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THE OCTAVIA COMPUTER CODE: PWR REACTOR PRESSURE VESSEL FAILURE PROBABILITIES DUE TO OPERATIONALLY CAUSED PRESSURE TRANSIENTS

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U. S. Nuclear Regulatory Commission

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729 003

ABSTRACT

The OCTAVIA computer code has been developed to calculate the probability of pressure vessel fail . from operationally caused pressure-transients which can occur in Pressurized Water Reactors. The analysis approach involves calculation of vessel failure pressures using fracture mechanics methods and estimation of pressure-transient characteristics using historical nuclear data. Any of the parameters in the code can be modified for sensitivity analyses. The Surry 1 pressure vessel is analyzed as an example problem to demonstrate the code's capabilities.

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A. CALCULATION TECHNIQUES

1. GENERAL APPROACH

The OCTAVIA computer code has been developed to calculate the probability of pressure vessel failure from operationally caused pressure-transients which can occur in a Pressurized Water Reactor (PWR).[1] A given PWR pressure vessel is first described by inputting the vessel characteristics and operating environment characteristics. For the given vessel and environment, OCTAVIA then computes the failure pressure at which the vessel will fail for different- sized flaws existing in the beltline. Only axially oriented flaws in the vessel beltline are considered.

Having calculated the vessel failure pressure for a given flaw size, the OCTAVIA code then calculates the probability of vessel failure per reactor year due to the flaw. The probability of vessel failure is the product of two factors; the probability that the maximum-sized flaw in the beltline is of the given size, and the probability that the transient will occur and will have a pressure exceeding the vessel failure pressure associated with the flaw size. The probabilities of vessel failure are summed over the various flaw sizes to obtain the total vessel failure probability.

The vessel failure probabilities can be printed or plotted for different fluences and temperatures. The failure pressures for the different flaw sizes can also be output and the relative importance of the flaws can be obtained. The user can override any parameter values used in the code, such as the values for the different flaw size probabilities. Sensitivity studies can also be easily performed to investigate different vessel or operating characteristics in the same computer run.

2. FAILURE PRESSURE CALCULATIONS

The pressure vessel is first described by inputting a set of vessel and operating characteristics. The vessel characteristics include the vessel wall thickness, inside radius, copper content, and phosphorus content. Additional failure characteristics which are input include the residual stress, flaw sizes, the flaw depth-to-length ratio, initial RT_{NDT}, yield strength, ultimate strength, and stable crack growth percentage. An upper limit on the toughness attainable by the vessel material may also be input. The operating characteristics include the fluence and actual temperature.

[1]OCTAVIA is an acronym for Operationally Caused Transients And Vessel Integrity Analysis.

The flaw sizes (flaw depths) considered are $\frac{1}{8}$", $\frac{1}{4}$", $\frac{1}{2}$", 1", 2", and 3"; and failure pressures are computed for flaws of each size existing in the vessel beltline. For a given flaw, the failure pressure is computed using linear-elastic and elastic-plastic methods. The failure pressure calculation can lie in one of four regions depending on the temperature: a linear-elastic regime, a gross yield plateau, an elastic-plastic regime, and the upper shelf plastic instability regime. The failure pressure calculations are essentially those of ORNL-TM-5090 [1] and are further described in Appendix I. In the failure pressure calculations, a best fit curve is used for toughness (K_{Ic}) versus temperature; the basic data for this fit are obtained from the HSST program [2].

At the user's request, the OCTAVIA code will print or plot a two-dimensional table of failure pressure versus temperature and fluence for a given flaw size. Using the change case options in OCTAVIA, the user can also analyze one or more vessels or different vessel characteristics in the same computer run.

3. FAILURE PROBABILITY EVALUATIONS

Having calculated the failure pressure for a given flaw size, the probability evaluation is next performed. First a probability P_S is assigned that the maximum-sized flaw in the vessel is of the given size; only discrete flaw sizes are considered. The probability P_T is then computed that an operational transient will occur, per reactor year, and have a pressure exceeding the failure pressure associated with the flaw. The product of probabilities $P_S \times P_T$ is then the probability per reactor year that the pressure vessel will fail from the particular size flaw. The probabilities for the different flaw sizes are then summed to obtain the total probability of pressure vessel failure from the various flaws which might exist in the vessel.

Based on operational information and discussions with metallurgical personnel, the OCTAVIA code uses the following values of P_S:

Flaw size S (inches)	P_S
$\frac{1}{8}$	.25
$\frac{1}{4}$	.125
$\frac{1}{2}$	.025
1	.0025
2	.00025
3	.000025

Since the flaw size probabilities P_S are discrete, they apply to a range of flaw sizes about the given reference point, i.e., P_S for S = 1" is the probability that a flaw between $\frac{3}{4}$" and 1 $\frac{1}{2}$" exists. The flaw size probability for $\frac{1}{8}$" applies to sizes from approximately 0 to $\frac{3}{16}$" and the flaw size probability for 3" applies to sizes larger than approximately 2 $\frac{1}{2}$". Evaluations have shown that flaw sizes smaller than approximately $\frac{1}{16}$" and larger than approximately 3 $\frac{1}{2}$" make insignificant contributions to the vessel failure probability. The flaw size probabilities P_S apply to vessels at the end of their life (~ 40 yrs) and are conservative for new vessels. If the user feels he has more appropriate values of P_S, he can override the code's values of P_S and input his own values.[2]

The probability P_T that a transient will occur and have a pressure exceeding the failure pressure is computed using the formula

$$P_T = \Lambda \exp\left(-(p_i-800)/P\right)$$

where Λ is the occurrence rate, per reactor year, of pressure-transients having pressures exceeding 800 psi; p_i is the failure pressure for the given flaw size; and P+800 is the average maximum pressure associated with the transient.

The above formula is based on statistical analyses of historical transient data as described in Appendix II. The formula is limited to failure pressures above 800 psi. Based on these statistical analyses, the OCTAVIA code uses values of Λ = 0.080 per year and P = 440 psi for best estimate (median) evaluations. The upper 95% confidence bound for Λ is 0.136 per year and the upper 95% confidence bound for P is 806 psi. These 95% values are used to obtain approximate 95% bounds on the vessel failure probability. The user can override these values of Λ and P and input his own if he so desires; different functions for P_T can also be incorporated into the code if deemed more appropriate.

The formula for P_T is based on recorded transient pressures which range from 800 psi to 3326 psi. When the failure pressure p_i is much larger than 3000 psi, say 4000 psi or greater, there will be large uncertainties in the failure probabilities due to the large extrapolations of pressure involved. Examination of the tables of failure pressures of the contributing flaw sizes is useful in determining the amount of pressure extrapolation involved. The 95% confidence bounds incorporate the extrapolation uncertainties and hence also reflect the "hardness" of the calculated probabilities. High confidence bounds do not necessarily mean that the actual probability is high but only that the evaluation technique is highly uncertain.

The failure probabilities $P_S \times P_T$, summed over the different flaw sizes, are finally printed or plotted as the total vessel failure probability. The individual flaw size contributions are also printed or plotted if desired. The code will terminate the run unless change cases are input, whereupon the code will repeat all the calculations for the different vessel and operating characteristics input.

---

[2]The PS values can also be interpreted as the expected number of maximum-sized flaws of the given size. Because the P_S values are small, expected values and probabilities of one flaw existing are, within the accuracies of the estimates, numerically the same.

B. INPUT DESCRIPTION

1. INTRODUCTION

The input to OCTAVIA consists of data describing the particular vessels and operating environments to be studied and the output options to be exercised. The data are subdivided into cases, several of which may be executed in a single OCTAVIA run.

2. CASES

An OCTAVIA run consists of one or more cases. A case is described by the following data:

- Constants describing the physical characteristics of the pressure vessel.
- Temperatures at which failure pressures are to be computed.
- Fluences at which failure pressures are to be computed.
- Flaw sizes at which failure pressures are to be computed.
- Titles, print, and plot options.

The data input scheme allows a simple method for running multiple cases whereby only those data which differ from the previous case need be entered. The program terminates when no further cases are detected in the input stream.

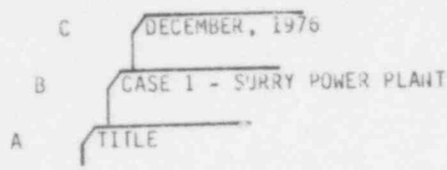
3. DATA GROUPS

Cases are described by 7 sets of data cards which we will call "data groups." Each data group consists of a keyword card which identifies the data group, and 1 or more additional cards. Only the first four characters of the keyword need be entered for proper identification of the data group. The seven data groups are described below.

3.1 Data Group 1: TITLE

This data group specifies the title for the case to be run. It consists of a keyword card beginning with the characters "TITL" followed by 2 cards of text (one or both may be blank) to appear as a header on the printed and/or plotted output for the case.

The TITLE data group is depicted in Table B-1.



CARD TYPE	COLUMNS	PROGRAM VARIABLE	FORMAT	DESCRIPTION
A	1-4	AKEY	A4	Keyword "TITL"
B	1-80	TITLE1	20A4	First title card
C	1-80	TITLE2	20A4	Second title card

TABLE B-1.

Data Group 1 - TITLE

3.2 Data Group 2: CONSTANTS

This data group describes the physical characteristics of the reactor pressure vessel. It consists of a keyword card beginning with the characters "CONS" followed by 2 cards containing the following constants:

- ASP — Flaw depth to length ratio
- TH — Reactor pressure vessel (RPV) wall thickness (inches)
- RI — RPV inside radius (inches)
- RT — Initial RT_{NDT} (F°)
- CU — Percent copper content
- PH — Percent phosphorous content
- SU — Ultimate strength (ksi)
- SCC — Stable crack growth (%/100)
- TUFLIM — An upper limit on the toughness attainable by the vessel (ksi) (leave blank if no limit)

The CONSTANTS data group is depicted in Table B-2.

CARD TYPE	COLUMNS	PROGRAM VARIABLE	FORMAT	DESCRIPTION
A	1-4	AKEY	A4	Keyword "CONS"
B	1-10	ASP	F10.0	Flaw depth to length ratio
	11-20	TH	F10.0	RPV wall thickness (inches)
	21-30	RI	F10.0	RPV inside radius (inches)
	31-40	RT	F10.0	Initial RTNDT (F°)
	41-50	CU	F10.0	% copper content
	51-60	PH	F10.0	% phosphorous content
	61-70	SU	F10.0	Ultimate strength (ksi)
	71-80	SCG	F10.00	Stable crack growth (%100)
C	1-10	TUFLIM	F10.0	Upper limit on the toughness attainable by the vessel (leave blank if no limit)

TABLE B-2.

Data Group 2 - CONSTANTS

3.3 Data Group 3: TEMPERATURES

This data group specifies the temperatures at which failure pressures are to be computed. The TEMPERATURES data group is identified by a keyword card beginning with the characters "TEMP." This card must be followed by a card containing the following data:

- NT The number of temperatures
- TSTART The starting temperature
- TINC The temperature increment
- TMAX The maximum temperature

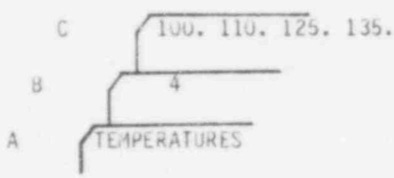
If NT is less than zero, TSTART, TINC, and TMAX are ignored; and the program uses the 95% lower bound, median, and 95% upper bound temperatures. No further temperature cards are required in this case.[3]

[3] The 95% lower bound, median, and 95% upper bound temperatures were computed based on a statistical analysis of recorded operating vessel temperatures. See NRC internal memorandum from James W. Johnson to W. E. Vesely: "The W Test for Normality of the Logarithms of Vessel Temperatures," May 26, 1977.

If NT is zero, the program generates temperatures at increments of TINC beginning at TSTART and ending with the first temperature to equal or exceed TMAX (up to 100 temperatures are allowed). No further temperature cards are required in this case.

If NT is greater than zero, TSTART, TINC, and TMAX are ignored; and the program expects NT temperatures to be input on the succeeding card(s), 16 temperatures per card, up to a maximum of 100 temperatures. All temperatures are in degrees Fahrenheit.

The TEMPERATURES data group is depicted in Table B-3.



CARD TYPE	COLUMNS	PROGRAM VARIABLE	FORMAT	DESCRIPTION
A	1-4	AKEY	A4	Keyword "TEMP"
B	1-5	NT*	I5	Number of temperatures (maximum=100)
	6-10	TSTART	F5.0	Starting temperature
	11-15	TINC	F5.0	Temperature increment
	16-20	TMAX	F5.0	Maximum temperature
C	1-80	T(K)	16F5.0	Temperatures (use as many cards as required when NT > 0)

*If NT = -1, the 95% lower bound, median, and 95% upper bound temperatures are used, and TSTART, TINC, and TMAX are ignored.

If NT = 0, the program generates temperatures at increments of TINC, starting at TSTART, up to TMAX.

If NT > 0, TSTART, TINC, and TMAX are ignored, and NT temperatures (T(K), K = 1 to NT) are read from the Type "C" cards(s).

TABLE B-3

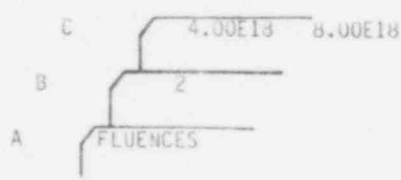
Data Group 3 - TEMPERATURES

3.4 Data Group 4: FLUENCES

This data group specifies the fluences for which failure pressures are to be computed. It is identified by a keyword card beginning with the characters "FLUE." After the keyword card, a card with the number of fluences, NFL, is required. This card may also contain the fluence to reactor age conversion factor AGECON. After the NFL card, the program expects NFL fluences in units of neutrons per centimeter squared (n/cm^2) to be input on the succeeding card(s), 8 fluences per card, up to a maximum of 12 fluences. If a non-zero value is entered for the constant AGECON, fluence is converted to the age of the vessel on all of the output according to the formula:

$$\text{vessel age (years)} = \text{AGECON} * \text{fluence}$$

The FLUENCES data group is depicted in Table B-4.



CARD TYPE	COLUMNS	PROGRAM VARIABLE	FORMAT	DESCRIPTION
A	1-4	AKEY	A4	Keyword "FLUE"
B	1-5	NFL	I5	Number of fluences (maximum = 12)
	6-15	AGECON	F10.0	Fluence to age conversion factor (optional)
C	1-80	FL(J)	8F10.0	Fluences (use 1 or 2 cards as required)

TABLE B-4

Data Group 4 - FLUENCES

3.5 Data Group 5: FLAW SIZES

This data group specifies the flaw sizes for which failure pressures are to be computed. It is identified by a keyword card beginning with the characters "FLAW." After the keyword card, a card with the number of flaw sizes, NA, is required.

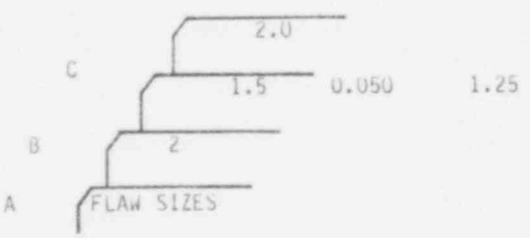
If NA is zero the program uses the following default data:

	FLAW SIZE (INCHES)	FLAW SIZE PROBABILITY	SQUARE ROOT OF THE MODULUS RATIO	RESIDUAL STRESS
I	A(I)	EF(I)	ER(I)	RESID(I)
1	0.125	.25	.116	0.0
2	0.25	.125	.222	0.0
3	0.50	.025	.430	0.0
4	1.00	.0025	.840	0.0
5	2.00	.00025	1.550	0.0
6	3.00	.000025	2.130	0.0

The number of flaw sizes, NA, is set to 6.

If NA is greater than zero, the program expects NA additional cards. Each of these cards must contain a flaw size in inches and corresponding EF, ER, and RESID (flaw size probability, square root of the modulus ratio, and residual stress). If EF and/or ER are left blank and the flaw size is one of the 6 listed above, the program will supply the corresponding EF and/or ER. If no residual stress is input, zero stress is assumed.

The FLAW SIZE data group is depicted in Table B-5.



CARD TYPE	COLUMNS	PROGRAM VARIABLE	FORMAT	DESCRIPTION
A	1-4	AKEY	A4	Keyword "FLAW"
B	1-5	NA	I5	Number of flaw sizes (maximum=8) if NA-0, 6 default flaw sizes are used and no additional cards are needed
C	1-10	A(I)	F10.0	Flaw size
	11-20	EF(I)	F10.0	Flaw size probability
	21-30	ER(I)	F10.0	Square root of th modulus ratio
	31-40	RESID(I)	F10.0	Residual stress (ksi)

Note: If EF(I) and/or ER(I) are left blank on card type C, and A(I) is one of the 6 default flaw sizes (.125, .25, .5, 1.0, 2.0, or 3.0), then the EF(I) and/or ER(I) are set to the default values for the given flaw size.

TABLE B-5

Data Group 5 - FLAW SIZES

729 016

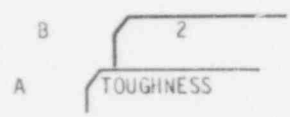
3.6 Data Group 6: TOUGHNESS (Optional)

This data group specifies the toughness function to be used. It is identified by a keyword card beginning with the characters "TOUG." After the keyword card, a card with the toughness function identifier, ITOUGH, is required. The value of ITOUGH specifies the toughness function to be used as indicated in the table below.

ITOUGH	Toughness Function
0	best estimate toughness
1	lower 95% bound on toughness
2	upper 95% bound on toughness

If the TOUGHNESS data group is omitted entirely, the best estimate toughness function is used.

The TOUGHNESS data group is depicted in Table B-6.



CARD TYPE	COLUMNS	PROGRAM VARIABLE	FORMAT	DESCRIPTION
A	1-4	AKEY	A4	Keyword "TOUG"
B	1-5	ITOUGH*	I5	Toughness function identifier

*If ITOUGH = 0, best estimate toughness is used.
If ITOUGH = 1, lower 95% bound on toughness is used.
If ITOUGH = 2, upper 95% bound on toughness is used.

TABLE B-6

Data Group 6 - TOUGHNESS

3.7 Data Group 7: RUN

This data group defines the parameters of the failure probability function(s), Λ exp[-(p-800)/p], selects the output to be printed and/or plotted, and causes the case to be executed. The other 6 data groups must be input (in any order) before the RUN data group. The RUN data group is identified by a keyword card beginning with the characters "RUN." After the keyword card, a card containing the number of output requests NREQ, must be input. The program then expects NREQ cards, each containing the following data:

- FREQ Failure occurrence rate, Λ (per year)
- SCALE Average pressure minus 800, p (psi)
- IOUT Output set type (see Table B-7)

729 017

0 - An output table containing the sum of the failure probabilities over all flaw sizes will be computed.

1 - Output tables containing the failure probabilities for individual flaw sizes will be computed. These failure probabilities include the flaw size probability.

2 - Same as 1 except the flaw size probability is not included.

3 - Output table containing the percent contributions of individual flaw sizes to the sum of probabilities over all flaw sizes will be computed.

4 - Output tables containing the failure pressures for individual flaw sizes will be computed.

5 - An output table showing the shift in RT_{NDT} due to fluence for each flaw size and fluence is computed.

Output Set Type	Number of Tables Computed	Number of Rows in Each Table	Number of Columns in Each Table	Value of Table Entry
0	1	1 per temperature until upper shelf or toughness limit is reached in all columns for all flaw sizes	1 per fluence	Failure probability at a particular temperature and fluence summed over all flaw sizes
1	1 per flaw size	1 per temperature until upper shelf or toughness limit is reached in all columns	1 per fluence	Failure probability for a particular temperature, fluence and flaw size (including flaw probability)
2	1 per flaw size	1 per temperature until upper shelf or toughness limit is reached in all columns	1 per fluence	Failure probability (not including flaw probability) for a particular temperature, fluence, and flaw size
3	1 per flaw size	1 per temperature until upper shelf or toughness limit is reached in all columns	1 per fluence	Percent contribution of a single flaw size to the total failure probability for a particular temperature and fluence
4	1 per flaw size	1 per temperature until upper shelf or toughness is reached in all columns	1 per fluence	Failure pressure for a particular temperature, fluence, and flaw size
5	1	1 per flaw size	1 per fluence	Shift in RTNDT due to fluence

TABLE B-7

Description of Output Tables

729 018

- IPRINT Printed output option

  0 - The tables computed for this output set are printed

  1 - Printed output is suppressed

- IPLOT Graphic output option

  0 - Plots are suppressed

  1 - The columns of the output tables are plotted (one plot per table)

  2 - The rows of the output tables are plotted (one plot per table)

  3 - Both the rows and columns of the output tables are plotted (two plots per table)

  Options 2 and 3 for IPLOT are invalid when a single fluence is run; and plots may not be produced when IOUT=5

- TITLE3 Title describing the failure probability function (optional).

In terms of the mnemonic symobls FREQ and SCALE, the failure probability is computed according to the formula:

$$PROB = FREQ * e^{(-(p-800)/SCALE)}$$

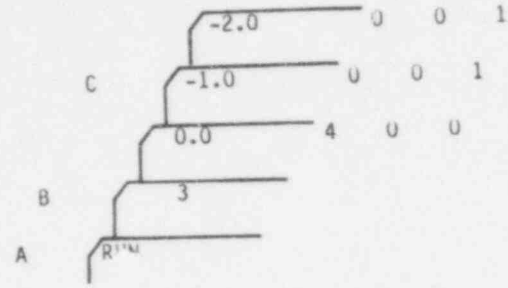
where PROB is the probability of exceeding the failure pressure p. Three "special" values for FREQ have the following meaning:

FREQ = 0.0	Failure pressures only are computed and output.
FREQ =-1.0	The code's best estimate values for FREQ and SCALE are used (FREQ = .08, SCALE = 440).
FREQ =-2.0	The code's 95% upper bound values for FREQ and SCALE are used (FREQ = 1.36, SCALE = 806).

When pressures only (FREQ = 0) are computed, the output set type (IOUT) is always set to 4. When probabilities are computed (FREQ ≠ 0.0), the output set type may be 0, 1, 2, or 3. When the output set type is 5, FREQ and SCALE are ignored.

TITLE3 is automatically set by the program when the special values (0.0, -1.0, or -2.0) are input for FREQ.

The RUN data group is depicted in Table B-8.



CARD TYPE	COLUMNS	PROGRAM VARIABLE	FORMAT	DESCRIPTION
A	1-4	AKEY	A4	Keyword "RUN"
B	1-5	NREQ	I5	Number of output requests
C	1-5	FREQ	F5.0	Frequency (G)
	6-10	SCALE	F5.0	Scale (P)
	11-15	IOUT	I5	Output request type (0, 1, 2, 3, 4, or 5)
	16-20	IPRINT	I5	Print option (0-print, 1-suppress)
	21-25	IPLOT	I5	Plot option (0-no plots, 1-temperature, 2-fluence, 3-both)
	26-80	TITLE3	13A4, A3	

Notes: If FREQ=0, pressures only are computed, SCALE and TITLE3 should be left blank, and IOUT-4.

If FREQ=-1, best estimate parameters are supplied by the program, SCALE and TITLE3 should be left blank, and IOUT=0, 1, 2, or 3.

If FREQ=-2, 95% upper bound parameters are supplied by the program, SCALE and TITLE3 should be left blank, and IOUT=0, 1, 2, or 3.

If IOUT=5, FREQ, SCALE, and IPLOT are ignored.

TABLE B-8

Data Group 7 - RUN

4. CHANGE CASES

All data groups (except RUN) remain in effect until they are changed. To run change cases, simply modify the data by re-inputting the appropriate data groups and follow these modifications by another RUN data group.

C. SAMPLE PROBLEM

This section discusses the use of the OCTAVIA code to run a sample problem. The sample problem involves an example analysis of the Surry 1 pressure vessel.

1 INPUT

The following characteristics will be used to describe the pressure vessel:

- flaw depth-to-length ratio	1/6 (.16667)
- wall thickness (inches)	7.875
- inside radius (inches)	78.5
- initial RT_{NDT} (F°)	9.0
- % copper content	.25
- % phosphorous content	.011
- ultimate strength (ksi)	87.0
- stable crack growth (%/100)	0.2
- upper limit on the toughness attainable by the vessel beltline material	blank (unlimited)

For this problem failure probabilities and fail re pressures are desired for temperatures from 40° to 200° at 10° intervals and for 11 input fluences using the 6 default flaw sizes. A listing of the OCTAVIA input required to run this problem is shown in Figure C-1.

```
TITLE
NUCLEAR REACTOR PRESSURE VESSEL FAILURE PROBABILITY ANALYSIS   -   SAMPLE DATA
OFFICE OF NUCLEAR REGULATORY RESEARCH                                 JAN, 1979
CONSTANTS
.16667    7.875     78.5      9.0       0.25      0.011     87.0      0.2

TEMPERATURE
    0  40.  10. 200.
FLUENCES
   11
       0.0 0.1172E18 0.2344E18 0.4688E18 0.9375E18  1.875E19   3.75E18   7.50E18
   1.50E19   3.00E19   6.00E19
FLAW SIZES
    0
RUN
    5
  0.0          4     0     3
 -1.0          0     0     3
 -1.0          1     0     3
 -2.0          0     0     3
 -2.0          1     0     3
```

Figure C-1

Listing of Input for Sample Run

POOR ORIGINAL

2. PRINTED OUTPUT

The printed output produced by the OCTAVIA program has two parts: a printout of the input data and a printout of output requests from data group RUN.

Figure C-2 shows the first page of output produced by running the sample input. This output echos back the input up to the first RUN card so that the user can check his data. The names of the constants are printed as a checking aid. Also, the default flaw sizes with corresponding detection inefficiencies, square roots of the dulus ratio, and residual stresses are provided when the user inputs NA = 0.

The next page of output, Figure C-3, shows the parameters of the first output request of the RUN data group.

```
CASE 1                    U.S. NUCLEAR REGULATORY COMMISSION  -  THE OCTAVIA CODE       REQUEST 1

                 NUCLEAR REACTOR PRESSURE VESSEL FAILURE PROBABILITY ANALYSIS   -   SAMPLE DATA
                 OFFICE OF NUCLEAR REGULATORY RESEARCH                                JAN, 1978

FREQUENCY    SCALE    OUTPUT   PRINT   PLOT     TITLE
                       SET      OPT     OPT

  0.0         0.0       4        0       3      VESSEL FAILURE PRESSURES (KSI)
```

Figure C-3

Run Data Group - Output Request 1

Since FREQ = 0.0, only the failure pressures are to be computed. Figure C-4 shows one page of the output resulting from this request. It shows the failure pressures for the third flaw size (0.5 in) at each of the input temperatures and fluences. At the bottom, several additional pieces of information are printed for each fluence. They are:

P(GY)	The gross yield pressure.
T(GY-LB)	The temperature at the beginning of the gross yield plateau.
KIC(GY-LB)	The toughness required at the beginning of the gross yield plateau.
T(GY-UB)	The temperature at the end of the gross yield plateau.
KIC(GY-UB)	The toughness required at the end of the gross yield plateau.

CASE 1 U.S. NUCLEAR REGULATORY COMMISSION - THE OCTAVIA CODE

TITLE
NUCLEAR REACTOR PRESSURE VESSEL FAILURE PROBABILITY ANALYSIS - SAMPLE DATA
OFFICE OF NUCLEAR REGULATORY RESEARCH JAN, 1978

CONSTANTS

ASPECT RATIO	THICKNESS (INCHES)	INSIDE RADIUS (INCHES)	INITIAL RTNDT (F)	COPPER (%)	PHOSPHORUS (%)	ULT STRENGTH (KSI)	STABLE CRACK GROWTH (%)	KIC UPPER LIMIT (KSI/SQRT(IN))
0.1667	7.8750	78.5000	9.0000	0.2500	0.0110	87.0000	0.2000	5000.0000

TEMPERATURE

NUMBER OF TEMPS	START TEMP	TEMP INCREMENT	MAX TEMP
17	40.0	10.0	200.0

FLUENCES
11 0.0
0.0 1.17E+17 2.34E+17 4.69E+17 9.38E+17 1.88E+18 3.75E+18 7.50E+18
1.50E+19 3.00E+19 6.00E+19

FLAW SIZES
0

FLAW SIZE	FLAW PROBABILITY	SQRT(MODULUS RATIO)	RESIDUAL STRESS
0.1250	0.250000	0.1160	0.0
0.2500	0.125000	0.2220	0.0
0.5000	0.025000	0.4300	0.0
1.0000	0.002500	0.8400	0.0
2.0000	0.000250	1.5500	0.0
3.0000	0.000025	2.1300	0.0

RUN
5

Figure C-2

Output Listing of OCTAVIA Input

CASE 1 — U.S. NUCLEAR REGULATORY COMMISSION - THE OCTAVIA CODE — REQUEST 1

NUCLEAR REACTOR PRESSURE VESSEL FAILURE PROBABILITY ANALYSIS - SAMPLE DATA
OFFICE OF NUCLEAR REGULATORY RESEARCH — JAN. 1978
VESSEL FAILURE PRESSURES (KSI)

FLAW SIZE (INCHES) = 0.500

TEMP (F)	FLUENCE AT VESSEL ID (N/CM**2) 0.0	1.17E+17	2.34E+17	4.69E+17	9.38E+17	1.88E+18	3.75E+18	7.50E+18	1.50E+19	3.00E+19	6.00E+19
40.0	6.45E+00	6.21E+00	6.21E+00	5.64E+00	4.90E+00	4.20E+00	3.63E+00	3.27E+00	3.10E+00	3.05E+00	3.04E+00
0.0	6.65E+00	6.24E+00	6.21E+00	6.16E+00	5.27E+00	4.43E+00	3.75E+00	3.31E+00	3.11E+00	3.05E+00	3.04E+00
60.0	6.90E+00	6.40E+00	6.25E+00	6.21E+00	5.71E+00	4.71E+00	3.89E+00	3.37E+00	3.12E+00	3.05E+00	3.04E+00
70.0	7.20E+00	6.60E+00	6.41E+00	6.21E+00	6.21E+00	5.03E+00	4.06E+00	3.43E+00	3.1[illegible]E+00	3.06E+00	3.04E+00
80.0	7.55E+00	6.84E+00	6.62E+00	6.36E+00	6.21E+00	5.43E+00	4.26E+00	3.51E+00	3.16E+00	3.06E+00	3.05E+00
90.0	7.97E+00	7.12E+00	6.85E+00	6.55E+00	6.22E+00	5.90E+00	4.50E+00	3.61E+00	3.19E+00	3.07E+00	3.05E+00
100.0	7.99E+00	[illegible]46E+00	7.14E+00	6.78E+00	6.39E+00	[illegible].21E+00	4.79E+00	3.72E+00	3.22E+00	3.07E+00	3.05E+00
110.0	7.99E+00	7.86E+00	7.48E+00	7.05E+00	6.58E+00	6.21E+00	5.14E+00	3.85E+00	3.25E+00	3.08E+00	3.05E+00
120.0	7.99E+00	7.99E+00	7.89E+00	7.37E+00	6.81E+00	6.28E+00	5.55E+00	4.02E+00	3.29E+00	3.09E+00	3.06E+00
130.0	7.99E+00	7.99E+00	7.99E+00	7.76E+00	7.09E+00	6.45E+00	6.05E+00	4.21E+00	3.34E+00	3.10E+00	3.06E+00
140.0	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.42E+00	6.66E+00	6.21E+00	4.44E+00	3.40E+00	3.12E+00	3.07E+00
150.0	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.82E+00	6.91E+00	6.21E+00	4.71E+00	3.48E+00	3.13E+00	3.07E+00
160.0	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.21E+00	6.32E+00	5.04E+00	3.56E+00	3.15E+00	[illegible].08E+00
[illegible].0	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.56E+00	6.51E+00	5.44E+00	3.67E+00	3.17E+00	3.09E+00
180.0	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	6.72E+00	5.91E+00	3.79E+00	3.20E+00	3.10E+00
190.0	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	6.99E+00	6.21E+00	3.94E+00	3.23E+00	3.12E+00
200.0	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.30E+00	6.21E+00	4.12E+00	3.27E+00	3.13E+00
P(GY)	6.21E+00	6.21E+00	6.21E+00	6.21E+00	6.21E+00	6.21E+00	6.21E+00	6.21E+00	6.21E+00	6.21E+00	6.21E+00
T(GY-LB)	6.1	29.6	37.9	51.0	69.6	95.9	133.0	185.6	25[illegible].9	344.7	393.5
KIC(GY-LB)	75.6	75.6	75.6	75.6	75.6	75.6	75.6	75.6	75.6	75.6	75.6
T(GY-UB)	24.5	47.0	56.2	69.4	88.0	114.2	151.4	204.0	278.3	363.0	411.9
KIC(GY-UB)	90.7	90.7	90.7	90.7	90.7	90.7	90.7	90.7	90.7	90.7	90.7
P(US)	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00	7.99E+00
T(US)	90.3	112.8	122.1	135.2	153.8	180.0	217.2	269.8	344.1	428.9	477.7
KIC(US)	212.2	212.2	212.2	212.2	212.2	212.2	21[illegible].2	212.2	212.2	212.2	212.2

Figure C-4

Failure Pressures for Half Flaw

P(US) — The upper shelf plastic instability pressure

T(US) — The temperature at the beginning of the upper shelf plastic instability region.

KIC(US) — The toughness required at the beginning of the upper shelf plastic instability region.

These data are printed only when pressures are printed. The rest of the output request (not shown) consists of a similar page for each of the other 5 flaw sizes. Note that the last temperature printed is 200.0, the value input for TMAX. If the upper shelf pressure or input toughness limit had been reached for all input fluences at a temperature lower than TMAX, say at 180°, the output would have stopped at 180°.

Figure C-5 shows the first page of output for the second request.

```
CASE  1                         U.S. NUCLEAR REGULATORY COMMISSION  -  THE OCTAVIA CODE       REQUEST  2

                     NUCLEAR REACTOR PRESSURE VESSEL FAILURE PROBABILITY ANALYSIS   -   SAMPLE DATA
                     OFFICE OF NUCLEAR REGULATORY RESEARCH                                JAN, 1978

FREQUENCY    SCALE    OUTPUT   PRINT   PLOT    TITLE
                        SET     OPT     OPT

 0.0800      440.0      0        2       3     FAILURE PROBS FOR BEST ESTIMATE OCCURRENCE RATES
```

Figure C-5

Run Data Group - Output Request 2

In this request, FREQ = -1.0, so best estimate parameters were used in computing the probabilities.

Figure C-6 shows the output produced by the second request. Since the output type requested was zero, the probabilities are summed over all the input flaw sizes.

Figure C-7 shows one page of the third output request. FREQ was set to -1.0 as in the second request, but this time the output set type was 1, so the probabilities are printed with each flaw size on a separate page and with the flaw size probability, EF(I), included. The rest of the output (not shown) consists of a similar page for each of the other 5 flaw sizes.

Figures C-8 and C-9 are similar to C-6 and C-7, but they show the 95% bound probabilities.

The printed output ends with the message "END OF OCTAVIA RUN."

3. GRAPHIC OUTPUT

In addition to the printed output, OCTAVIA will produce, if requested, CALCOMP plots of the rows and/or columns of the output tables.

CASE 1 U.S. NUCLEAR REGULATORY COMMISSION - THE OCTAVIA CODE REQUEST 2

NUCLEAR REACTOR PRESSURE VESSEL FAILURE PROBABILITY ANALYSIS - SAMPLE DATA
OFFICE OF NUCLEAR REGULATORY RESEARCH JAN. 1978
FAILURE PROBS FOR BEST ESTIMATE OCCURRENCE RATES
SUMMED OVER ALL INPUT FLAW SIZES

	FLUENCE AT VESSEL ID (N/CM**2)										
TEMP (F)	0.0	1.17E+17	2.34E+17	4.69E+17	9.38E+17	1.88E+18	3.75E+18	7.50E+18	1.50E+19	3.00E+19	6.00E+19
40.0	2.55E-08	1.06E-07	1.91E-07	3.90E-07	1.03E-06	3.09E-06	8.79E-06	1.84E-05	2.68E-05	3.02E-05	3.08E-05
50.0	1.22E-08	5.12E-08	8.98E-08	1.94E-07	5.80E-07	2.01E-06	6.88E-06	1.66E-05	2.60E-05	3.00E-05	3.07E-05
60.0	6.17E-09	2.31E-08	4.33E-08	9.62E-08	3.00E-07	1.24E-06	5.15E-06	1.47E-05	2.51E-05	2.97E-05	3.06E-05
70.0	3.75E-09	1.16E-08	1.99E-08	4.73E-08	1.44E-07	7.10E-07	3.65E-06	1.27E-05	2.40E-05	2.95E-05	3.05E-05
80.0	2.74E-09	6.29E-09	1.04E-08	2.24E-08	7.11E-08	3.72E-07	2.42E-06	1.06E-05	2.29E-05	2.91E-05	3.04E-05
90.0	2.24E-09	3.87E-09	5.91E-09	1.17E-08	3.62E-08	1.80E-07	1.49E-06	8.63E-06	2.15E-05	2.88E-05	3.02E-05
100.0	2.11E-09	2.85E-09	3.72E-09	6.76E-09	1.82E-08	8.62E-08	8.69E-07	6.72E-06	2.00E-05	2.83E-05	3.01E-05
110.0	[illegible]	2.30E-09	2.78E-09	4.24E-09	1.02E-08	4.47E-08	4.70E-07	4.99E-06	1.84E-05	2.78E-05	2.98E-05
120.0	1.99E-09	2.12E-09	2.26E-09	2.98E-09	6.25E-09	2.45E-08	2.32E-07	3.50E-06	1.66E-05	2.72E-05	2.96E-05
130.0	1.98E-09	2.02E-09	2.10E-09	2.37E-09	3.94E-09	1.39E-08	1.08E-07	2.30E-06	1.46E-05	[illegible]	2.93E-05
140.0	1.98E-09	1.98E-09	2.00E-09	2.12E-09	2.83E-09	8.41E-09	[illegible]	1.39E-06	1.26E-05	2.56E-05	2.89E-05
150.0	1.98E-09	1.98E-09	1.98E-09	2.01E-09	2.28E-09	5.42E-09	3.31E-08	7.85E-07	1.06E-05	2.46E-05	2.85E-05
160.0	1.98E-09	1.98E-09	1.98E-09	1.98E-09	[illegible]	3.32E-09	2.02E-08	4.18E-07	8.61E-06	2.36E-05	2.80E-05
170.0	1.98E-09	1.98E-09	1.98E-09	1.98E-09	1.99E-09	2.55E-09	1.23E-08	2.09E-07	6.71E-06	2.23E-05	2.74E-05
180.0	1.98E-09	1.98E-09	1.98E-09	1.98E-09	1.98E-09	2.12E-09	7.73E-09	1.01E-07	4.99E-06	2.09E-05	2.67E-05
190.0	1.98E-09	1.98E-09	1.98E-09	1.98E-09	1.98E-09	2.00E-09	4.73E-09	5.46E-08	3.51E-06	1.94E-05	2.59E-05
200.0	1.98E-09	1.98E-09	1.98E-09	1.98E-09	1.98E-09	1.98E-09	2.98E-09	3.57E-08	2.31E-06	1.77E-05	2.50E-05

Figure C-6

Failure Probabilities for Best Estimate Occurrence Rates Summed Over All Flaw Sizes

CASE 1 U.S. NUCLEAR REGULATORY COMMISSION - THE OCTAVIA CODE REQUEST 3

NUCLEAR REACTOR PRESSURE VESSEL FAILURE PROBABILITY ANALYSIS - SAMPLE DATA
OFFICE OF NUCLEAR REGULATORY RESEARCH JAN. 1978
FAILURE PROBS FOR BEST ESTIMATE OCCURRENCE RATES

FLAW SIZE (INCHES) = 0.500, FLAW PROBABILITY = 0.025000

TEMP (F)	FLUENCE AT VESSEL ID (N/CM**2) 0.0	1.17E+17	2.34E+17	4.69E+17	9.38E+17	1.88E+18	3.75E+18	7.50E+18	1.50E+19	3.00E+19	6.00E+19
40.0	5.31E-09	9.06E-09	9.06E-09	3.31E-08	1.78E-07	8.78E-07	3.19E-06	7.33E-06	1.08E-05	1.21E-05	1.23E-05
50.0	3.35E-09	8.63E-09	9.06E-09	1.03E-08	7.71E-08	5.21E-07	2.44E-06	6.60E-06	1.05E-05	1.20E-05	1.23E-05
60.0	1.90E-09	5.91E-09	8.43E-09	9.06E-09	2.84E-08	2.79E-07	1.77E-06	5.83E-06	1.02E-05	1.19E-05	1.22E-05
70.0	9.69E-10	3.77E-09	5.77E-09	9.06E-09	9.06E-09	1.32E-07	1.21E-06	5.02E-06	9.80E-06	1.18E-05	1.22E-05
80.0	4.34E-10	2.19E-09	3.64E-09	6.50E-09	9.06E-09	5.42E-08	7.64E-07	4.20E-06	9.35E-06	1.17E-05	1.21E-05
90.0	1.67E-10	1.16E-09	2.11E-09	4.25E-09	8.94E-09	1.86E-08	4.42E-07	3.39E-06	8.84E-06	1.16E-05	1.21E-05
100.0	1.60E-10	5.37E-10	1.10E-09	2.52E-09	6.12E-09	9.06E-09	2.29E-07	2.63E-06	8.26E-06	1.14E-05	1.20E-05
110.0	1.60E-10	2.14E-10	5.36E-10	1.37E-09	3.96E-09	9.06E-09	1.04E-07	1.93E-06	7.62E-06	1.12E-05	1.19E-05
120.0	1.60E-10	1.50E-10	1.99E-10	6.56E-10	2.32E-09	7.85E-09	4.08E-08	1.34E-06	6.92E-06	1.10E-05	1.18E-05
130.0	1.60E-10	1.60E-10	1.60E-10	2.70E-10	1.24E-09	5.25E-09	1.33E-08	8.66E-07	6.17E-06	1.07E-05	1.17E-05
140.0	1.60E-10	1.60E-10	1.60E-10	1.60E-10	3.83E-10	3.27E-09	9.06E-09	5.13E-07	5.37E-06	1.04E-05	1.15E-05
150.0	1.60E-10	1.60E-10	1.60E-10	1.60E-10	2.35E-10	1.88E-09	9.06E-09	2.74E-07	4.55E-06	1.00E-05	1.14E-05
160.0	1.60E-10	1.60E-10	1.60E-10	1.60E-10	1.60E-10	9.47E-10	7.06E-09	1.29E-07	3.74E-06	9.57E-06	1.12E-05
170.0	1.60E-10	1.60E-10	1.60E-10	1.60E-10	1.60E-10	4.24E-10	4.67E-09	5.27E-08	2.95E-06	9.09E-06	1.09E-05
180.0	1.60E-10	1.60E-10	1.60E-10	1.60E-10	1.60E-10	1.61E-10	2.84E-09	1.80E-08	2.22E-06	8.55E-06	1.06E-05
190.0	1.60E-10	1.60E-10	1.50E-10	1.60E-10	1.60E-10	1.60E-10	1.55E-09	9.06E-09	1.58E-06	7.94E-06	1.03E-05
200.0	1.60E-10	1.60E-10	1.60E-10	1.60E-10	1.60E-10	1.60E-10	7.65E-10	9.06E-09	1.06E-06	7.26E-06	9.95E-06

Figure C-7

Failure Probabilities for Best Estimate Occurrence Rates for a Half Inch Flaw

729 027

CASE 1 U.S. NUCLEAR REGULATORY COMMISSION - THE OCTAVIA CODE REQUEST 4

NUCLEAR REACTOR PRESSURE VESSEL FAILURE PROBABILITY ANALYSIS - SAMPLE DATA
OFFICE OF NUCLEAR REGULATORY RESEARCH JAN. 1978
FAILURE PROBS FOR 95% UPPER BOUND OCCURRENCE RATES
SUMMED OVER ALL INPUT FLAW SIZES

TEMP (F)	FLUENCE AT VESSEL ID (N/CM**2) 0.0	1.17E+17	2.34E+17	4.69E+17	9.38E+17	1.88E+18	3.75E+18	7.50E+18	1.50E+19	3.00E+19	6.00E+19
40.0	1.37E-05	2.71E-05	3.39E-05	4.92E-05	7.81E-05	1.38E-04	2.67E-04	4.17E-04	5.17E-04	5.52E-04	5.58E-04
50.0	1.10E-05	2.07E-05	2.66E-05	3.67E-05	6.15E-05	1.08E-04	2.32E-04	3.95E-04	5.08E-04	5.50E-04	5.57E-04
60.0	8.70E-06	1.48E-05	2.03E-05	2.88E-05	4.70E-05	8.78E-05	1.97E-04	3.69E-04	4.99E-04	5.47E-04	5.56E-04
70.0	7.37E-06	1.16E-05	1.46E-05	2.24E-05	3.53E-05	7.15E-05	1.62E-04	3.41E-04	4.88E-04	5.44E-04	5.55E-04
80.0	6.82E-06	9.25E-06	1.15E-05	1.64E-05	2.79E-05	5.55E-05	1.29E-04	3.10E-04	4.76E-04	5.41E-04	5.54E-04
90.0	6.42E-06	7.49E-06	9.15E-06	1.23E-05	2.17E-05	4.22E-05	1.00E-04	2.77E-04	4.62E-04	5.36E-04	5.52E-04
100.0	6.34E-06	6.93E-06	7.44E-06	9.87E-06	1.59E-05	3.26E-05	8.17E-05	2.42E-04	4.45E-04	5.31E-04	5.50E-04
110.0	6.28E-06	6.49E-06	6.38E-06	7.92E-06	1.20E-05	2.58E-05	5.62E-05	2.06E-04	4.26E-04	5.26E-04	5.47E-04
120.0	6.27E-06	6.34E-06	6.46E-06	7.03E-06	9.66E-06	1.98E-05	5.13E-05	1.71E-04	4.05E-04	5.18E-04	5.44E-04
130.0	6.26E-06	6.28E-06	6.34E-06	6.57E-06	7.74E-06	1.45E-05	3.90E-05	1.38E-04	3.81E-04	5.10E-04	5.41E-04
140.0	6.26E-06	6.27E-06	6.27E-06	6.35E-06	6.95E-06	1.12E-05	3.09E-05	1.07E-04	3.54E-04	5.02E-04	5.36E-04
150.0	6.26E-06	6.26E-06	6.26E-06	6.28E-06	6.50E-06	9.05E-06	2.47E-05	8.45E-05	3.24E-04	4.92E-04	5.31E-04
160.0	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.33E-06	7.26E-06	1.89E-05	6.83E-05	2.92E-04	4.80E-04	5.26E-04
170.0	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.27E-06	6.75E-06	1.39E-05	5.48E-05	2.58E-04	4.66E-04	5.19E-04
180.0	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.35E-06	1.08E-05	4.22E-05	2.23E-04	4.51E-04	5.10E-04
190.0	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.28E-06	8.65E-06	3.34E-05	1.87E-04	4.33E-04	5.02E-04
200.0	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.26E-06	6.26E-06	7.08E-06	2.72E-05	1.53E-04	4.12E-04	4.92E-04

Figure C-8

Failure Probabilities for 95% Upper Bound Occurrence Rates Summed Over All Flaw Sizes

CASE 1 U.S. NUCLEAR REGULATORY COMMISSION - THE OCTAVIA CODE REQUEST 5

NUCLEAR REACTOR PRESSURE VESSEL FAILURE PROBABILITY ANALYSIS - SAMPLE DATA
OFFICE OF NUCLEAR REGULATORY RESEARCH JAN, 1978
FAILURE PROBS FOR 95% UPPER BOUND OCCURRENCE RATES

FLAW SIZE (INCHES) = 0.500, FLAW PROBABILITY = 0.025000

FLUENCE AT VESSEL ID (N/CM**2)

TEMP (F)	0.0	1.17E+17	2.34E+17	4.69E+17	9.38E+17	1.88E+18	3.75E+18	7.50E+18	1.50E+19	3.00E+19	6.00E+19
40.0	3.07E-06	4.11E-06	4.11E-06	8.34E-06	2.09E-05	4.99E-05	1.01E-04	1.59E-04	1.97E-04	2.09E-04	2.11E-04
50.0	2.39E-06	4.01E-06	4.11E-06	4.41E-06	1.32E-05	3.76E-05	8.73E-05	1.50E-04	1.94E-04	2.08E-04	2.11E-04
60.0	1.75E-06	3.26E-06	3.95E-06	4.11E-06	7.67E-06	2.67E-05	7.33E-05	1.40E-04	1.91E-04	2.08E-04	2.10E-04
70.0	1.21E-06	2.55E-06	3.22E-06	4.11E-06	4.11E-06	1.78E-05	5.35E-05	1.29E-04	1.86E-04	2.07E-04	2.10E-04
80.0	7.83E-07	1.90E-06	2.50E-06	3.43E-06	4.11E-06	1.09E-05	4.63E-05	1.17E-04	1.82E-04	2.05E-04	2.10E-04
90.0	4.64E-07	1.34E-06	1.86E-06	2.72E-06	4.08E-06	6.10E-06	3.43E-05	1.04E-04	1.76E-04	2.04E-04	2.09E-04
100.0	4.54E-07	8.79E-07	1.30E-06	2.05E-06	3.32E-06	4.11E-06	2.40E-05	9.09E-05	1.70E-04	2.02E-04	2.08E-04
110.0	4.54E-07	5.32E-07	8.51E-07	1.46E-06	2.62E-06	4.11E-06	1.56E-05	7.69E-05	1.63E-04	2.00E-04	2.07E-04
120.0	4.54E-07	4.54E-07	5.11E-07	9.81E-07	1.96E-06	3.80E-06	9.36E-06	6.30E-05	1.54E-04	1.98E-04	2.06E-04
130.0	4.54E-07	4.54E-07	4.54E-07	6.05E-07	1.39E-06	3.05E-06	5.07E-06	4.96E-05	1.45E-04	1.95E-04	2.05E-04
140.0	4.54E-07	4.54E-07	4.54E-07	4.54E-07	9.20E-07	2.36E-06	4.11E-06	3.72E-05	1.34E-04	1.92E-04	2.04E-04
150.0	4.54E-07	4.54E-07	4.54E-07	4.54E-07	5.60E-07	1.74E-06	4.11E-06	2.64E-05	1.23E-04	1.88E-04	2.02E-04
160.0	4.54E-07	4.54E-07	4.54E-07	4.54E-07	4.54E-07	1.20E-06	3.59E-06	1.76E-05	1.10E-04	1.84E-04	2.00E-04
170.0	4.54E-07	4.54E-07	4.54E-07	4.54E-07	4.54E-07	7.73E-07	2.86E-06	1.08E-05	9.68E-05	1.79E-04	1.98E-04
180.0	4.54E-07	4.54E-07	4.54E-07	4.54E-07	4.54E-07	4.55E-07	2.18E-06	5.99E-06	8.27E-05	1.73E-04	1.95E-04
190.0	4.54E-07	4.54E-07	4.54E-07	4.54E-07	4.54E-07	4.54E-07	1.57E-06	4.11E-06	6.89E-05	1.66E-04	1.92E-04
200.0	4.54E-07	4.54E-07	4.54E-07	4.54E-07	4.54E-07	4.54E-07	1.57E-06	4.11E-06	5.53E-05	1.58E-04	1.88E-04

<u>Figure C-9</u>

Failure Probabilities for 95% Upper Bound Occurrence Rates for a Half Inch Flaw

In the sample input, notice that in subgroup RUN, IPLOT = 3 in each output request. Therefore, both the rows and columns of the output tables are to be plotted. Figures C-10 and C-11 show the pressure plots for flaw size 0.5 in. Figure C-10 is a pressure vs. temperature plot for the 11 input fluences (i.e., the columns of Figure C-4 have been plotted). Figure C-11 is a pressure vs. fluence plot for a series of temperatures (i.e., selected rows of Figure C-4 have been plotted). Figures C-12 and C-13 are the plots of the columns and rows, respectively, of the output table shown in Figure C-7. Two plots are produced for all the other flaw sizes, and another complete set of plots is produced for the 95% bound tables. Figures C-16 and C-17 correspond to Figure C-8 for the 95% bounds; Figures C-18 and C-19 correspond to the table in Figure C-9.

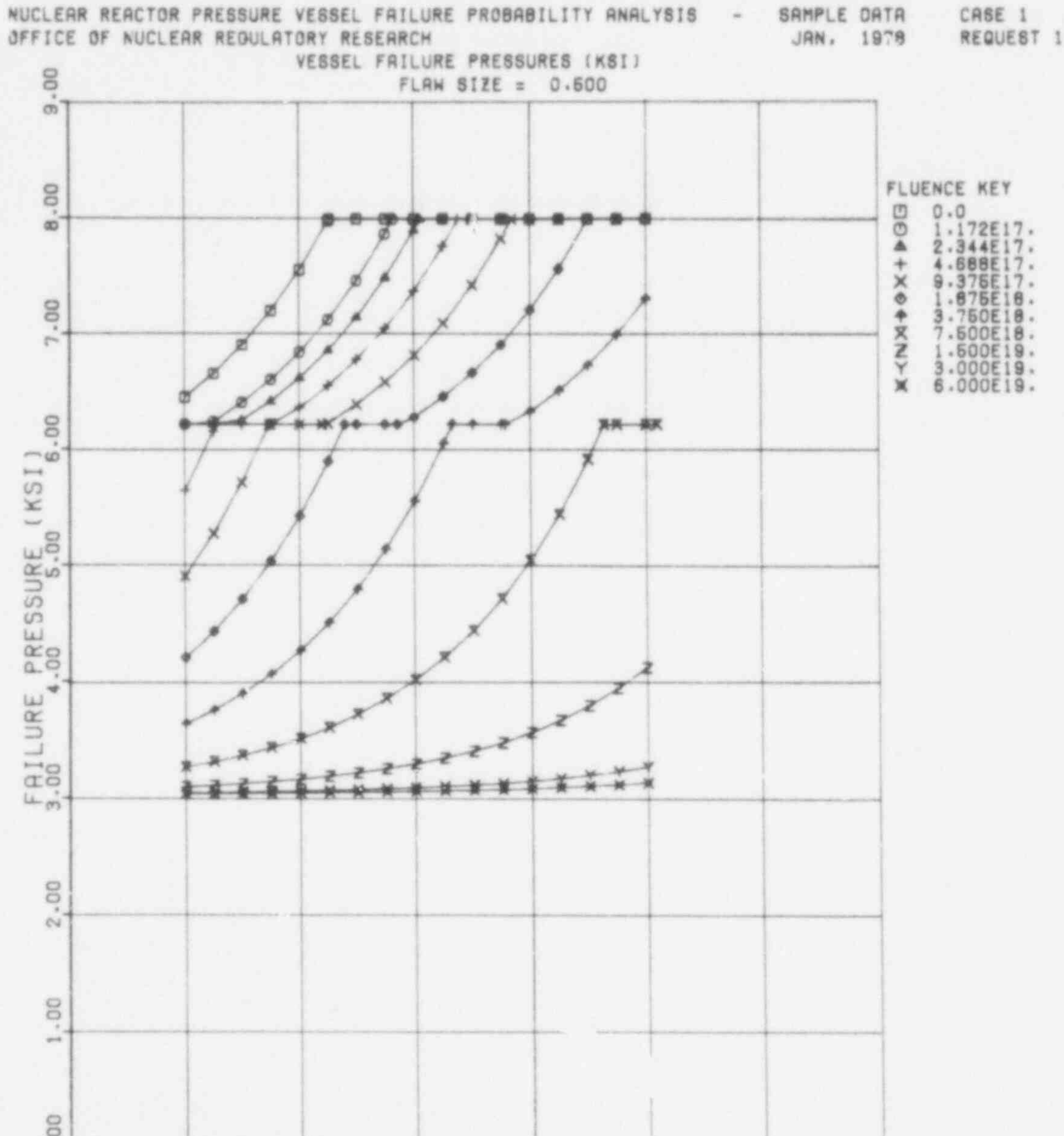


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Figure C-10

Failure Pressure vs. Temperature

NUCLEAR REACTOR PRESSURE VESSEL FAILURE PROBABILITY ANALYSIS   SAMPLE DATA   CASE 1
OFFICE OF NUCLEAR REGULATORY RESEARCH   JAN. 1978   REQUEST 1

VESSEL FAILURE PRESSURES (KSI)
FLAW SIZE = 0.500

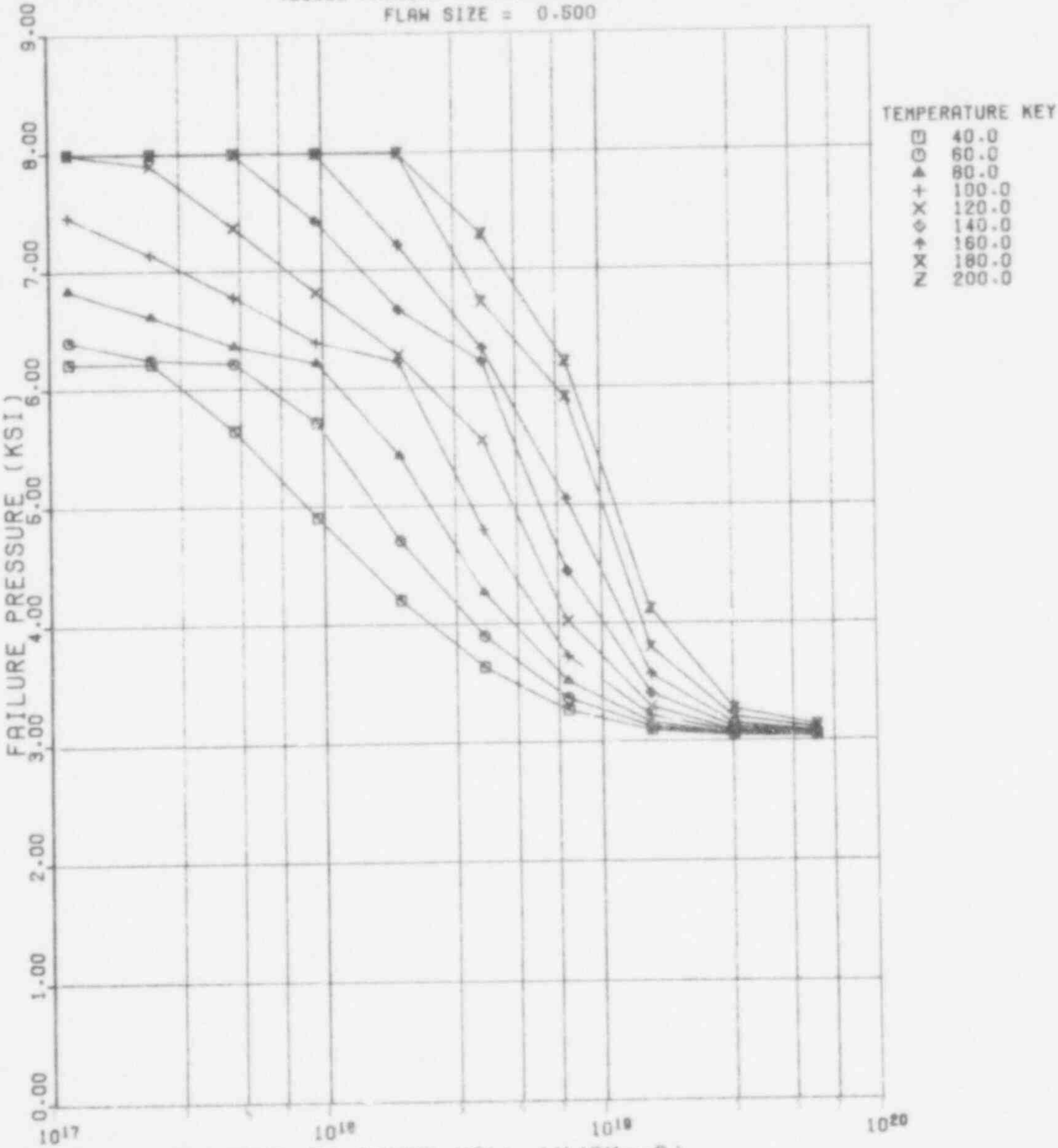

Figure C-11
Failure Pressure vs. Fluence

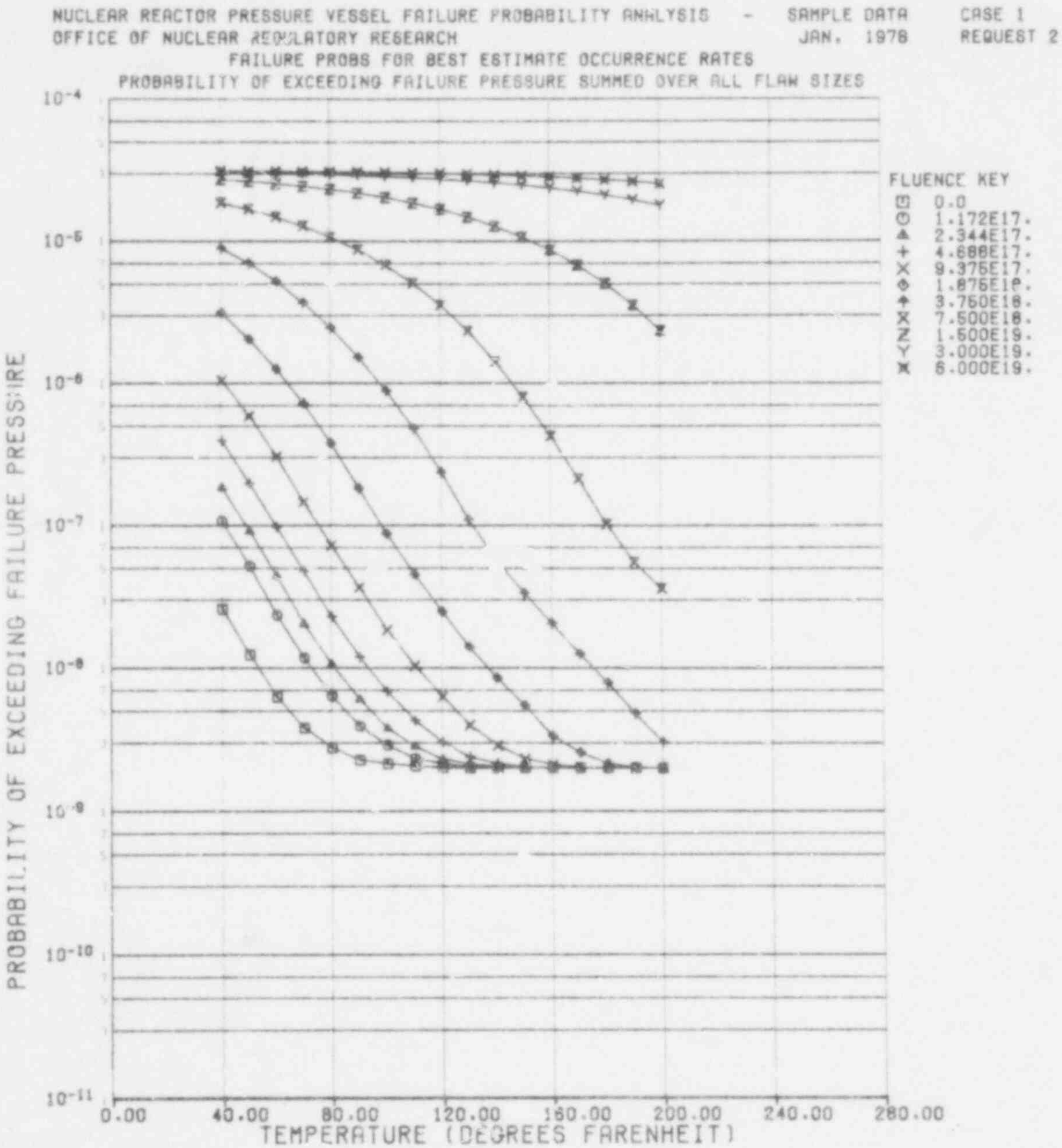

Figure C-12

Best Estimate Failure Probability vs. Temperature

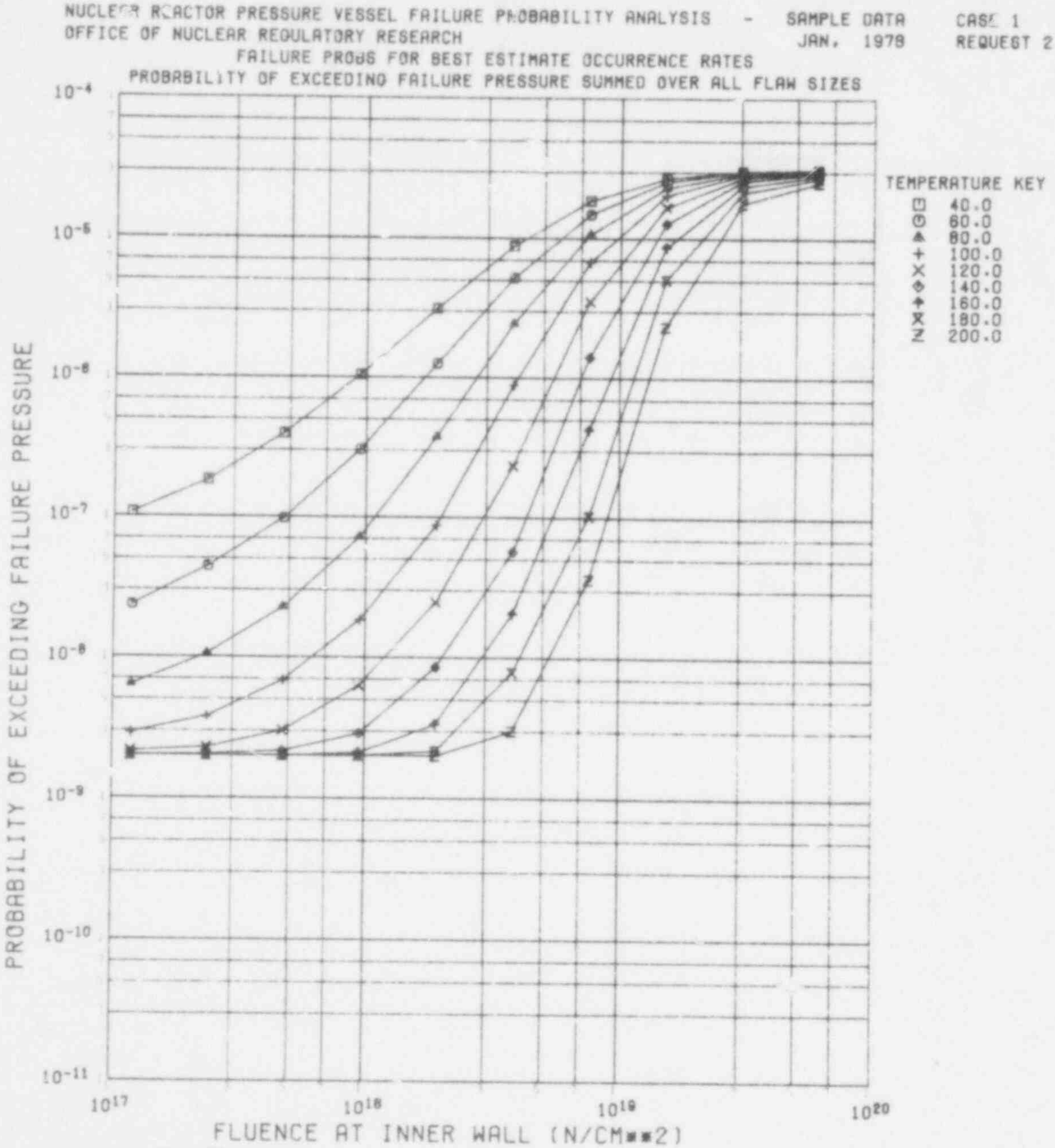

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Figure C-13

Best Estimate Failure Probability vs. Fluence

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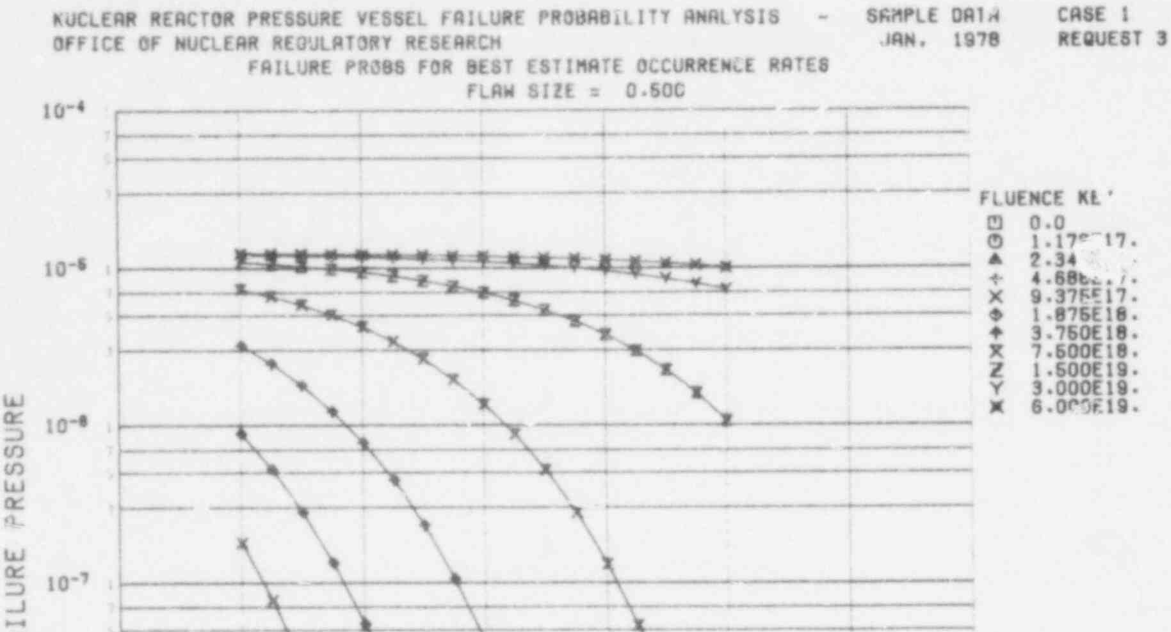

Figure C-14

Best Estimate Failure Probability vs. Temperature

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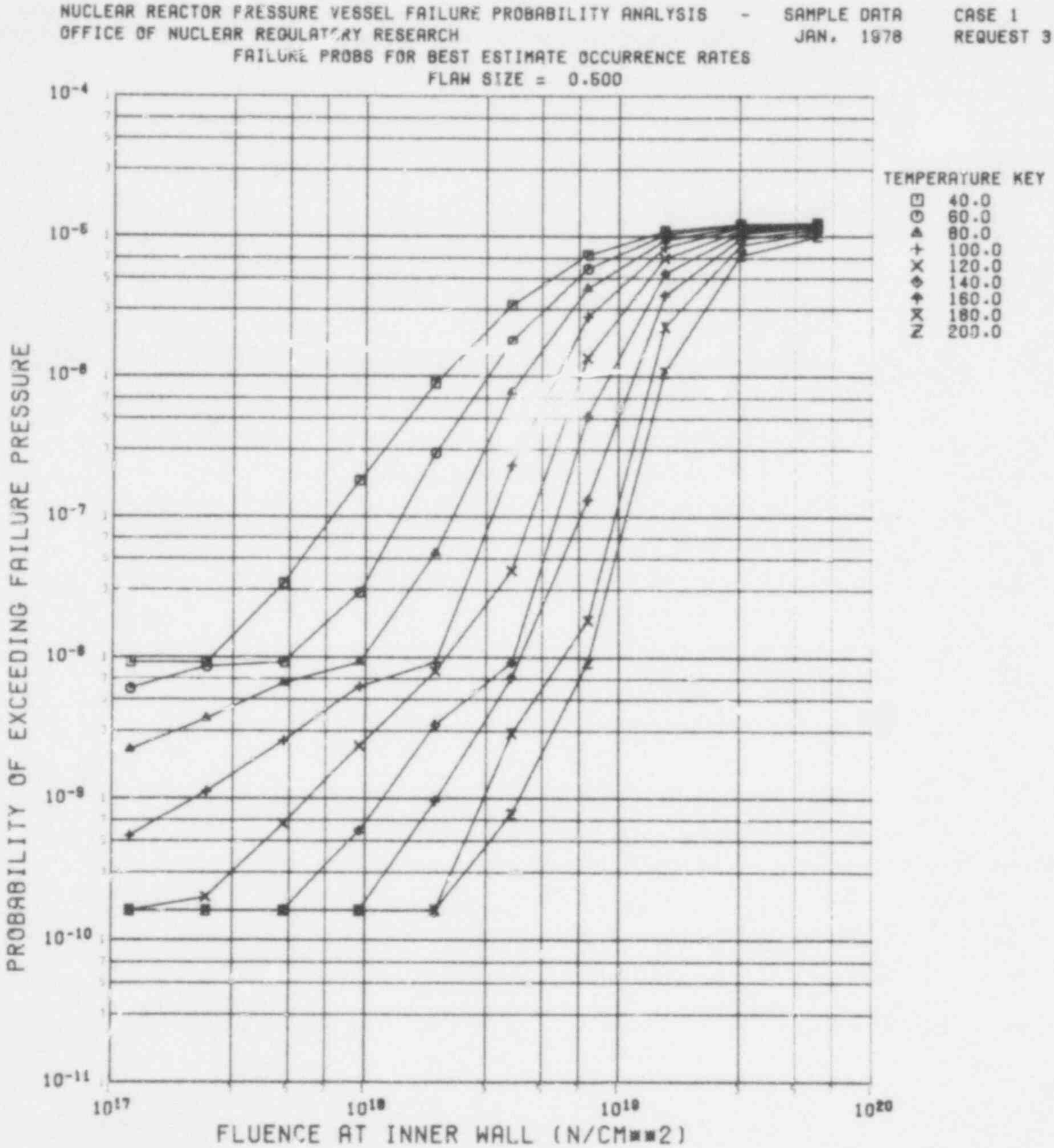

Figure C-15

Best Estimate Failure Probability vs. Fluence

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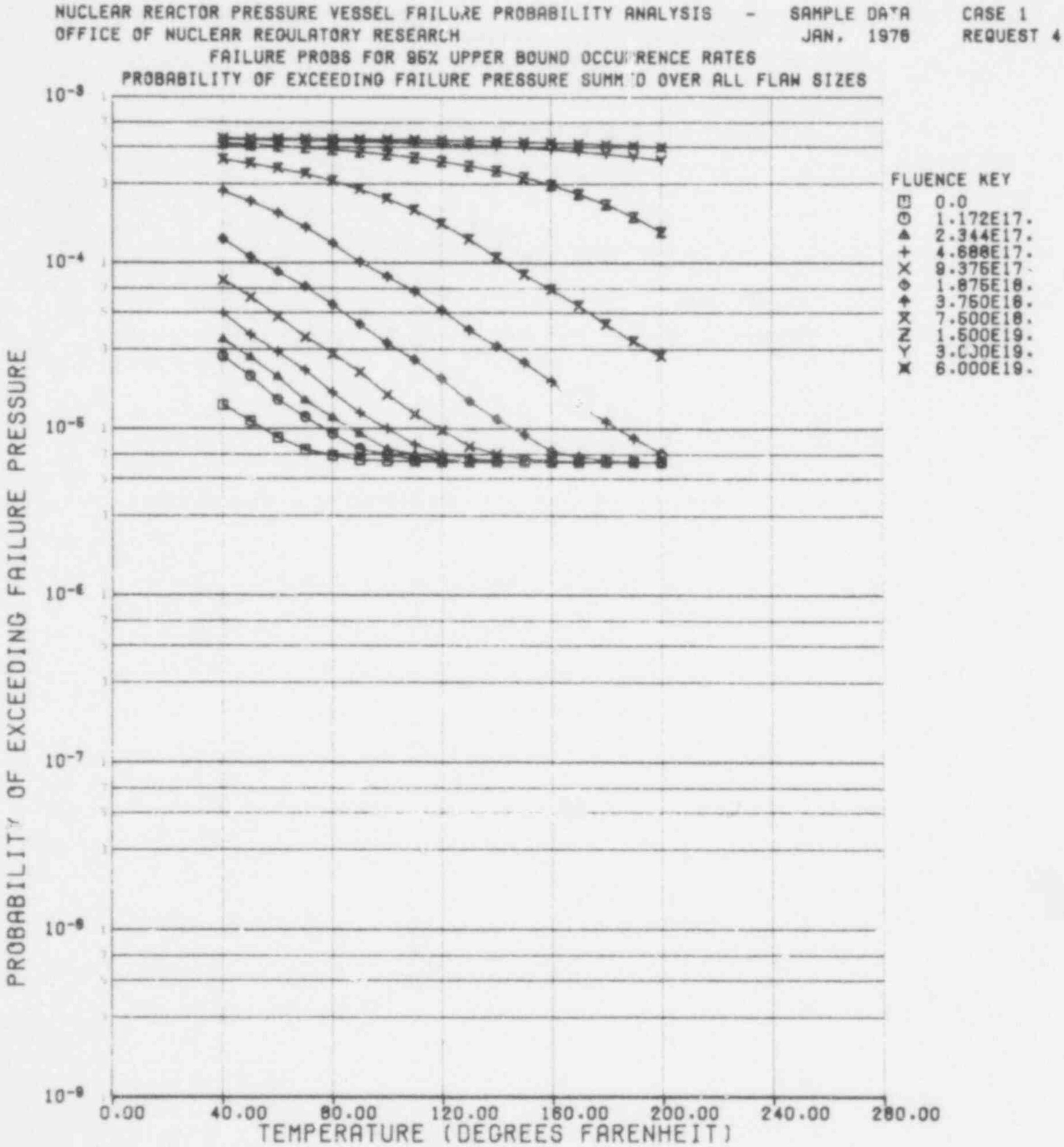

Figure C-16

95% Bound Failure Probability vs. Temperature

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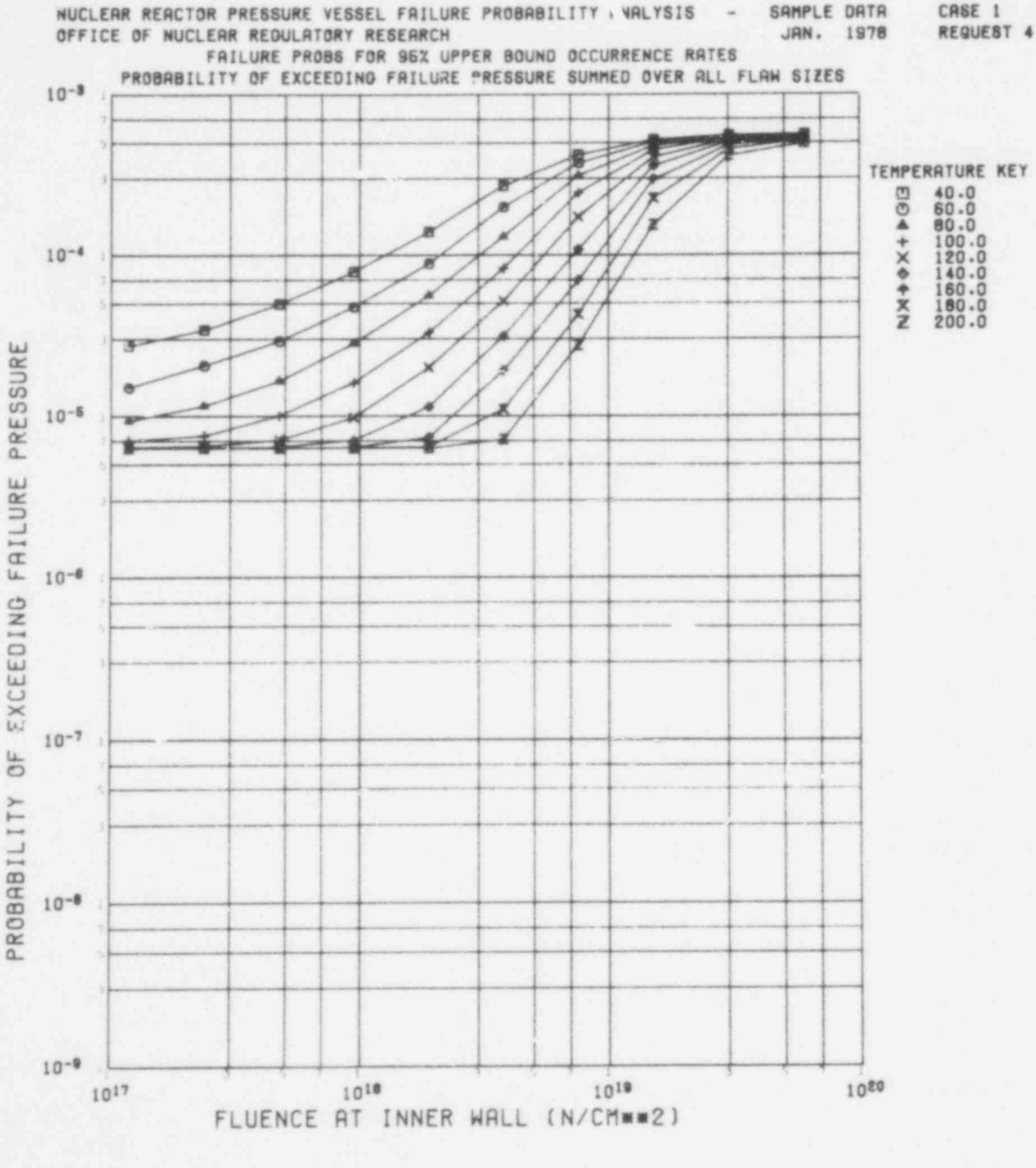

Figure C-17

95% Bound Failure Probability vs. Fluence

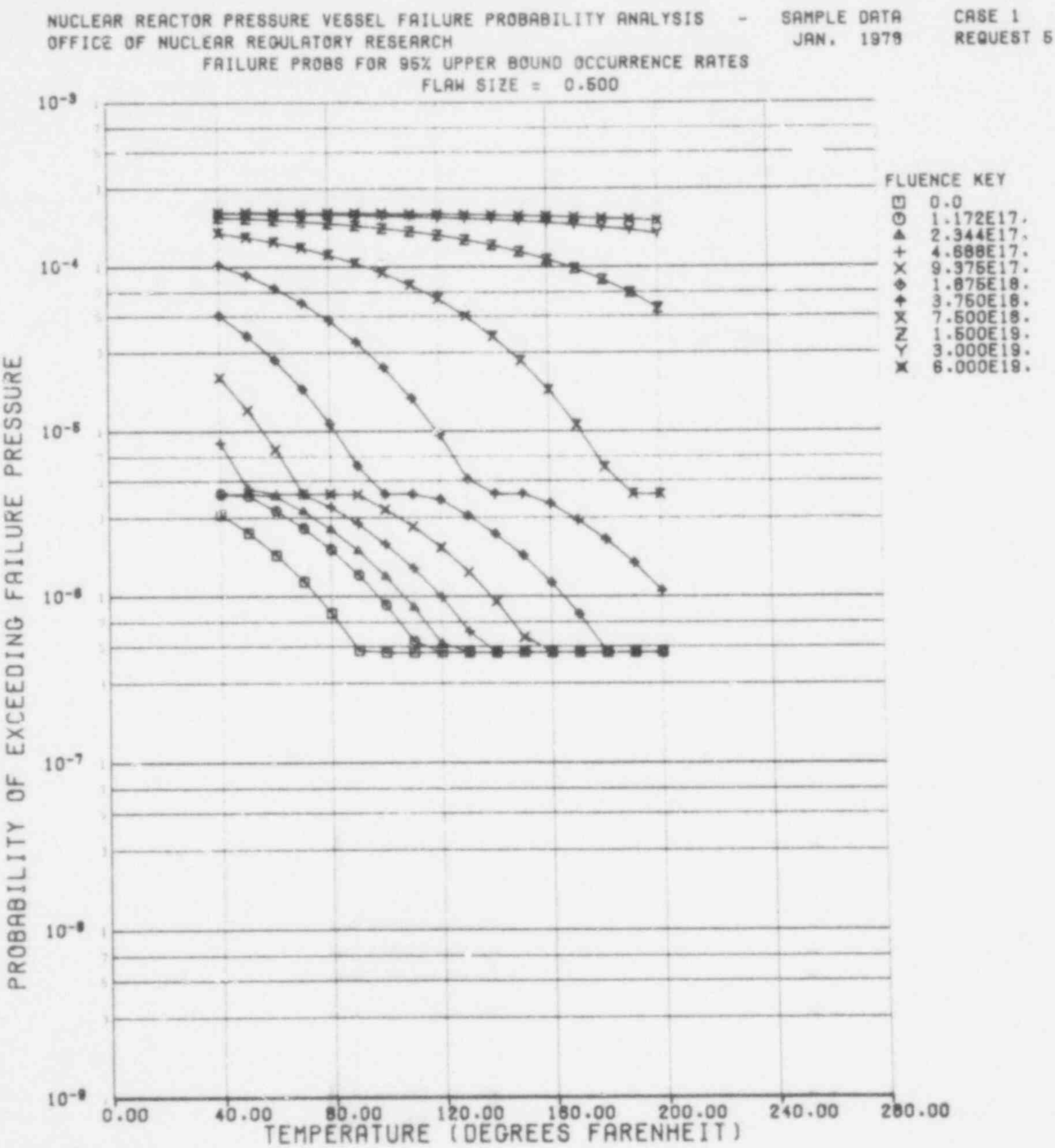

Figure C-18

95% Bound Failure Probability vs. Temperature

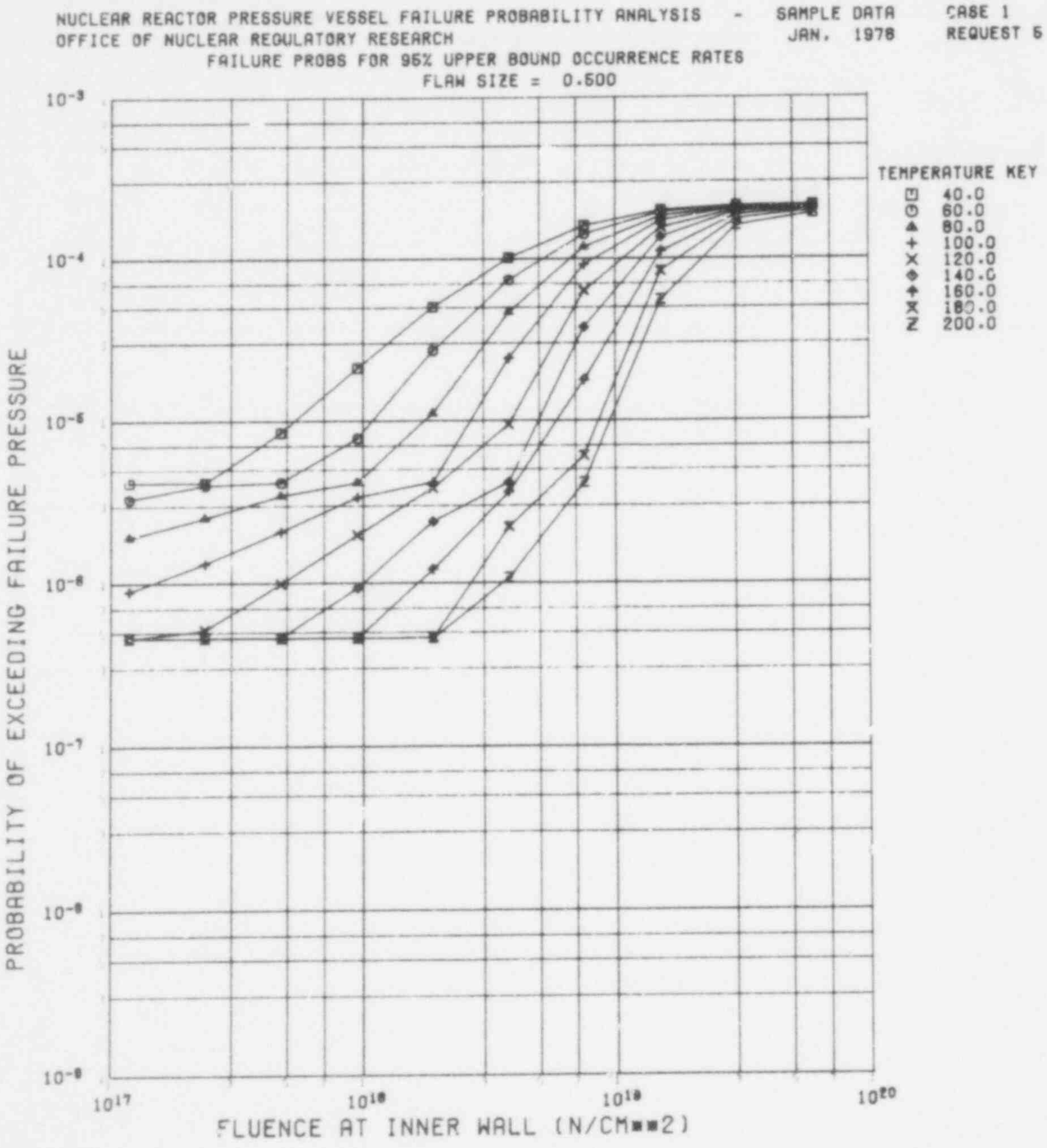

Figure C-19

95% Bound Failure Probability vs. Fluence

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REFERENCES

1. J. G. Merkle, G. D. Whitman, R. H. Bryan, "An Evaluation of the HSST Program Intermediate Pressure Vessel Tests in Terms of Light-Water-Reactor Pressure Vessel Safety," ORNL-TM-5090, November 1975. Available for purchase from NTIS.

2. HSST Quarterly Progress Report, ORNL-TM-4914, March 1975. Available for purchase from NTIS.

APPENDIX I - FAILURE PRESSURE ANALYTICAL METHODOLOGY

The fracture mechanics methods that are used in this program are essentially those used in ORNL-TM-5090, "An Evaluation of the HSST Program Intermediate Pressure Vessel Tests in Terms of Light-Water-Reactor Pressure Vessel Safety," by J. G. Merkle, G. D. Whitman, and R. H. Bryan, November 1975.

In relating RPV failure pressure to temperature for various flaw sizes, there are four distinct regimes, as depicted in Figure I-1. In terms of increasing predicted failure pressure, these regimes are linear-elastic fracture mechanics (LEFM); gross yield plateau, elastic-plastic fracture mechanics (EPFM), and the upper shelf plastic instability pressure.

The LEFM regime is the most important, in that it is the governing regime for pressures up to the gross yield pressure of the vessel. This regime is the best characterized because of the significant advances in LEFM in recent years. The equations used, though not as exact as those that might be obtained from specific finite element analyses, are close approximations for describing the imposed stress intensity factor at the deepest point in a semi-elliptical flaw, and most importantly, they do contain the important variables that must be considered, such as front and back free-face correction factors and flaw aspect ratio consideration.

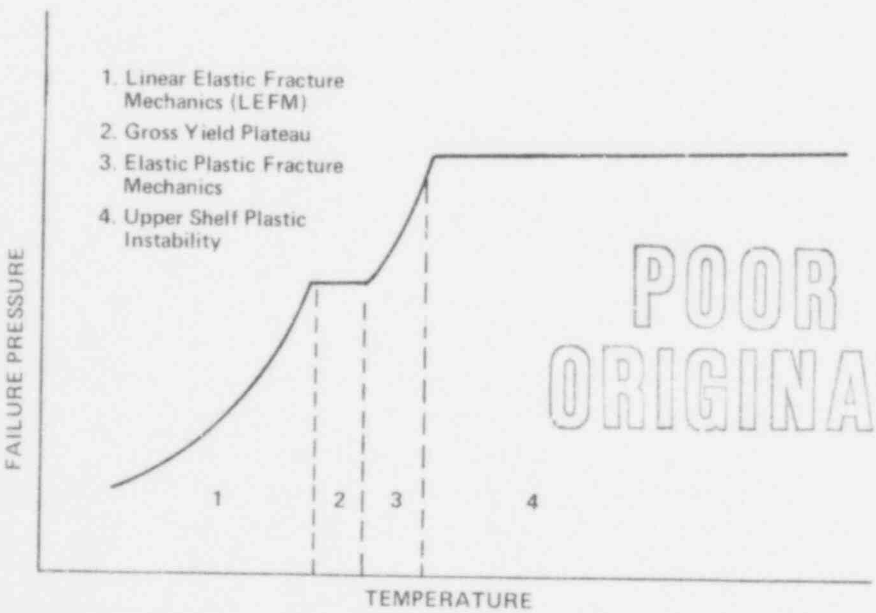

Figure I-1
The Four Regimes for Pressure vs. Temperature

The gross yield plateau regime exists because of the yield plateau in the stress versus strain relationship for RPV materials, as depicted in Figure I-2. As seen from the figure, until strain hardening occurs, there can be no increase in the failure pressure over the gross yield pressure.

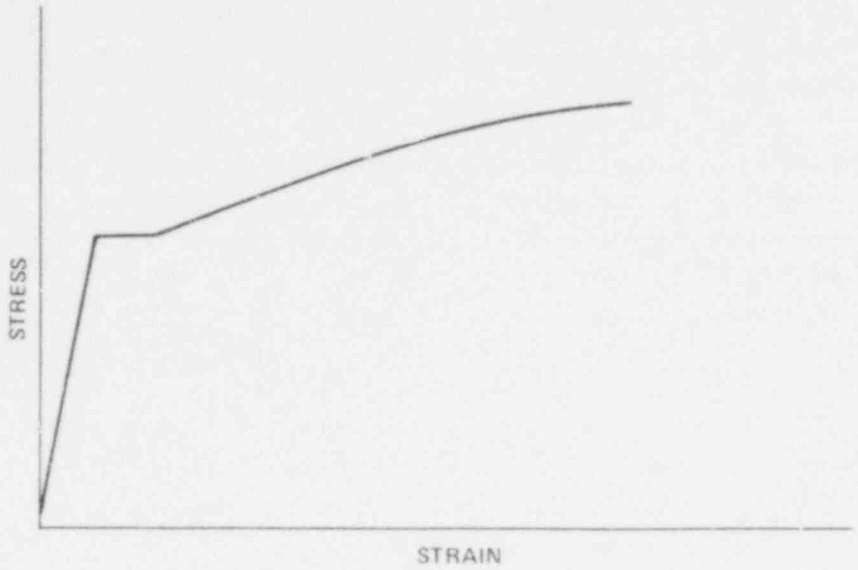

Figure I-2
Stress vs. Strain Relationship

The EPFM regime relects the additional toughness available if the material has the capability of straining into the strain hardening region. The method of analyzing this regime was developed during the testing of the intermediate test vessels in the HSST program, and is described in detail in Appendix H of ORNL-5059, "Test of Six-Inch-Thick Pressure Vessels, Series 2: Intermediate Test Vessels V-3, V-4, and V-6," by R. H. Bryan, J. G. Merkle, M. N. Raftenberg, G. C. Robinson, and J. E. Smith, November 1975.

The upper shelf plastic instability pressure regime is determined by estimating the pressure at which plastic instability occurs in the region surrounding the flaw. This estimation procedure was developed during the testing of the intermediate test vessels in the HSST program, and is described in ORNL-4895, "Test of Six-Inch-Thick Pressure Vessels, Series 1: Intermediate Test Vessels V1 and V2," by R. W. Derby, et.al., February 1975.

Although most of the procedures used in the OCTAVIA program are the same as those reported in ORNL-TM-5090, there are two significant changes made that affect the results. The first of these is the modeling used for the degradation caused by irradiation, and the second is the relationship used for fracture toughness versus temperature.

In the OCT^^IA program, irradiatirn degradation caused by fluence is evaluated in the manner recommende. U.S. NRC Regulatory Guide 1.99, revision 1. In general this evaluation results in more degradation than that reported in ORNL-TM-5090, particularly with high residual elements in the steel. Furthermore, only internal surface flaws are considered for they are far more critical in the presence of irradiation than are external flaws.

The basic fracture toughness data versus temperature for RPV steel was developed by the HSST program and presented in HSST Quarterly Progress Report, ORNL-TM-4914 for January-March 1975. These data are a closer representation of the average of the fracture toughness data than that used in ORNL-TM-5090.

The best estimate of toughness (K_{Ic}) versus temperature is based on a regression analysis of the HSST data. If $\hat{K}_{Ic}$ is the best estimate and t is the temperature (°F), then OCTAVIA uses the formula

$$\hat{K}_{Ic} = a + ce^{bt}$$

where:

a = 36.94 (± 1.011)
b = 0.01794 (± 0.002179)
c = 40.73 (± 3.655)

The numbers in parentheses are the estimated standard deviations.[4]

The calculated failure pressures are based upon nominal or average fracture toughness as exhibited by HSST-02 plate material. Fracture toughness values exhibit spread as do other mechanical properties, and variation occurs from heat-to-heat and among welds. The results of the code should therefore be interpreted with this nominal toughness model in mind.

The value of the yield strength and the constants used to describe the stress versus strain relationship are internal parts of the program. These values and constants can be changed at a later time to reflect the changes induced by irradiation. These changes have not been put into the program to date because of the difficulty of defining the irradiated material stress versus strain relationships; the failure pressures, as calculated, are conservative, that is, lower than if the irradiation effects were considered.

It is generally considered that surface flaws are most likely to reside in weld regions. For this reason, this program has been oriented in favor of materials that have not been quench and tempered. That is, a fixed value of the initial RT_{NDT} is input for use with various flaw

[4]The regression analysis is described in more detail in the letter from W. E. Vesely to E. K. Lynn, "Statistical Analysis of the HSST Basic Fracture Toughness Data Versus Temperatures," dated May 20, 1977.

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depths. The quench and tempering that occurs with plates and forgings causes a significant decrease in the initial RT_{NDT} near the surface, which in turn, causes an increase in the fracture toughness, above that of the weld region, to approximately one fourth of the way from each surface.

APPENDIX II - STATISTICAL EVALUATIONS

Listed in Table II-1 are the major transients incidents which have been reported, where "major" is defined as a transient having a maximum pressure exceeding 800 psi. The transient incidents which occurred before criticality are denoted with an asterisk. Since the vessel failure pressure is generally larger than 800 psi, the "minor" transient incidents (<800 psi) are not considered here. The statistical fitting techniques which are used are somewhat insensitive to the possibility that one or more transients have not been reported.

Only the transients which occurred after criticality will be used since, as shown later, the transients occurring before criticality are marginal in the similarity of distributions. Figure II-1 is the empirical probability distribution of the maximum pressures of the transients occurring after criticality.

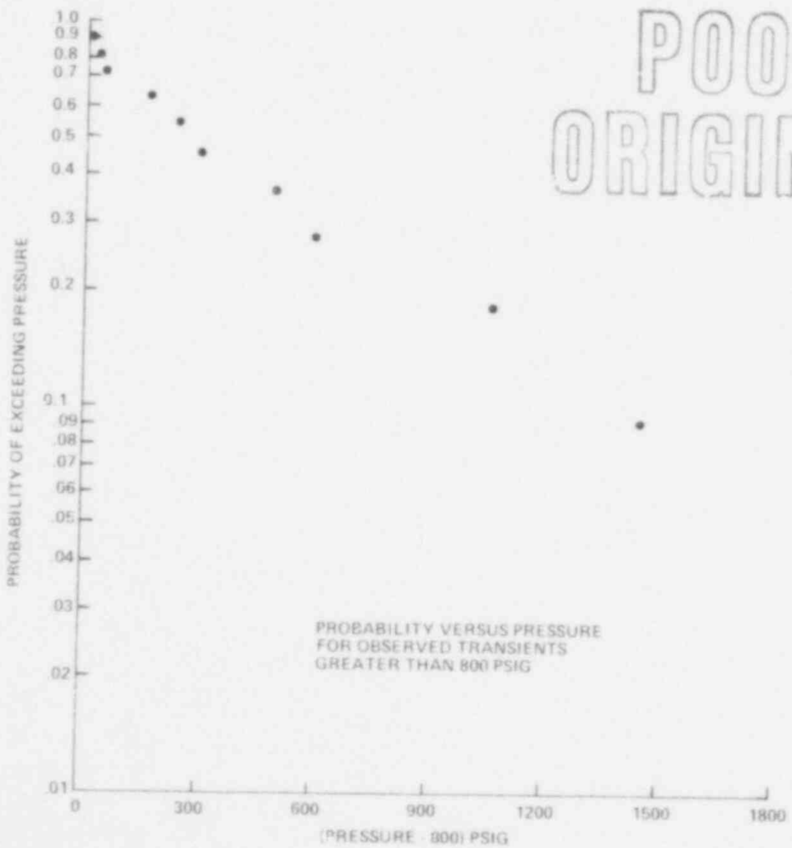

Figure II-1

Empirical Probability Plot

LOCATIONS OF INCIDENTS	DATE	PRESSURE TRANSIENT FROM (PSIG)	TO	VESSEL TEMPERATURE (°F)	TECH SPEC PRESSURE LIMIT (PSIG)	LIMITING RT_{NDT}+ (°F)
1. Beaver Valley Unit No. 1*	2/24/76	400	1000	130	440	75
2. Oconee Nuclear Station Unit 2	11/15/73	800	1860	300	1600	60
3. Palisades	9/1/74	---	960	150	---	65
4. Point Beach Unit No. 2	12/10/74	345	1400	170	615	110
5. Point Beach Unit No. 2	2/28/76	400	830	168	615	125
6. Prairie Island* Unit No. 1	10/31/73	420	1100	132	720	15
7. Prairie Island Unit No. 1	1/16/74	395	840	90	610	15
8. Prairie Island* Unit No. 2	11/27/74	---	900	155	800	5
9. Trojan*	7/22/75	400	3326	100	520	40
10. Turkey Point Unit No. 3	12/3/74	50	800	105	510	75
11. Zion Unit No. 1*	6/13/73	110	1290	105	460	40
12. Zion Unit No. 1	6/3/75	100	1100	115	480	75
13. Zion Unit No. 2	9/18/75	95	1300	88	450	60
14. Ginna*	1969	---	2485	100-150	600	45
15. Beaver Valley Unit No. 1*	3/5/76	400	1150	150	440	75
16. D. C. Cook Unit No. 1	4/14/76	---	1040	110	110	40
17. St. Lucie Unit No. 1	6/17/76	435	815	100	520	20
18. Indian Point Unit No. 3	9/30/76	50	2250	185	740	75

+The limiting RTNDT value is based on the fluence at the time of the incident.

*Incidents occurring before criticality.

TABLE II-1

Major Pressure Transient Incidents

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The ordinate is the probability that the maximum pressure of the transient will exceed a given value. A value of 800 psi has been used as the origin (location) and the abscissa is the recorded maximum pressure minus 800 psi. Table II-2 gives the tabulations used for the figure.

I	Pressure p (PSIG)	p - 800* (PSIG)	$\frac{I}{N+1}$	$1 - \frac{I}{N+1}$
0	800	0		
1.	815	15	.091	.909
2.	830	30	.182	.818
3.	840	40	.273	.727
4.	960	160	.364	.636
5.	1040	240	.455	.545
6.	1100	300	.545	.455
7.	1300	500	.636	.364
8.	1400	600	.727	.273
9.	1860	1060	.818	.182
10.	2250	1450	.909	.091

*Average (p-800) = 440

TABLE II-2

Empirical Distribution Tabulations

The exponential distribution was initially assumed (giving rise to the semi-log plot in Figure II-1) because of its simplicity and its general adequacy of describing extreme phenomena. A formal Lilliefors statistical test does not reject the exponential as being inadequate, having an observed significance level of 0.75.

Figure II-1 should only be taken as a rough indication of the probability distribution and more formal techniques need to be used to obtain the actual distribution. Maximum likelihood techniques are used here which allowed Lilliefors test to be performed. If P_o is the probability of exceeding a pressure p (psi) given a transient, then from maximum likelihood, the formula for P_o is determined to be

$$P_o = \exp\left[\frac{-(p-800)}{440}\right], \quad p > 800$$

Since there have been 10 transients exceeding 800 psi, the best estimate of the occurrence rate Λ for these transients is

$$\Lambda = \frac{10}{125} = 0.08 \text{ per reactor year}$$

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where 125 reactor years is used as the approximate PWR experience. The best estimate probability P_T for a transient occurring and exceeding a given pressure is thus

$$P_T = 0.08 \exp\left[\frac{-(p-800)}{440}\right], \quad p > 800$$

which is the formula used in OCTAVIA. This best estimate is also an approximate 50% confidence value ("median" value).

The upper 95% confidence bound for P_T is obtained by using upper 95% confidence bound values for Λ and the maximum pressure (scale factor).

$$P_T(95\%) = 0.136 \exp \frac{-(p-800)}{806}, \quad p > 800$$

The bound is not a precise 95% bound, but it is greater than 90% (using Bonferonni's inequality) and should be near 95% because the upper bound (800 psi) on P dominates the upper bound on the vessel failure probability.

It is of interest to compare the above probabilities with those obtained from the transients which occurred before criticality. Using the asterisked data in Table II-1 and using the same techniques as before, the best estimate for P_T is determined to be

$$P_T \text{ (before criticality)} = 0.06 \exp \frac{-(p-800)}{807}$$

The exponential is again found not to be inadequate with a significance level of 0.73 observed for Lilliefors test.

Comparison of the two best estimates of P_T for before and after criticality, in particular, comparing the scale parameters 440 versus 807, results in enough statistical difference so as to be possibly significant.[6] It is interesting to note that the best estimate of P_T for the transients before criticality is approximately the 95% value for P_T for transients after criticality.

[6] The observed F statistic value (f1=14, f2=20) is 1.83 which is near the 10% significance level (1.85).

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