that once the initial half-day of operation is passed successfully, the probability of operating an additional fixed amount of time is independent of how long the reactor has been operating to date. To some, this is a result that is difficult to accept, the argument being that after operating 20 days, say, we are "due" for an outage very shortly. In actual fact, we are no more "due" after operating 20 days than we are after having operated for only one day. Under the model developed in reference(2), this was not the case, since in this development, the increasing rupture potential with time was a part of the model. However, the extensive outage data now available do not justify using this complex model, and it appears that this increasing rupture potential with operation, while no doubt real, because of increasing "ripeness" of the metal, is not large enough to influence to any great degree the conditional probability of operating an additional H hours.

Since figures (2) and (4) give the plots of $e^{-\lambda_2 t}$ vs. t , it is clear that conditional probabilities, after the initial 12 hours of operation, may be found from the same figures by simply replacing t by H . Thus, for example, from figure (2), the conditional probability of operating one of the old reactors for an additional 4 days (96 hours) is about .50, while the conditional probability of operating an additional 1 day (24 hours) is about .84. These probabilities are independent of how long the reactor had operated, once the initial 12 hours are successfully covered.

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To cover the initial period of operation, figure (5) has been prepared. To illustrate by example, we see that the conditional probability of operating successfully an old reactor for 4 additional hours, given that it has already been operating for 6 hours, is about .96. Note that the probability curves in figure (5) approach asymptotically the values which may be read from figures (2) and (4).

TABLE I - RAW DATA

AGE

REACTOR DR	REACTOR F	REACTOR H	REACTOR KE	REACTOR KW
0.8	220.3	22.8	68.1	393.8
46.5	334.6	2.7	269.9	477.6
3.4	323.1	14.6	*473.9	20.9
99.7	15.3	0.6	1.6	0.5
268.1	146.0	85.4	3.8	12.9
55.2	173.2	148.1	502.9	48.4
711.2	10.4	87.3	2.4	299.1
123.3	86.3	15.9	56.6	1.0
315.9	212.1	44.4	92.9	*436.4
25.7	417.6	131.0	0.7	154.1
61.3	6.6	336.5	24.5	103.5
174.4	234.4	59.9	32.4	15.6
212.5	17.3	1.5	0.7	*514.9
2.6	73.3	0.3	307.7	3.3
97.7	342.8	54.2	1.8	322.8
273.7	371.9	268.7	0.3	*386.0
208.5	189.2	124.7	186.3	13.6
162.5	68.5	7.9	133.2	224.6
13.3	67.4	392.8	323.1	41.6
51.1	174.6	2.4	6.4	*706.1
403.7	66.8	169.7	332.9	168.9
69.1	2.5	2.6	5.7	4.5
81.3	12.0	147.5	220.7	556.2
5.9	105.8	2.9	275.2	*700.5
115.3	1.0	3.5	*570.2	5.1
248.3	10.1	*129.0	262.9	*466.9
80.5	538.8	1.6	148.0	*412.3
174.8	230.5	205.3	*484.8	0.4
144.2	130.5	0.1	41.8	*642.1
*86.6	14.6	16.9	308.2	2.0
173.9	62.9	232.0	130.9	51.5
0.9	2.0	28.6	*482.3	285.3
140.9	110.9	122.1	1.0	1.1
99.1	*121.7	192.0	226.4	0.2
61.3	375.3	16.3	*468.7	1.1
41.3	60.9	187.9	247.9	0.7
93.7	12.7	375.1	208.3	1.0
0.5	374.2	0.9	268.8	67.5
72.4	28.6	2.7	27.6	*379.3
0.9	106.3	1.1	542.8	5.7
26.8	1.5	14.4	0.6	179.2
0.8	4.6	155.7	483.7	357.3
36.9	105.0	325.2	4.1	55.9
388.7	1.0	26.6	*333.4	472.3

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24.1	526.2	12.2	13.2	168.3
273.8	139.8	61.7	82.0	296.4
270.4	446.8	*99.9	4.2	1.3
*26.9	*37.9	0.3	469.2	*517.3
48.6	2.7	1.4	1.4	*397.7
33.8	42.2	0.6	19.1	59.4
424.0	*556.8	*69.6	317.3	6.7
506.7	2.4	36.6	6.7	36.9
185.7	228.7	88.2	41.9	*102.3
55.8	*449.0	188.6	0.7	45.3
20.8	*372.9	182.5	0.1	724.9
57.9	3.4	92.5	1.9	162.9
0.6	218.0	73.4	87.2	293.8
187.4	245.7	92.3	*576.9	8.2
54.0	1.9	156.4	0.4	0.1
0.7	25.1	3.9	1.0	510.3
104.5	65.4	1.0	0.4	5.1
88.2	4.0	11.7	1.9	129.5
116.9	58.2	3.3	0.2	1.9
633.0	280.3	15.5	429.3	311.8
*54.5	*297.1	5.3	*92.4	27.9
7.0	2.5	65.6	9.8	*403.4
1.4	35.2	52.3	6.1	
211.2	3.7	30.6	87.2	
81.6	*326.4	0.9	2.3	
123.5	674.2	102.1	114.0	
0.3	82.8	70.7	*574.6	
64.3	349.0	89.5	119.7	
1.7	118.3	19.0	398.6	
564.7	46.0	113.6	1.7	
11.2	214.7	8.3	5.6	
2.5	153.9	129.8	8.0	
516.0	3.1	45.6	2.9	
93.6	292.3	59.1	750.4	
108.2		37.7	*177.9	
39.2		12.2	85.1	
43.8		57.6	2.6	
57.2		1.1	3.9	
0.8		73.1	23.7	
75.2		79.0	5.7	
83.0		64.1	2.2	
1.8		*23.3	1.0	
29.7		1.7	3.2	
0.4		648.1		
44.6		0.9		
338.5		0.6		
2.4		6.8		
46.7		69.2		
0.5		209.8		
232.8		*36.9		

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1.1	3.3
6.1	66.1
4.3	141.3
144.8	0.1
130.6	37.2
1.8	118.9
10.6	133.7
188.1	210.6
211.2	
* 40.0	

0.7
9.6
1.1
157.4
32.7
293.8
2.7
* 88.3
0.2
20.7
3.3
57.2
0.1
104.6
26.5
169.0
* 119.7
137.5
502.1
61.1
169.3
241.5
206.8
60.5
2.6
33.1
119.9
285.5
507.5
48.5
* 82.2
1.8
96.2
7.8
21.5

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TABLE II - FREQUENCIES OF UNSCHEDULED OUTAGES

t=Time in hours	Reactors 1 - 6		Reactors 7 - 8	
	Freq.	G(t)	Freq.	G(t)
0.0 to 1.0	43	.924	19	.856
1.1 - 2.0	34	.864	11	.773
2.1 - 3.0	23	.823	5	.735
3.1 - 4.0	17	.793	4	.704
4.1 - 5.0	6	.782	3	.682
5.1 - 6.0	7	.770	6	.636
6.1 - 7.0	6	.759	4	.606
7.1 - 8.0	4	.752	1	.598
8.1 - 12.0	20	.717	2	.583
12.1 - 16.0	18	.685	4	.553
16.1 - 20.0	8	.671	1	.545
20.1 - 24.0	8	.657	2	.530
24.1 - 32.0	22	.618	3	.508
32.1 - 40.0	14	.593	2	.492
40.1 - 48.0	16	.565	4	.462
48.1 - 60.0	23	.524	5	.424
60.1 - 72.0	25	.480	2	.409
72.1 - 84.0	24	.437	1	.402
84.1 - 96.0	15	.411	4	.371
96.1 - 108.0	22	.372	1	.364
108.1 - 120.0	21	.335	2	.348
120.1 - 132.0	18	.303	2	.333
132.1 - 144.0	13	.280	1	.326
144.1 - 156.0	13	.257	2	.311
156.1 - 168.0	8	.242	1	.303
168.1 - 180.0	14	.218	4	.273
180.1 - 192.0	17	.188	1	.265
192.1 - 204.0	3	.182	0	.265
204.1 - 216.0	12	.161	1	.258
216.1 - 228.0	3	.156	3	.235
228.1 - 240.0	10	.138	0	.235
240.1 - 264.0	7	.126	2	.220
264.1 - 288.0	12	.104	4	.189
288.1 - 312.0	7	.0920	6	.144
312.1 - 336.0	9	.0761	4	.114
336.1 - 360.0	8	.0619	1	.106
360.1 - 408.0	12	.0407	3	.0833
408.1 - 456.0	5	.0319	1	.0758
456.1 - 504.0	3	.0265	6	.0303
504.1 - 552.0	8	.0124	2	.0152
552.1 - 600.0	1	.0106	1	.00758
600.1 - 648.0	3	.00531	0	.00758
648.1 - 696.0	2	.00177	0	.00758
696.1 - 744.0	1	.00000	1	.00000

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TABLE III - TEST OF MODEL ADEQUACY

Interval		Expected	Reactors 1 - 6: $G(t) = .2e^{-.50t} + .8e^{-.0071t}$			
		Prob.	Exp. #	Obs. #	(Exp. - obs)	(Exp - obs) ² /Exp.
0	- 1.0	.0844	47.7	43	4.7	.46
1.1	- 2.0	.0533	30.1	34	-3.9	.51
2.1	- 3.0	.0346	19.5	23	-3.5	.63
3.1	- 4.0	.0230	13.0	17	-4.0	1.23
4.1	- 6.0	.0281	15.9	13	2.9	.53
6.1	- 8.0	.0171	9.7	10	-0.3	.01
8.1	- 12.0	.0244	13.8	20	-6.2	2.79
12.1	- 16.0	.0210	11.9	18	-6.1	3.13
16.1	- 20.0	.0200	11.3	8	3.3	.96
20.1	- 24.0	.0195	11.0	8	3.0	.89
24.1	- 32.0	.0372	21.0	22	-1.0	.05
32.1	- 40.0	.0352	19.9	14	5.9	1.75
40.1	- 48.0	.0332	18.8	16	2.8	.42
48.1	- 60.0	.0465	26.3	23	3.3	.41
60.1	- 72.0	.0427	24.1	25	-0.9	.00
72.1	- 84.0	.0392	22.1	24	-1.9	.16
84.1	- 96.0	.0360	20.3	15	5.3	1.38
96.1	-108.0	.0330	18.6	22	-3.4	.62
108.1	-120.0	.0303	17.1	21	-3.9	.89
120.1	-132.0	.0279	15.8	18	-2.2	.31
132.1	-144.0	.0256	14.5	13	1.5	.16
144.1	-156.0	.0235	13.3	13	0.3	.01
156.1	-168.0	.0216	12.2	8	4.2	1.45
168.1	-180.0	.0198	11.2	14	-2.8	.70
180.1	-192.0	.0183	10.3	17	-6.7	4.36
192.1	-204.0	.0167	9.4	3	6.4	4.36
204.1	-216.0	.0153	8.6	12	-3.4	1.34
216.1	-228.0	.0141	8.0	3	5.0	3.12
228.1	-240.0	.0130	7.3	10	-2.7	1.00
240.1	-264.0	.0228	12.9	7	5.9	2.70
264.1	-288.0	.0192	10.8	12	-1.2	.13
288.1	-312.0	.0162	9.2	7	2.2	.53
312.1	-336.0	.0137	7.7	9	-1.3	.22
336.1	-360.0	.0115	6.5	8	-1.5	.35
360.1	-408.0	.0179	10.1	12	-1.9	.36
408.1	-504.0	.0219	12.4	8	4.4	1.56
504.1	-600.0	.0110	6.2	9	-2.8	1.27
≥ 600.1		.0113	6.4	6	0.4	.03
Total		1.0000	565	565	0.0	40.79

The observed chi-square value of 40.79 is well below the upper limit which might be expected with 34 degrees of freedom →

The fit is adequate.

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		Reactors 7 - 8				
Interval	Expected Prob.	Exp. #	Obs. #	(Exp. - obs)	(Exp - obs) ² / Exp.	
0 - 1.0	.1211	16.0	19	-3.0	.56	
1.1 - 2.0	.0861	11.4	11	0.4	.02	
2.1 - 4.0	.1058	14.0	9	5.0	1.79	
4.1 - 8.0	.0857	11.3	14	-2.7	.69	
8.1 - 16.0	.0451	6.0	6	0.0	.00	
16.1 - 32.0	.0433	5.7	6	-0.3	.02	
32.1 - 48.0	.0387	5.1	6	-0.9	.16	
48.1 - 72.0	.0526	6.9	7	-0.1	.00	
72.1 - 96.0	.0468	6.2	5	1.2	.23	
96.1 - 144.0	.0785	10.4	6	4.4	1.86	
144.1 - 192.0	.0621	8.2	8	0.2	.00	
192.1 - 240.0	.0491	6.5	4	2.5	.96	
240.1 - 288.0	.0388	5.1	6	-0.9	.16	
288.1 - 360.0	.0435	5.7	11	-5.3	4.92	
360.1 - 456.0	.0385	5.1	4	1.1	.24	
≥ 456.1	.0643	8.5	10	-1.5	.26	
Total	1.0000	132	132	0.0	11.87	

The observed chi-square value of 11.87 is well below the upper limit which might be expected with 12 degrees of freedom →

The fit is adequate.

Reactors 1 - 6

t Hours

Probability
of going t
hours without
an unscheduled
outage.

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DATE

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8 / 1 / 94

END