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**PRAISE ENHANCEMENTS TO INCLUDE
GENERAL STRAIN HARDENING EXPONENTS
AND MID-LIFE RESIDUAL STRESS AND
WATER CHEMISTRY CHANGES**

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MASTER

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1.0 INTRODUCTION

The purpose of this document is to describe some recent changes made to the PRAISE Code to provide some additional capabilities. The major changes are associated with the new capability to analyze cases where there is a mid-life change in residual stresses and/or water chemistry. Such changes have been proposed as a means of improving the reliability of BWR piping by reducing the oxygen content of the coolant (or other favorable chemistry changes) or altering the residual stresses near welds to provide a stress distribution less favorable to crack initiation and growth. Induction heating stress improvement (IHSI) and mechanical stress improvement process (MSIP) are considered, with the time at which the process is implemented defined by the user. As-welded residual stresses are considered to be present prior to the stress improvement treatment.

Improved pre- and post-processors were also developed and are described, which should be particularly useful to users of the PC version of PRAISE. In addition, improved J-integral solutions are incorporated that allow a treatment of general Ramberg-Osgood strain hardening, rather than the specific values of the strain hardening exponent included in earlier versions of the PRAISE Code.

This document discusses only the new additions to the code and is an addition to earlier documentation. Some example results are presented, and the Appendix provides a complete updated description of the input cards for the newly expanded PRAISE-CC Code.

2.0 CHARACTERIZATION OF REMEDIAL RESIDUAL STRESSES

As-welded residual stresses often have a detrimental effect on the initiation and growth of stress corrosion cracks in sensitized weldments of BWR piping. Earlier versions of PRAISE contain default statistical distributions of residual stresses. It has been suggested that the residual stresses could be altered to become favorable, thereby improving the reliability of BWR piping. Two procedures have been proposed, induction-heating stress improvement (IHSI) and mechanical stress improvement process (MSIP). The resulting residual stress distributions will be characterized in this section.

2.1 Post-IHSI Stresses

The induction heating stress improvement (IHSI) process is suggested as one of the counter-measures for intergranular stress corrosion cracking (IGSCC) [1,2]. The process results in axial residual stresses that are compressive on the ID and, thus, are favorable for impeding stress corrosion crack initiation and growth. The resulting residual stresses are also axisymmetric and self-equilibrating through the thickness.

References 1 and 2 provide experimental and analytical post-IHSI residual stress distributions through the wall. In the context of PRAISE, only the axial stresses are of interest here. These references contain results for 4, 10, 12, 16, and 26 inch lines. Based on the information available [1,2,3], these stresses vary approximately linearly through the wall.

Post-IHSI stresses at the ID and OD were gathered from References 1 and 2. When the stresses are linearly varying through the wall, axisymmetric and self-equilibrating, the stresses at the ID and OD are related to one another by the expression

$$\sigma_{ID} = -\sigma_{OD} \frac{3R_i + 2h}{3R_i + h}$$

where R_i = inside radius of the pipe
 h = wall thickness of the pipe

Thirty-one sets of through-wall stresses were available. From these 31 sets of data, 62 values of stresses at the ID were obtained; 31 values directly, and 31 values using the OD data converted to ID values by use of the above equation. The post-IHSI stresses from References 1 and 2 were grouped in several different ways, and the mean and standard deviation for each group were calculated. The results are summarized in Table 1. For each of the categories (except the last one) shown in Table 1, the stresses were plotted in the

Table 1
Summary of Post-IHSI
Stresses at the ID

Category	Number of Data	Mean (ksi)	Standard Deviation (ksi)
All	62	-40.8	13.6
ID Data	31	-43.3	9.7
Projected from OD to ID	31	-38.4	16.4
All Experimental	46	-44.7	11.6
All Analytical	16	-29.9	13.2
All 4 Inch	4	-38.8	7.5
All 10 Inch	10	-29.2	16.3
All 12 Inch	36	-45.1	11.0
All 16 Inch	10	-41.5	13.5
All 26 Inch	2	-22.8	8.2

form of histograms with the normal distribution based on the calculated mean and standard deviation superimposed (Figure 1). In each of the categories, normal distribution seems to reasonably characterize the scatter present in the data.

Based on the results summarized in Table 1 and Figure 1, along with supporting results from References 1 and 2, it appears that the post-IHSI residual stresses can be adequately described as axisymmetric with a linear through-wall gradient. For a given pipe size and thickness, such a spatial distribution can be characterized by a single number, such as the value of the stress at the ID. The results of Figure 2 indicate that the statistical distribution of the ID residual stress is normally distributed, and the results of Table 1 show no consistent variation of the mean and standard deviation with pipe size. Hence, it is suggested that mean and standard deviation of post-IHSI residual stresses can be taken as the sum of all pipe sizes. The values corresponding to "all experimental" are suggested, which are a mean of -44.7 ksi and a standard deviation of 11.6 ksi.

The mean and standard deviation of the post-IHSI residual stresses are input by the PRAISE user. The values referred to immediately above are suggested for use.

2.2 Post-MSIP Stresses

The mechanical stress improvement process (MSIP) consists of applying compressive stresses around the circumference on the outside of a pipe by applying a ring that squeezes a short portion of the pipe. The magnitude of the applied ring load is sufficient to produce permanent reduction of the diameter of the pipe under the ring, which produces compressive axial residual stresses on the ID that extend a short distance away from the location of the ring. This process can thus be used to produce favorable residual stresses in the vicinity of a circumferential weld to impede IGSCC.

References 4, 5, 6, and 7 provide analytical results for 4-, 10-, 12-, and 28-inch nozzles treated with MSIP. The through-wall stress distributions in the heat-affected zone (HAZ) (half-thickness away from weld centerline) on either side of the weld were obtained from

Figure 1. Distributions of post-IHSI σ_{ID} for various categories.

MS2800IT.DAT 02-06-1990

Figure 2. Post-MSIP stress distribution in the "thicker" section of a 28 inch nozzle (ODI FE results).

the color contour plots included in the references. Reference 8 contains experimental measurements of through-wall post-MSIP stresses in 12- and 28-inch lines in the region of the HAZ. The data forms in References 4-8 were collected and are summarized in Figures 2-7. Since the pipe is squeezed only on one side of the weld, the stresses in the HAZ between the weld and the tool is referred to as the "tool side," and the stresses in the HAZ on the other side of the weld is referred to as "across weld." The "ksi" values indicated in the tables and in the figures correspond to the average radial stress under the indenting ring. From Figures 2-7, the following is concluded:

1. The axial MSIP stresses in the HAZs of a weld can be characterized as linearly varying through the wall and axisymmetric. The stresses are therefore self-equilibrating through the wall and, knowing the stress on the ID and the pipe geometry, the through-wall stress distribution can be obtained.
2. The stresses on the ID are a function of the axial distance from the tool and are also a function of the applied compression under the tool. Generally, the stresses in the range of -20 to -40 ksi are produced on the ID of the pipe.

Based on the limited available information, it is not possible to statistically characterize the MSIP stresses. The through-wall stress distributions seem to be similar to those obtained by IHSI treatment. The post-MSIP stresses are input to PRAISE in a manner identical to the IHSI stresses.

MS28001.DAT 02-08-1990

Figure 3. Post-MSIP stress distribution in the "thinner" section of a 28 inch nozzle (ODI FE results).

MS12001.DAT 02-06-1990

Figure 4. Post-MSIP stress distribution in a 12 inch nozzle (ODI FE results).

MS10ODI.DAT 02-08-1990

Figure 5. Post-MSIP stress distribution in a 10 inch nozzle (ODI FE results).

MS28EXP.DAT 02-06-1990

Figure 6. Post-MSIP stress distribution in a 28 inch line (ANL experimental data).

MS12EXP.DAT 02-06-1990

Figure 7. Post-MSIP stress distribution in a 12-inch line (ANL experimental data).

3.0 MID-LIFE CHANGES IN OPERATING STRESSES, WATER CHEMISTRY, OR RESIDUAL STRESSES

Provisions have been made in the PRAISE Code to change one or more of the operating parameters at any arbitrary time during the plant operation. This makes it possible to evaluate the effect of changes of these parameters on the leak and LOCA probabilities.

The operating parameters that then can be changed at mid-life include the following:

1. Oxygen level at plant start-up
2. Oxygen level during steady-state operation
3. Coolant conductivity
4. Deadweight stress
5. Deadweight and restraint of thermal expansion components of stress in the hot normal operating conditions
6. Vibratory stresses
7. Wall thickness of the pipe
8. Residual stress distributions; these can be changed to model IHSI or MSIP treatments

Changes in operating parameters can be made at a maximum of four occasions. Whenever a change in one of the above parameters is made, all the other parameters have to be respecified, whether or not they changed.

The PRAISE Code has been modified such that during each replication, the current values of the operating parameters are used for crack initiation and growth calculations. If wall thickness of the pipe is changed in mid-life, then the stresses due to pressure are recalculated. If the thickness is changed, the residual stress distributions are renormalized such that the stress is the same as before at any given fractional depth through the wall. If a change in residual stress is desired in mid-life, it can only be changed to axisymmetric self-equilibrating through the wall (MSIP or IHSI).

4.0 NEW CERT RESULTS FOR 304

Additional crack initiation results for CERT tests [8] have become available since the last update [9] to the PRAISE Code. These results include the effects of chromates, oxygen scavengers, and organic acids on crack initiation and growth. The oxygen, temperature, conductivity, strain rate, and degree of sensitization for these tests are also reported. The results for time to initiation and crack velocity at initiation are plotted as a function of the damage parameter, D_c , [9] in Figures 8 and 9, respectively. The earlier results of Reference 9 are also plotted in the same figures. The effects of oxygen, temperature, conductivity, strain rate, and the degree of sensitization enter into the definition of D_c . From Figures 8 and 9, the new data appear to fall within the scatter band of earlier data reported in Reference 9; and the effects of these new variables will not be explicitly considered in the PRAISE Code.

Figure 8. Time to initiation versus D_e for 304 CERT tests.

Figure 9. Average crack growth rate at initiation versus D_e for 304 CERT tests.

5.0 EXPANDED J-SOLUTIONS

The existing version of the PRAISE Code [9] contained J-solutions for complete circumferential and through-wall cracks that were used for the elastic-plastic failure criteria. The J-solutions for both of these crack models were valid only for strain hardening exponent (n) of 5 and for R_i/h ratios of 5 and 10. The J-solutions in the current version have now been expanded to be valid for a range of n values. The exponent, n , is now a user-input variable. The implementation of the new J-solutions is described in Reference 10. The following is the range of validity of these J-solutions.

	Complete Circumferential Crack	Through-Wall Crack
Crack Depths	$0.125 \leq a/h \leq 0.75$	$0.0625 \leq (a/\pi R) \leq 0.5$
R_i/h	5, 10, 20	5, 10, 20
Exponent, n	1 - 10	1 - 7

The J-solutions are available for discrete values of crack depths, n , and R_i/h ratios. For crack depth and n , bi-cubic spline interpolation or extrapolation is used to get J-values for any arbitrary input values of crack depth and n . No interpolation is performed on R_i/h ; instead the nearest value is used.

6.0 PRAISE PRE- AND POST-PROCESSORS

Pre- and post-processors that have been developed to aid the user in running the code are described in the following subsections.

6.1 PRAISE Input-Processor (PR_INPUT)

PR_INPUT is a utility to aide the user in setting up a PRAISE input file. It prompts the user to input values of the variables, one at a time. It displays the current value of the variable and also the valid range for the variable. When the PR-INPUT command is invoked, it first prompts the user with an option to read a template file. [A template file (extension.TPL) is a binary file containing the input data that are processed by PR_INPUT. A template file is written by the input processor at the end of the run.] If a template file is specified by the user, all the variables are initialized to values stored in the template file. Next, the processor requests inputs generally in the same order as they appear in Appendix A. A typical prompt for input is as follows:

Failure Criteria (IFAILC)

0 : Net-section stress
1 : J_{lc}, T_{mat} exceedance
2 : Both

The current value is 0 [valid range is ≥ 0 and ≤ 2]
Press ENTER to accept the current values, or Enter a new value.

For every prompt, the input-processor displays the FORTRAN variable name of the requested input as well as the valid range of inputs. The input-processor requests only the information required for the selected analysis and, if necessary, fills in the PRAISE compatible input file with dummy values. For example, the input processor will request the values of J_{lc} and T_{mat} only if the selected failure criteria requires those values (IFAILC = 1 or 2).

The input-processor expects the following group of inputs, each of which requires a large number of data, to be saved in a file. The input processor requests the name of the file and then includes the file in a PRAISE input file. These groups of inputs are as follows:

1. **Stratification.** If the user selects to input coordinates of each cell (ISQARE = 0), then the user is expected to create a file containing the information requested on Card 5A.
2. **Stress Intensity Factors for Radial Gradient Thermal Stresses.** If more than one transient (KTYPE > 1) are to be considered in the analysis, the tabular inputs required on Cards 6E through 6F should be contained in a file.
3. **Seismic Data.** If seismic events are to be considered in the analysis (NQUAKE = 1), then the inputs required on Cards 7A and 7B should be contained in a file.
4. **Residual Stresses.** If the user selects the residual stress option (ISIGRS = 1), it requires coefficients of the polynomials defining the contribution of residual stresses to the stress intensity factors. The inputs required on Cards 6G and 6H should be saved in a file.

When all the inputs are completed, the input-processor prompts the user to enter file names for storing data in a template file and in a PRAISE-compatible input file.

6.2 PRAISE Post-Processor (PR_PLOT)

PR_PLOT is a plotting program to provide plots of leak and LOCA probabilities and also to display stratification maps with number of samples and failures from each stratum. The program is invoked as follows:

PR_PLOT FNAME

where FNAME is the file name (without the extension). The program then searches for files FNAME.SLK, FNAME.BLK, FNAME.LOC, and FNAME.STT, and displays the plot selection menu, which typically looks as follows:

PRAISE - Plot Section Menu

- 1 : Time versus Probability of Leak
- 2 : Time versus Probability of Big Leak
- 3 : Time versus Probability of LOCA
- 4 : Stratification Map
- 0 : Exit

Make a selection (Enter a number) ?

If plot option 1, 2, or 3 is selected, the following menu appears:

```
A : MIN-MAX VALUES   X-MINIMUM   X-MAXIMUM   Y-MINIMUM   Y-MAXIMUM
                        0             10           0             0.0025
B : TIC INTERVALS     X-MAJOR      X-MINOR     Y-MAJOR     Y-MINOR
                        2             1           0.0005     0
E : X-AXIS LABEL = 'Time (years)'
E : Y-AXIS LABEL = 'Probability of leak'
M : MODE (LINEAR/LOG) : X-AXIS...LIN           Y-AXIS...LIN
F : PHYSICAL PLOT SIZE: X-AXIS... 3.5 - 2.5 cms Y-AXIS... 3.5 - 18.5 cms
G : DATA SETS :      1
   SYMBOLS :         11
P : PEN NUMBER:       1
S : SAVE THE PLOTTING PARAMETERS IN A FILE
L : LOAD PLOTTING PARAMETERS FROM A FILE
X : PLOT ON THE SCREEN
Z : PLOT ON THE 7470A PLOTTER
O : OVERPLOT OPTION TOGGLE (ON/OFF)
N : READ A NEW DATA FILE
Q : QUIT
CURRENT FILE IS ..FATIG.SLK
```

Enter desired option to change format or to plot

When this menu appears, a plot can be made on the screen by entering X (or Z for plotting on a pen plotter). Any of the parameters listed on this menu can be changed by entering the corresponding letter that appears in the first column. A brief description of each of the options follows:

Min-Max Values (A) -- By default, the minimum and maximum values of data are used as plotting limits. When this option is selected, the user will be prompted to enter minimum and maximum limits for plotting on the X- and Y-axes. Data that fall outside these plotting limits will not be plotted.

Tic Intervals (B) -- By default, there are five major tic intervals on each axis where labels are printed. Also by default, five minor tics are drawn between two major tic intervals. These can be redefined by the user. To completely suppress minor tics, enter the minor tic interval as 0 (zero).

Axis Labels (E) -- This option can be used to redefine axis labels. Both upper and lower case characters can be used.

Plotting Mode (M) -- One of the following four plotting modes can be selected:

1. linear on X, linear on Y
2. linear on X, log on Y
3. log on X, linear on Y
4. log on X, log on Y

By default, both axes are plotted on a linear scale.

Physical Plot Size (F) -- *This option is applicable only to pen plotters.* By selecting this option, the physical size of the plot can be defined in terms of dimensions of X- and Y-axis and coordinates of the left-bottom corner of the plot with reference to a 8-1/2 x 11-inch paper in landscape mode.

Symbols (G) -- A set of ten discrete symbols and ten different types of lines are provided. By selecting this option, the user can reassign symbols to data sets.

Pen Number (P) -- *This option is applicable only to multi-pen plotters like the HP7470A plotter.* By selecting this option, different colors can be assigned to data sets.

Save Plotting Parameters in a File (S) -- When this option is selected, the user will be prompted to enter a file name for saving the plotting parameters. The parameters saved are -- minimum and maximum plotting limits, tic intervals, axes labels, plotting mode, physical plot size, assigned symbols, and pen numbers.

Load Plotting Parameters from a File (L) -- By selecting this option, the user can recall the plotting parameters that were saved using the "S" option. A file name is requested from the user when this option is selected.

Plot on the Screen (X) -- This option is used to plot the data on the screen.

Plot on a Pen Plotter (Z) -- This option is used to plot the data on a HP7470A or compatible pen plotter. Follow the instructions that appear on the screen.

Overplot Option (O) -- *This option is applicable only for the pen plotters.* By default, the overplot option is turned off. When the overplot option is turned on, ties, labels, and axes are not plotted.

Read a New Data File (N) -- This option is used to select another file for plotting. When this option is selected, display returns to Plotting File Menu, from which another plot file can be selected.

Quit (Q) -- This option is used to EXIT from the plotting program.

If option 4 is selected from the plot selection menu, a color-coded stratification scheme as shown in Figure 10 is displayed. By default, leak results are provided. If all the samples from a stratum resulted in a leak, the cell is painted red; if no leaks occurred for a stratum, it is painted green; if some leaks occurred, the stratum is painted yellow. At the bottom of the screen, six options are listed for altering the display or for exiting to the plot selection menu.

Option A (New Scale): By selecting this option, a selective display of the stratification map can be obtained. The user is promoted to enter new limits of a/b and a/h for display.

A: New Scale B: Leaks C: Big Leaks D: LOCA N: Numbers On/Off Q: Quit

Figure 10. A typical display of leak results on the stratification map.

Option B (Leaks): This is the default display. When this option is selected, the results of leaks are displayed.

Option C (Big Leaks): When this option is selected, the results of big leaks are displayed.

Option D (LOCA): When this option is selected, the results of LOCA are displayed.

Option N (Numbers On/Off): When this option is selected, the user is provided with options to display any or all of the following:

- Number of samples in each cell.
- Number of failures (leaks, big leaks, or LOCA) in each cell.
- Stratum number.

By default, none of these are displayed when the display is first generated.

Option Q (Quit): This option is selected to return to the plot selection menu.

The program does not have the capability to generate a hard copy of the stratification display on a pen-plotter. A hard copy of the display can be obtained by a graphics-dump of the screen if a compatible printer is connected to the computer.

7.0 REPRESENTATIVE RESULTS

The new capabilities incorporated into the PRAISE Code for changing operating conditions during mid-life were exercised to generate leak probabilities. The base case inputs considered for all the results presented in this section are summarized below:

- Small lines ($R_i = 1.91$ inch, $h = 0.34$ inch)
- SCC initiated cracks only (304 properties)
- Maximum number of cracks at a weld = 6
- Fatigue crack growth coefficient (C) normally distributed
 - $C_{50} = 9.14 \times 10^{-11}$
 - $C_{90} = 3.5 \times 10^{-11}$
 - $m = 4$
 - $\Delta K_{th} = 4.6$
- Flow stress normally distributed
 - Mean = 43.0
 - Standard Deviation = 4.2
- PSI, No ISI
- Detectable leak = 3 gpm
- No vibratory stresses
- Residual stress for small lines
- O_2 at start-up = 8 ppm
- O_2 at steady-state = 0.2 ppm
- Steady-state temp = 560 °F
- Coolant conductivity = 0.2 $\mu S/cm$
- Heat-up duration = 5 hrs.
- Deadweight stress = 0.95 ksi
- DW + TE stresses = 8.02 ksi
- Operating pressure = 1.33 ksi
- Proof pressure = 1.56 ksi

Starting with this base case, the following variables were changed during mid-life (at 20 years in all the cases):

- 1) Steady-state and starting oxygen
- 2) Dead weight and thermal expansion stresses
- 3) Residual stresses

Figure 11 presents effects of reducing dissolved oxygen level during mid-life on the leak probabilities. Reducing the steady-state oxygen from 0.2 to 0.05 ppm decreases the cumulative probability of leak at 10 years by a factor of two. A change in the oxygen level during plant loading has much less influence on leak probabilities. The effect of lowering

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Figure 11. Effect of lowering oxygen at 20 years. The two numbers by each line are the oxygen concentration (ppm) in the coolant during plant start-up and steady state operation, respectively.

operating stresses on the leak probabilities is shown in Figure 12. Results are presented for the cases when the dead weight and thermal expansion stresses were reduced by a factor of two.

Figure 13 presents results for the cases where residual stresses were changed by IHSI or MSIP treatment to obtain linearly varying, axisymmetric residual stresses in the weld region. The distribution of these residual stresses is defined by specifying the mean and standard deviation of the stresses on the ID of the pipe. The recommended post-IHSI stress distribution based on the data analyzed in this report (mean = -44.7 ksi, standard deviation = 11.6 ksi) has a large effect on reducing the leak probabilities following the IHSI treatment.

PRI429A.SLK 06-06-1990

Figure 12. Effect of lowering operating stresses at 20 years. The two numbers by each line are the DW and DW + TE during steady-state operation, respectively.

PRI42RA.SLK 08-06-1990

Figure 13. Effect of changing residual stresses during mid-life.

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Appendix A

Detailed Formats for Input Cards

Detailed descriptions of the input cards read by PRAISE-CC are given in this section. The name, position on the card, format, and description of each variable are given.

CARD TITLE CARD
READ Always

ID 1A

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
TITLE	1-80	10A8	Problem description.

CARD PROBLEM CONTROL VARIABLES
READ Always

ID 0B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
INCIAT	1-5	I5	0: Run for pre-existing cracks. Include initiated cracks only if the sampled crack is below the BNDRY. 1: SCC initiated cracks only. 2: Pre-existing cracks only.
IFAILC	6-10	I5	Failure criteria to be used: 0: Net section failure. 1: J_{Ic} , dj/da exceedance. 2: Both.
ICRAKS	11-15	I5	Stress corrosion crack initiation sites.
IREPLS	16-20	I5	Number of replications for crack initiation problem (not used for INCIAT = 0).
IPRAIS	21-25	I5	0: Default to pre-existing cracks only.
IREPAR	26-30	I5	= 0: Leakers not repaired. = 1: Leakers that are detected are repaired. At the time of repair, all leakers are repaired.
BNDRY	31-40	F10.3	Boundary in terms of a/h , above which initiated cracks are not included. For example, 1.1: Initiated cracks will always be included. -0.1: Initiated cracks will never be included.
MTTYPE	41-45	I5	Material type. = 1: 304 = 2: 316NG
ISEED	46-60	I5	Seed for the random number generator.

CARD PROBLEM CONTROL VARIABLES (Cont'd)
READ Always

ID 0B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
IREMED	61-65	I5	Number of future remedial actions (change in water chemistry, IHSI, weld overlays, etc.).

CARD PROBLEM SPECIFICATION
READ Always

ID 1B

VARIABLE	COLUMNS FORMAT		DESCRIPTION
NTRIES	1-5	I5	<p>Option for number of replications to be drawn from each cell.</p> <p>When $NTRIES < 0$: Then $ABS(NTRIES)$ replications will be taken from each and every cell.</p> <p>If $NTRIES = 0$: Not used.</p> <p>If $NTRIES > 0$: The user inputs a number for each cell. This number is then multiplied by $NTRIES$ to obtain the number of samples for each cell.</p>
ISQARE	6-10	I5	<p>Cell definition option.</p> <p>$ISQARE = 0$: User inputs coordinates for each cell in the state space.</p> <p>$ISQARE = 1$: PRAISE-B internally sets up a regular grid of rectangular cells.</p> <p>$ISQARE = 2$: If $INCIAT = 1$.</p>
KTYPES	11-15	I5	<p>Number of transient types experienced by plant.</p>
KRKDIS	16-20	I5	<p>Initial crack size distributions.</p> <p>$KRKDIS = 1$: Crack depth is log-normal. Aspect ratio is log-normal.</p> <p>$KRKDIS = 2$: Crack depth is log-normal. Aspect ratio is exponential.</p> <p>$KRKDIS = 3$: Crack depth is exponential. Aspect ratio is log-normal.</p>

CARD PROBLEM SPECIFICATION (Cont'd)
READ Always

ID 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
			KRKDIS = 4: Crack depth is exponential. Aspect ratio is exponential.
NEVAL	21-25	I5	Option for times during plant lifetime when the reliability is to be evaluated. NEVAL < 0: Evaluation is performed for every ABS (NEVAL) year. NEVAL > 0: Number of user supplied times that an evaluation is performed.
NINSPT	26-30	I5	Number of user specified in-service inspection times.
NQUAKE	31-35	I5	Seismic evaluation option. NQUAKE = 0: No earthquakes are modeled. NQUAKE = 1: Earthquakes at each evaluation time.
IDEBUG	36-40	I5	Debugging output option. IDEBUG = 0: Normal output is printed. IDEBUG = 1: Additional debugging output will be supplied.
KONPRP	41-45	I5	Option for material constant (C) in the fatigue crack growth relationship. KONPRP = 0: C is log-normally distributed. KONPRP = 1: C is constant; i.e., the crack growth relationship is deterministic.

CARD PROBLEM SPECIFICATION (Cont'd)

ID 1B

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NEQINT	46-50	I5	<p>Number of seismic intensity classes to be simulated.</p> <p>If NQUAKE = 0: set NEQINT = 0.</p> <p>PRAISE-B, as presently dimensioned, can handle up to 10 classes.</p>
MCELLS	51-55	I5	<p>Number of cells in the calculational grid.</p> <p>If ISQARE = 1: The value of MCELLS is ignored.</p>
KNSFLO	56-60	I5	<p>Option for flow stress definition.</p> <p>KNSFLO = 0: Flow stress is normally distributed.</p> <p>KNSFLO = 1: Flow stress is constant.</p>
NSKIP	61-65	I5	<p>Parameter to specify the number of evaluation times which are skipped in the printout of the indicator functions.</p> <p>Subroutine OUTS prints every NSKIP-th evaluation time.</p>
NPSI	66-70	I5	<p>Option for pre-service ultrasonic inspection.</p> <p>NPSI = 0: No pre-service inspection.</p> <p>NPSI = 1: A pre-service inspection is modeled.</p>

CARD PROBLEM SPECIFICATION (Cont'd)
READ Always

ID 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
ISCC	71-75	I5	<p>Option for modeling stress corrosion cracking (SCC).</p> <p>ISCC = 1: Stress corrosion cracking only. ISCC = 0: Fatigue only (no SCC). ISCC = -1: Both SCC and fatigue. [If INCIAT $\neq$ 0, then ISCC should be either 1 or -1.]</p>
ISIGRS	76-80	I5	<p>Option for modeling contribution of welding residual stresses.</p> <p>ISIGRS = 0: Residual stresses are not modeled.</p> <p>ISIGRS = 1: Contribution of residual stresses is modeled (coefficients to be entered by the user).</p> <p>ISIGRS = 2: Contribution of residual stresses is modeled. Built-in residual stresses for large (20-30 inch) line used.</p> <p>ISIGRS = 3: Contribution of residual stresses is modeled. Built-in residual stresses for intermediate (10-20 inch) line used.</p> <p>ISIGRS = 4: Contribution of residual stresses is modeled. Built-in residual stresses for small (<10 inch) line used.</p> <p>ISIGRS = 5: Contribution of IHSI residual stresses is modeled. User to input stresses on the inside and outside surface.</p>

CARD PROBLEM SPECIFICATION (Cont'd)
READ Always

ID 1B

VARIABLE COLUMNS FORMAT

DESCRIPTION

ISIGRS = 6: Contribution of IHSI or MSIP residual stresses is modeled. User to input the mean and the standard deviation of stress at the ID.

CARD IHSI and MSIP RESIDUAL STRESS DEFINITION

ID 1C0

READ Only if ISIGRS = 5 or 6, on Card 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
RSIN	1-10	E10.3	Residual stress on the inside surface of a pipe (ksi). (For ISIGRS = 5)
RSOUT	11-20	E10.3	Residual stress on the outside surface of a pipe (ksi). (For ISIGRS = 5)
RSINM	1-10	E10.3	Mean of the IHSI or MSIP residual stress on the ID in ksi. (For ISIGRS = 6)
RSINSD	1-10	E10.3	Standard deviation of the IHSI or MSIP stress on the ID in ksi. (For ISIGRS = 6)

CARD RESIDUAL STRESSES MODEL DEFINITION
READ Only if ISIGRS = 1 on Card 1B

ID 1C

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
KKA	1-5	I5	The number of (a/b) terms in the polynomial which define the contribution of residual stress to the "RMS-averaged" stress intensity factor in the depth direction.
LLA	6-10	I5	The number of (a/h) terms in the polynomial which define the contribution of residual stress to the "RMS-averaged" stress intensity factor in the depth direction.
KKB	11-15	I5	The number of (a/b) terms in the polynomial which define the contribution on residual stress to the "RMS-averaged" stress intensity factor in the length direction.
LLB	16-20	15	The number of (a/h) terms in the polynomial which define the contribution of residual stress to the "RMS-averaged" stress intensity factor in the length direction.

CARD TIME PARAMETERS, NDE PARAMETERS
READ Always

ID 1D

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
THRIZN	1-10	E10.3	Maximum plant lifetime for the simulation (years).
DTSCC	11-20	E10.3	Time step to be used in calculating SCC growth (years). Used only if ISCC = 1 on Card 1B.
ICTYPE	21-25	I5	Crack orientation flag. = 0: Circumferential crack analysis = 1: Longitudinal crack analysis (disabled in current PC-PRAISE).
IPTYPE	26-30	I5	Default sets of NDE parameters EPST, ASTAR and ANUU for various pipe types. = 0: Thick-walled austenitic pipe = 1: Thick-walled ferritic pipe = 2: Thin-walled austenitic pipe

Default values are as follows:

IPTYPE	EPST	ASTAR	ANUU
0	0.	0.5*THICK	1.6
1	0.005	0.25	3.0
2	0.005	0.25	1.33

CARD TIME PARAMETERS, NDE PARAMETERS (Cont'd)

ID 1D

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
EPST	31-40	E10.0	User-specified value of "ε" parameter; overrides default value. Leave blank to use default.
ASTAR	41-50	E10.0	User-specified depth of crack with 50% probability of detection (inches); overrides default value. Leave blank to use default.
TRANSD	51-60	E10.0	Transducer diameter (inches); default = 1.0 inch.
ANUU	61-70	E10.0	User-specified value of "v" parameter; overrides default value. Leave blank to use default.

CARD TIME PARAMETERS
READ Always

ID 1D

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
THRIZN	1-10	E10.3	Maximum plant lifetime for the simulation.
DTSCC	11-20	E10.3	Time step to be used in calculating SCC growth. Used only if ISCC = 1 or -1 on Card 1B.

CARD PIPE DIMENSIONS
READ Always

ID 2A

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
THICK	1-10	E10.3	Wall thickness of the pipe (inches).
RIN	11-20	E10.3	Inside radius of the pipe (inches).
ELOVRR	21-30	E10.3	L/R ratio: Not required if IFAILC = 0.

CARD FATIGUE CRACK GROWTH CHARACTERISTICS
READ Always

ID 2B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
THRHLD	1-10	E10.3	Threshold value in the crack growth relationship ($\text{ksi-in}^{1/2}$).
EMEXP	11-20	E10.3	Exponent in the crack growth relationship.
CONSMU	21-30	E10.3	Parameter for the constant in the crack growth relationship. If KONPRP = 1: CONSMU is the constant. If KONPRP = 0: CONSMU is the median of the log-normal distribution that describes the constant.
CONS90	31-40	E10.3	Parameter for the constant in the crack growth relationship. If KONPRP = 1: CONS90 is ignored. If KONPRP = 0: CONS90 is the 90th percentile of the log-normal distribution.

CARD SCC VARIABLE
READ Always

ID 2B-1

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
OSTART	1-10	F10.5	O ₂ at start-up (ppm).
OSTEDY	11-20	F10.5	O ₂ at steady state (ppm).
TFSTDY	21-30	F10.5	Steady-state temperature (°F).
DURATN	31-40	F10.5	Duration of heat-up transient (in hours).
CONDOC	41-50	F10.5	Coolant conductivity (μS/cm).

CARD FLOW STRESS
READ Always

ID 2C

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
SFLOMU	1-10	E10.4	The mean value of the flow stress (ksi).
SFLOSD	11-20	E10.4	Standard deviation of the flow stress (ksi). (Read if KNSFLO = 0.)
XJIC	21-30	E10.4	J_{Ic} (in-kips/in ²) Required only if IFAILC $\neq$ 0.
DJDAMT	31-40	E10.4	dJ/da in ksi Required only if IFAILC $\neq$ 0.
SIG0	41-50	E10.4	Yield strength in ksi. Required only if IFAILC $\neq$ 0.
DEE	51-60	E10.4	The constant D in ksi in the power law $\epsilon = (\sigma/D)^n$ for hardening material. Required only if IFAILC $\neq$ 0.
YOUNGS	61-70	E10.4	Young's modulus in ksi. Required only if IFAILC $\neq$ 0.
XN	71-80	E10.4	Exponent n in the power law $\epsilon = (\sigma/D)^n$ for hardening material. Required only if IFAILC $\neq$ 0.

CARD INITIAL CRACK DEPTH DISTRIBUTION
READ Only if INCIAT * 0

ID 3A

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
AMEDIN	1-10	E10.3	Median of the log-normal distribution on crack depth. (Read if KRKDIS = 1, 2)
ASIGMA	11-20	E10.3	Shape factor (= standard deviation of logarithm of A) of the log-normal distribution on crack depth. (Read if KRKDIS = 1, 2)
ALAMDA	1-10	E10.3	Rate parameter (IN^{-1}) for exponential distribution on crack depth. (Read if KRKDIS = 3, 4)

CARD INITIAL CRACK ASPECT RATIO DISTRIBUTION
READ Only if INCIAT = 0

ID 3B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
BOAMED	1-10	E10.3	Parameter analogous to the median in the truncated log-normal distribution on initial crack aspect ratio. (Read if KRKDIS = 1,3)
BOASIG	11-20	E10.3	Parameter analogous to the shape factor in the truncated log-normal distribution on initial crack aspect ratio. (Read if KRKDIS = 1, 3)
BOALDA	1-10	E10.3	Rate parameter for shifted exponential distribution on initial crack aspect ratio. (Read if KRKDIS = 2, 4)

CARD EARTHQUAKE EVALUATION TIMES
READ Only if NEVAL > 0

ID 4A

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
TEVAL	1-80	8E10.3	Evaluation time (years).

CARD IN-SERVICE INSPECTION TIMES
READ Only if NINSPT > 0

ID 4B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
TINSPT	1-80	8E10.3	In-service inspection time (years).

CARD LEAK RATE AND DETECTION DEFINITIONS
READ Always

ID 4C

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
FNDLEK	1-10	E10.3	Threshold for leak rates which are detectable.
ALKBIG	11-20	E10.3	Threshold for discriminating between leaks and big leaks.

CARD STRATIFIED SAMPLE SPACE
READ Only if ISQARE = 1

ID 5A

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NAOH	1-5	I5	<p>Number of divisions of the a/h coordinate in the sample space definition.</p> <p>If the entire length of the a/h coordinate is to be used, read in as NAOH. If the length of the a/h coordinate is limited to the interval $AOHLOW \leq a/h \leq AOHUP$, read in as -NAOH. The a/h coordinate is limited to the region $AOHLOW \leq a/h \leq AOHUP$.</p>
NAOB	6-10	I5	<p>Number of division of the a/b coordinate in the sample space definition.</p> <p>If the entire length of the a/b coordinate is to be used, read in as NAOB. If the length of the a/b coordinate is limited to the interval $AOBLFT \leq a/b \leq AOBRGT$, read in as -NAOB. The a/b coordinate is limited to the region $AOBLFT \leq a/b \leq AOBRGT$.</p>
AOHLOW	11-20	E10.3	Lower limit on the a/h coordinate. (Ignored if NAOH < 0.)
AOHUP	21-30	E10.3	Upper limit on the a/h coordinate. (Ignored if NAOH < 0.)
AOBLFT	31-40	E10.3	Lower limit on the a/b coordinate. (Ignored if NAOB < 0.)
AOBRGT	41-50	E10.3	Upper limit on the a/b coordinate. (Ignored if NAOB < 0.)

CARD STRATIFIED SAMPLE SPACE (Cont'd)

ID 5A

READ Only if ISQARE = 0

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
AOHSIZ(M,1)	1-10	E10.4	Lower boundary of the a/h coordinate in the definition of the m-th stratification cell.
AOHSIZ(M,2)	11-20	E10.4	Upper boundary of the a/h coordinate in the definition of the m-th stratification cell.
AOBSIZ(M,1)	21-30	E10.4	Left boundary of the a/b coordinate in the definition of the m-th stratification cell.
AOBSIZ(M,2)	31-40	E10.4	Right boundary of the a/b coordinate in the definition of the m-th stratification cell.
NUMTRY	41-50	I10	Number of replications to be taken from the m-th cell.

CARD STRATIFIED SAMPLE SPACE (Cont'd)
READ Only if ISQARE = 1 and NTRIES > 0

ID 5A

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NUMTRY(M)	1-50	5I10	Number of replications to be taken from the m-th cell.

CARD STRESS VALUES
READ Always

ID 6A

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
SIGCLD	1-10	E10.3	Deadweight stress (ksi). This is the load controlled stress in the cold shutdown condition.
SGDWTE	11-20	E10.3	Deadweight and restraint of thermal expansion components of stress in the hot normal operating condition.
OPPRES	21-30	E10.3	Normal operating pressure of the system (ksi).
PRFPRS	31-40	E10.3	Pressure in hydrostatic proof test (ksi). If no proof test is to be modeled, set this value to any arbitrary negative number.
SIGVIB	41-50	E10.3	Peak-to-peak amplitude of the high cycle vibratory stresses (ksi). If SIGVIB < 0: No vibratory stresses are modeled.
VBTHLD	51-60	E10.3	Threshold value of the load ratio (R^* in Section 3.9 of NUREG/CR-2301) which is used in the vibratory stress model.

CARD SPECIFICATIONS FOR THE TABLES IN THE $g_{\min}$
AND $g_{\max}$ FUNCTIONS
READ Only if KTYPES > 1

ID 6B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NX	1-5	I5	Number of entries in the a/b coordinate for the input of the $g_{\min}^*$ and $g_{\max}^*$ functions.
NY	6-10	I5	Number of entries in the a/h coordinate for the input of the $g_{\min}^*$ and $g_{\max}^*$ functions.
IX	11-15	I5	Number of entries in the a/b coordinate for the internal tables on the $g_{\min}$ and $g_{\max}$.
IY	16-20	I5	Number of entries in the a/h coordinate for the internal tables on $g_{\min}$ and $g_{\max}$.

**CARD A/H COORDINATES FOR TABULAR INPUT OF
CONTRIBUTION FROM RADIAL GRADIENT THERMAL
STRESSES TO STRESS INTENSITY FACTOR**

ID 6C

READ Only if KTYPES > 1

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
AAOH(I)	1-80	8F10.3	Values of the a/h coordinate in the tabulated input for the contribution of radial gradient thermal stress to the stress intensity factor (I = 1, ..., NY).

**CARD B/A COORDINATE FOR TABULAR INPUT OF
CONTRIBUTION FROM RADIAL GRADIENT THERMAL
STRESSES TO STRESS INTENSITY FACTORS**

ID 6D

READ Only if KTYPES > 1

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
ABOA(I)	1-80	8F10.3	Values of the b/a coordinate in the tabulated input for the contribution of radial gradient thermal stresses to the stress intensity problem ($I = 1, \dots, NY$).

**CARD FREQUENCY OF HEAT-UP/COOL-DOWN AND
TRANSIENTS**

ID 6E

READ Always

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NCYBLK	1-5	I5	Number of cycles in the equivalent event.
BLAMDA(K)	6-10	F5.2	Arrival time parameter for transients. If BLAMDA(K) > 0.0: Then k-th transient arrives at uniformly spaced intervals of BLAMDA(K) years. If BLAMDA (K) < 0.0: Then k-th transient is treated as a Poisson's process with ABS (BLAMDA(K)) as the average number of arrivals per unit time. If stress corrosion crack initiation is included, then BLAMDA(K) should always be greater than 0.0 (the transient arrival times uniformly spaced).
TEMP(K)	11-20	F10.5	Temperature excursion (°F) during the k-th transient.
TITLE(K)	21-80	6A10	Description for the k-th transient type.

CARD TABULATED FUNCTIONS FOR $g^*_{\min}$ AND $g^*_{\max}$
 READ All transients except the heat-up/cool-down, i.e., $K > 1$

ID 6F

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
			This outer loop is on the b/a coordinate and is read in reverse order or ($I = NX, NX-1, \dots, 1$).
GDAMIN(I,J,K)	1-72	9F8.5	$g^*_{\min,a} (J = 1, \dots, NY).$
GDAMAX(I,J,K)	1-72	9F8.5	$g^*_{\max,a} (J = 1, \dots, NY).$
GDAMIN(I,J,K)	1-72	9F8.5	$g^*_{\min,b} (J = 1, \dots, NY).$
GDAMAX(I,J,K)	1-72	9F8.5	$g^*_{\max,b} (J = 1, \dots, NY).$

**CARD COEFFICIENTS FOR THE POLYNOMIAL THAT DEFINES ID 6G
THE CONTRIBUTION OF WELDING RESIDUAL STRESSES
TO THE STRESS INTENSITY FACTOR IN THE DEPTH
DIRECTION**

READ Only if ISIGRS = 1 on Card 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
B(L,K)	1-80	8E10.3	(b(l,k), l = 1, LLA). A separate card is used for each value of k (k = 1, ..., KKA). LLA corresponds to L in Equation 3-11; KKA corresponds to K in Equation 3-11 (NUREG/CR-2301).

**CARD COEFFICIENTS FOR THE POLYNOMIAL THAT
 DEFINES THE CONTRIBUTION OF WELDING
 RESIDUAL STRESSES TO THE STRESS
 INTENSITY FACTOR IN THE LENGTH DIRECTION**

ID 6H

READ Only if ISIGRS = 1 on Card 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
B(L,K)	1-80	8E10.3	(b(l,k), l = 1, ..., LLB).

A separate card is used for each value of k
 (k = 1, ..., KKB).

LLB corresponds to L in Equation 3-11;
 KKA corresponds to K in Equation 3-11
 (NUREG/CR-2301).

CARD EARTHQUAKES PER MAGNITUDE CATEGORY

ID 7A

READ Only if NQUAKE = 1 on Card 1B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
NEQCLS(N)	1-80	I6I5	Number of earthquakes in the n-th magnitude category. A maximum of ten earthquakes can be modeled in each category.

CARD SEISMIC CRACK GROWTH PARAMETERS
 READ Only if NQUAKE = 1 on Card 1B

ID 7B

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
			The following card is repeated for each earthquake that is modeled. They are grouped by earthquake intensity category. N is the index on the intensity category, while LEQ is the index on earthquakes within an intensity category.
NCYCEQ(N,LEQ)	1-10	I10	Number of equivalent cycles used to represent the crack growth.
SIGEQ(N,LEQ)	11-20	F10.3	S^4 -- The fourth power of the S-factor.
SGEQMX(N,LEQ)	21-30	F10.3	The load-controlled stress (ksi).
TITLE(N,LEQ)	31-80	5A10	Description for this particular earthquake.

**CARD INPUTS FOR MID-LIFE CHANGES IN
OPERATING STRESSES, CHEMISTRY,
OR RESIDUAL STRESSES**

ID 8

READ Only if IREMED > 0

VARIABLE	COLUMNS	FORMAT	DESCRIPTION
RTIMES(I)	1-10	E10.4	Time (in years) at which one or more of the following variables are changed.
THICKS(I)	11-20	F10.4	Wall thickness of pipe (inches).
OSTARS(I)	21-30	E10.4	O ₂ at start-up (ppm).
OSTDYS(I)	31-40	E10.4	O ₂ at steady state (ppm).
CONDUS(I)	41-50	E10.4	Coolant conductivity (μ S/CM).
SGCLDS(I)	51-60	E10.4	Deadweight stress (ksi).
SDWTES(I)	61-70	E10.4	Deadweight and restraint of thermal expansion components of stress in the hot normal operating condition (ksi).
SGVIBS(I)	71-80	E10.4	Peak-to-peak amplitude of the high cycle vibratory stresses (ksi). If SIGVIB < 0, no vibratory stresses are modeled.
ISIGRX(I)	1-10	I10	IHSI or MSIP residual stress flag (6 or 7). A value of 7 indicates no change from the previous state.
RSINMS(I)	11-20	E10.4	Mean value of the stress at the ID in ksi (MSIP or IHSI stress). Not required if ISIGRX(I) is 7.
RSISDS(I)	21-30	E10.4	Standard deviation of the stress at the ID in ksi (MSIP or IHSI stress). Not required if ISIGRX(I) is 7.

END

DATE FILMED

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