Transactions of the 17th International Conference on **Paper # D03-5**
*Structural Mechanics in Reactor Technology (*SMiRT 17)
Prague, Czech Republic, August 17 –22, 2003

Structural Assessment of a Corrosion-Degraded Reactor Pressure Vessel Head[1]

Paul T. Williams, [1)] B. Richard Bass[1)]

1) Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

ABSTRACT

In support of United States Nuclear Regulatory Commission (NRC) investigations, structural assessments of the degraded closure head of a nuclear power reactor pressure vessel (RPV) are being carried out at Oak Ridge National Laboratory. The degradation resulted from significant corrosion of the low-alloy pressure vessel steel surrounding a control-rod drive mechanism (CRDM) nozzle penetration located near the center of the head. Leakage of borated primary reactor-coolant-system (RCS) water from a crack in a CRDM nozzle provided a boric-acid source that, combined with environmental mechanisms, is judged to have produced the wastage cavity around the nozzle. This wastage cavity had a “footprint” of approximately 127 mm × 152 mm, extending completely through the ferritic steel head and exposing the stainless-steel cladding layer.

A stochastic model has been developed that estimates the uncertainty in the predictive accuracy of finite-element simulations of failure by plastic collapse of the exposed clad layer in the wastage cavity. Given a computational prediction of the burst pressure for a specific configuration of the RPV wastage cavity, the scaled stochastic model provides an estimate of the cumulative probability that the true burst pressure will be less than a prescribed service pressure load. The technical bases for the stochastic failure model are (1) experimental data obtained from nine disk burst tests with geometries and material properties relevant to the RPV pressure loading, wastage cavity footprint, and cladding, (2) nonlinear, large- deformation, elastic-plastic discrete-element analyses of the disk burst test specimens, (3) nonlinear, finite-strain, elastic-plastic finite-element analyses performed for the current study, and (4) a theoretical model for plastic instability in a circular diaphragm under pressure loading applied to the disk burst tests.

The resulting stochastic model can be scaled by the results of a finite-element simulation of the wastage cavity to provide failure-probability estimates for the exposed clad layer in the RPV wastage cavity as a function of internal pressure loading. The failure mode addressed specifically by this model is *incipient tensile instability* or plastic collapse of the unbacked cladding layer. Other failure modes (not discussed in this paper) are also being investigated, including failure by unstable ductile tearing of possible surface flaws in the cladding. Combining these failure models allows a risk-informed assessment of the structural integrity of the degraded RPV to be carried out.

KEY WORDS: corrosion, damage, degradation, finite-element, nuclear, power plant, probability, pressure vessel,

INTRODUCTION

Pursuant to the United States Nuclear Regulatory Commission’s (NRC) Bulletin 2001-01 [1], workers at the Davis-Besse Nuclear Power Station in Oak Harbor, Ohio, USA, began a refueling outage [2] on 16 February 2002. This effort included the inspection of the reactor pressure vessel (RPV) head penetrations with emphasis on the control rod drive mechanism (CRDM) nozzles. During this inspection, indications were detected in 5 of the 69 CRDM nozzles penetrating the head. In three of the five nozzles (Nozzles 1, 2, and 3, located near the center of the RPV closure head), the indications were determined to be axial cracks that extended all the way through the nozzle, thereby allowing

---

[1] Research Sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission under Interagency Agreement 1886-N011-9B with the U.S. Department of Energy under Contract DE-AC05-00OR22725 with UT-Battelle, LLC. The submitted manuscript has been authored by a contractor of the U.S. Government. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes. This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

leakage of borated primary reactor cooling system (RCS) water with a subsequent buildup of boric acid deposits on the outside of the head.

Upon completion of boric acid removal on 7 March 2002, a visual examination of the RPV head identified a large external cavity adjacent to CRDM Nozzle 3 and extending downhill toward Nozzle 11 (see Fig. 1). Followup characterization by ultrasonic testing (UT) confirmed the wastage of the low-alloy steel head. The wastage region was found to extend approximately 127 mm (5 in.) downhill from Nozzle 3, with a cavity width ranging from approximately 102 to 127 mm (4 to 5 in.) and a depth of approximately 152 mm (6 in.). Corrosion, induced by the boric acid, degraded the vessel head and created this irregular cavity. The cavity had penetrated through the low alloy steel portion of the RPV wall, leaving only the stainless-steel cladding to maintain the integrity of the pressure boundary. The cladding thickness varied somewhat with a minimum design thickness of 3.2 mm (1/8 in.). Subsequent examination found evidence of a series of part-through cracks on the outer surface of the cladding.

In support of investigations by the NRC's Office of Nuclear Regulatory Research, the Heavy-Section Steel Technology (HSST) Program at Oak Ridge National Laboratory (ORNL) is developing failure models for the exposed stainless-steel cladding layer in the wastage cavity of the Davis-Besse RPV head. The specific failure mode addressed by the stochastic model described in this paper is *incipient tensile plastic instability* (i.e., plastic collapse) of the cladding. Other failure mechanisms (not discussed herein) are also being investigated, including the onset of stable ductile tearing with a transition to unstable ductile fracture. Combining these models, covering a range of potential failure mechanisms, allows a risk-informed assessment of the structural integrity of the degraded RPV to be carried out.

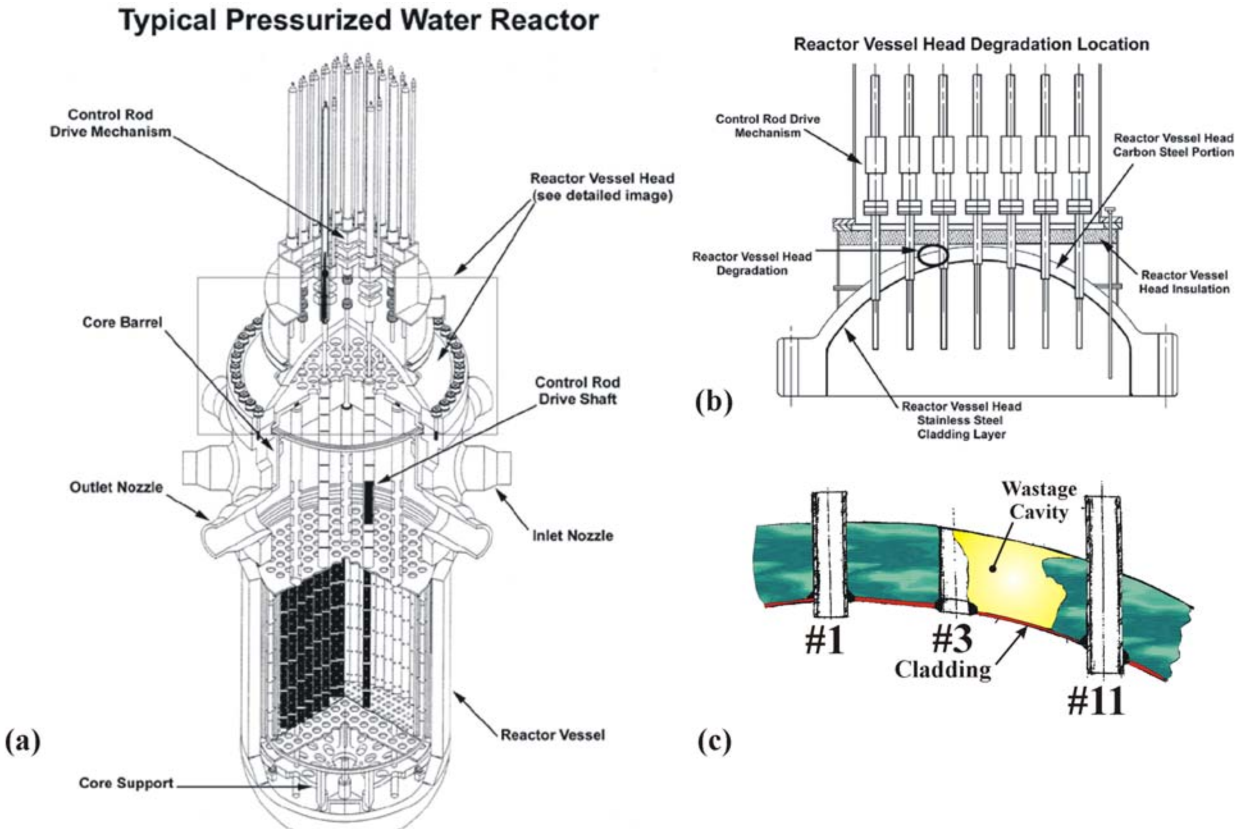

Fig. 1. (a) Schematic of a typical pressurized water reactor, (b) approximate location of wastage cavity near top of RPV head, and (c) sketch of cross section of wastage cavity.

STOCHASTIC MODEL DEVELOPMENT FOR PLASTIC COLLAPSE

The technical bases employed in the construction of the stochastic plastic collapse failure model are:

1) *experimental data* obtained during disk burst tests reported by Riccardella [3] with loadings, geometries, and materials relevant to the Davis-Besse pressure loading, wastage-area footprint, and cladding,

2) nonlinear, large-deformation, elastic-plastic *discrete-element analyses* of the disk burst tests also reported in [3] (GAPL-3 discrete-element code[4]),
3) nonlinear, finite-strain, elastic-plastic *finite-element analyses* performed for the current study (ABAQUS finite-element code[5]) of the nine disk burst test specimens reported in [3], and
4) a *theoretical criterion* for plastic instability in a circular diaphragm under pressure loading, due to Hill [6] with extensions by Chakrabarty and Alexander [7] (as cited in [8]), applied to the disk burst tests.

Experimental – Disk Burst Tests

In the early 1970s, constrained disk burst tests were carried out under the sponsorship of the *PVRC Subcommittee on Effective Utilization of Yield Strength* [9]. This test program employed a range of materials and specimen geometries that were relevant to components in a nuclear power plant steam supply system.[2] The geometries of the three test specimens analyzed in [3] are shown in Fig. 2, the test matrix is shown in Table 1, and the properties of the three materials are presented in Table 2. The nine disk burst tests produced three center failures and six edge failures over a range of burst pressures from 25.9 to 103.4 MPa (3.75 to 15 ksi) as shown in Table 1.

Table 1. Test Matrix for Disk Burst Tests [3]

Test Number	Material	Geometry	Fillet Radius (mm)	Diaphragm Thickness (mm)	Effective Diaphragm Radius (mm)	Experimental Results	
						Burst Pressure (MPa)	Location of Failure
1	SS 304	A	9.53	6.350	66.68	103.4	Edge
2		B	3.18	3.175	73.025	46.9	Center
3		C	9.53	3.175	66.675	53.1	Center
4	A533B	A	9.53	6.350	66.675	75.8	Edge
5		B	3.18	3.175	73.025	36.5	Edge
6		C	9.53	3.175	66.675	46.2	Center
7	ABS-C	A	9.53	6.350	66.675	67.6	Edge
8		B	3.18	3.175	73.025	25.9	Edge
9		C	9.53	3.175	66.675	34.1	Edge

Table 2. Property Data for Materials in Disk Burst Tests [3]

Material	Yield Strength 0.2% offset (MPa)	Ultimate Strength (MPa)	Strain at Ultimate (-)	True Stress 0.2% offset (MPa)	True Ultimate Stress (MPa)	Log Strain at Ultimate (-)	Power Law Fit*	
							K (MPa)	*n* (-)
SS304	234	579	0.54	235	892	0.432	1120	0.27
A-533B	510	662	0.17	511	774	0.157	961	0.12
ABS-C	269	441	0.31	269	578	0.270	725	0.17

*The power-law parameters in Table 2 were fitted for the current study where $\bar{\sigma} = K\bar{\varepsilon}^n$ and $\bar{\sigma}$, $\bar{\varepsilon}$ are the effective true stress and effective total true strain, respectively.

---

[2] The three materials were representative of reactor core support structures and piping, the reactor pressure vessel, and plant component support structures [3].

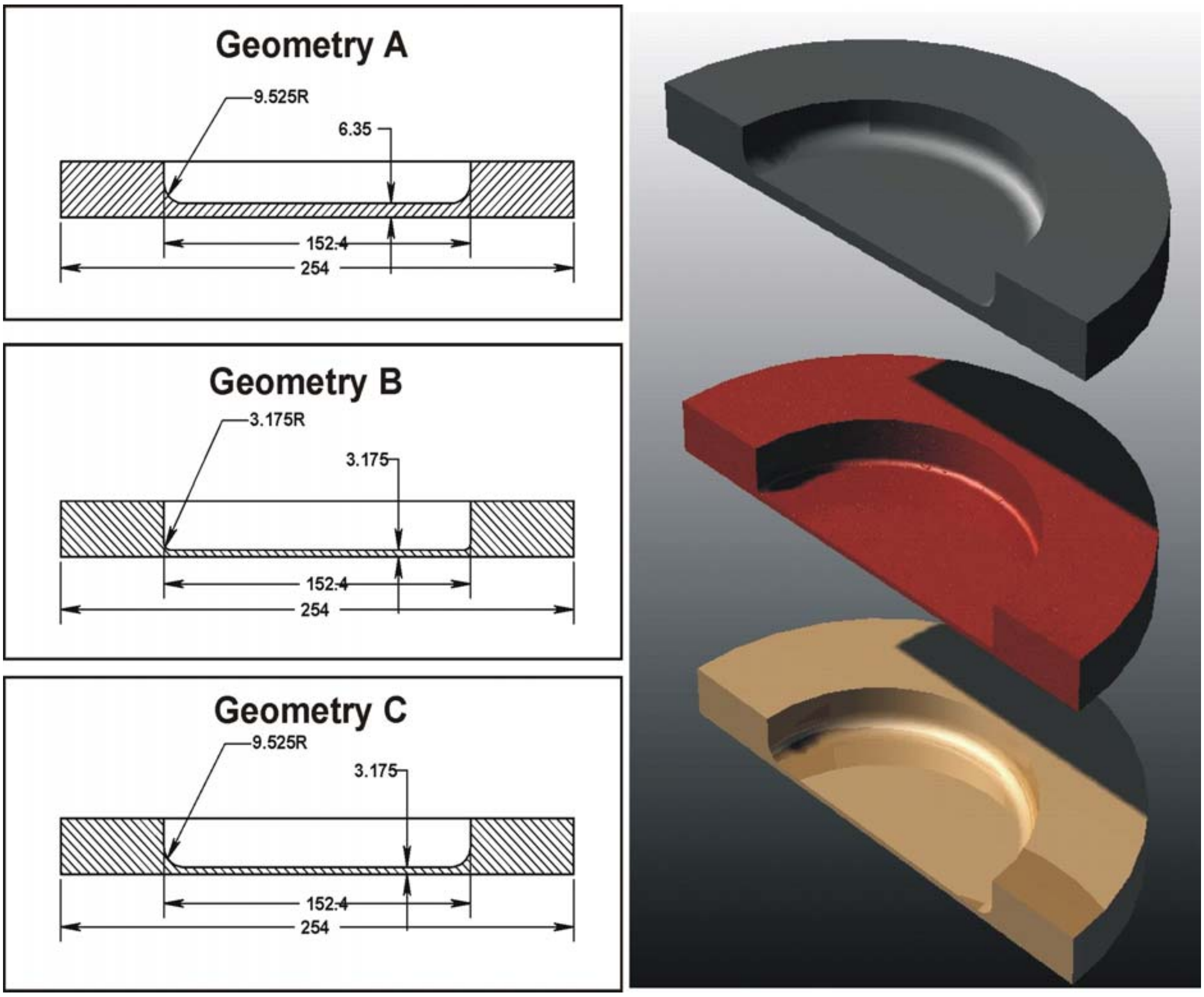

Fig. 2. Geometric descriptions of the three disk burst specimens used in [1] (all dimensions are in mm). Images on the right are computer-rendered views of ½-symmetry solid models of the three specimens.

Computational – Axisymmetric Discrete-Element and Finite-Element Models

The results of a computational study were presented in ref. [3] in which the nine tests were simulated using the GAPL-3 computer code. [4] GAPL-3 applied the *discrete-element* method using a two-layered system of elements: one layer for the strain-displacement field and a second layer for the stress field. The code performs an elastic-plastic large-deformation analysis of stresses, strains, loads, and displacements of thin plates or axisymmetric shells with pressure loading. At each incremental load step, the code iterated to resolve both geometric and material nonlinearities, thus establishing a condition of static equilibrium. The GAPL-3 code did not account for the reduction in thickness of the diaphragm with increasing load, and, therefore, was unable to demonstrate the "tailing up" of the experimental center-deflection histories. As discussed in [3], the thin-shell approximation of the GAPL-3 code is not strictly valid in the fillet region. The GAPL-3 model did include a plastic-hinge type of strain redistribution, but the strain concentration effect due to the fillet radius was not accounted for, since the predicted strain distribution in the cross-section of the fillet was linear by assumption. These approximations in the analysis were driven by the limitations of the computer resources available at the time of the study in 1972.

The current study reanalyzed all nine disk-burst tests using the ABAQUS [5] finite-element code. With current computing power, many of the simplifying assumptions required in 1972 could be removed to provide a more detailed analysis. The analyses applied a nonlinear finite-strain procedure with an incrementally increasing pressure load applied from zero up to the load at which numerical instabilities caused the ABAQUS code to abort the execution.

Theoretical – Plastic Instability Theory

A plastic instability theory due to Hill [6] with extensions by Chakrabarty and Alexander [7] for a pressurized circular diaphragm constrained at the edges is presented in ref. [8]. Applying a power-law constitutive form to relate effective stress to effective strain in the plastic region,

$$[\ \mathbf{M}\ ] \tag{1}$$

the effective strain at instability is shown by the theoretical treatment given in [6] to be

$$\bar{\varepsilon}_{crit} = \frac{4}{11}\left(2n+1\right) \tag{2}$$

where n is the power-law exponent in the constitutive equation, Eq. (1). Based on a Tresca yield surface, an alternative instability criterion was developed by Chakrabarty and Alexander [7] where they determined the critical effective strain as

$$\bar{\varepsilon}_{crit} = \frac{2\left(2-n\right)\left(1+2n\right)}{11-4n} \tag{3}$$

Computational and Theoretical Model Results

Computational results using the GAPL-3 code (see Table 3) were presented in ref. [3], where converged solutions were obtained for eight of the nine tests. Comparison of experimental and computational centerline deflections showed good agreement for the eight converged cases. In the nonconverged case (ABS-C, geometry C), some difficulty was reported in getting convergence at high pressures. In all cases the experimental data showed a "tailing up" as the pressure approached burst pressure, which the computational model was unable to capture. In general, the prediction of the burst pressure for the eight converged cases showed good agreement with the experimentally-determined burst pressures. Defining α as the ratio of the experimental burst pressure to the computationally-predicted pressure at numerical instability, the mean for α was 1.19 with a standard error for the mean of ± 0.484 and a standard deviation for the sample of 0.137.

The finite-element models developed for ABAQUS were able to obtain burst pressure predictions for all nine tests, where the *pressure at numerical instability*, P_{NI}, is defined as the pressure at which a breakdown occurs in the numerical procedure, causing the run to abort. For a nonlinear, finite-strain, static load step, ABAQUS uses automatic sizing of the load increment to maintain numerical stability. The number of iterations needed to find a converged solution for a load increment varies depending on the degree of nonlinearity in the system. If the solution has not converged within 16 iterations or if the solution appears to diverge, ABAQUS abandons the increment and starts again with the increment size set to 25% of its previous value. An attempt is then made at finding a converged solution with this smaller load increment. If the increment still fails to converge, ABAQUS reduces the increment size again. ABAQUS allows a maximum of five cutbacks in an increment before aborting the analysis. Therefore, the ABAQUS code will attempt a total of 96 iterations with six increments sizes before abandoning the solution. The initial load size for the failing increment was typically already very small due to difficulties in convergence with the previous and final successfully-converged load increment.

Table 3. Comparison of Computational Predictions to Experimental Burst Pressures

		Experimental		Discrete-Element Solutions			Plastic Instability Theory			Finite-Element Solutions		
Material Type	Geometry ID	Burst Pressure (BP) (MPa)	Location of Failure	Pressure at Instability (P_{NI}) (MPa)	Location of Failure	Exp. BP / P_{NI} α	Pressure at Instability (P_{NI}) (MPa)	Location of Failure	Exp. BP / P_{NI} α	Pressure at Instability (P_{NI}) (MPa)	Location of Failure	Exp. BP / P_{NI} α
SS 304	A	103.42	Edge	84.81	Edge	1.22	89.47	Center	1.16	91.62	Edge	1.13
	B	46.88	Center	33.09	Edge	1.42	40.84	Center	1.15	42.86	Edge	1.09
	C	53.09	Center	51.02	Center	1.04	44.73	Center	1.19	45.44	Center	1.17
A533B	A	75.84	Edge	67.57	Edge	1.12	85.32	Center	0.89	84.53	Edge	0.90
	B	36.54	Edge	28.96	Edge	1.26	38.95	Center	0.94	36.11	Edge	1.01
	C	46.19	Center	46.88	Center	0.99	42.66	Center	1.08	41.60	Edge	1.11
ABS-C	A	67.57	Edge	55.16	Edge	1.23	61.69	Center	1.10	62.41	Edge	1.08
	B	25.86	Edge	20.68	Edge	1.25	28.16	Center	0.92	28.91	Edge	0.89
	C	34.06	Edge				30.85	Center	1.10	30.76	Edge/Center	1.11

A summary of all 26 P_{NI} values is given in Table 3. Combining the 26 cases into a single sample gives a mean for α of 1.098 with a standard error for the mean of ± 0.0251 and a standard deviation for the sample of 0.1281. Even though the theoretical treatment is applicable only for center failures, the good agreement between the experiments (including those that failed at the edges) suggests that, for the edge-failure cases, the specimens were also close to a condition of plastic collapse at the center when they failed first at the edge.

Stochastic Plastic-Collapse Failure Model

It is postulated that the trends observed in the ratios of experimentally-observed failure pressures in the nine disk burst tests in ref. [3] to calculated P_{NI} values are representative of the uncertainty in the predictive accuracy of computational estimates of the burst pressure in the Davis-Besse wastage-area problem. Given a calculated P_{NI} for a specific configuration of the wastage area, the stochastic model can be scaled by P_{NI} to provide estimates of the cumulative probability that the true burst pressure will be less than a given service pressure, specifically providing a failure pressure with its associated probability.

This postulated linkage of the test specimens to the Davis-Besse problem is obviously an approximation, since the wastage area footprints and constraint conditions are not identical to the circular diaphragms used in the tests. The transferability of the results of the disk burst tests to the wastage-cavity problem is in part, therefore, dependent on the ability of the finite-element models to capture, as accurately as is feasible and based on the best current knowledge, the actual geometry of the wastage area footprint [10]. Accurate material properties are also an important input to the analysis. Experimental and computational studies are currently proceeding at ORNL under the NRC-sponsored HSST program to investigate the question of *transferability* of test specimen data to in-service conditions.

The *Expert Fit*$^{©}$ [11] computer program was used to construct several stochastic models of the sample data presented in Table 3. Using a combination of heuristic criteria and *Goodness of Fit* statistics, twenty-six continuous distributions [12] were examined, where the top-ranked model was a Log-Laplace distribution of the form (see Fig. 3)

$$f_{LP}(\alpha\,|\,0,1.1057,11.45441)=\begin{cases}5.17971\left(\dfrac{\alpha}{1.1057}\right)^{10.45441} & ;\ 0<\alpha<1.1057\\[2ex] 5.17971\left(\dfrac{\alpha}{1.1057}\right)^{-12.45441} & ;\ \alpha\ge 1.1057\end{cases}$$

$$\Pr(X\le\alpha)=F_{LP}(\alpha\,|\,0,1.1057,11.45441)=\begin{cases}\dfrac{1}{2}\left(\dfrac{\alpha}{1.1057}\right)^{11.45441} & ;\ 0<\alpha<1.1057\\[2ex] 1-\dfrac{1}{2}\left(\dfrac{\alpha}{1.1057}\right)^{-11.45441} & ;\ \alpha\ge 1.1057\end{cases} \quad (4)$$

where f_{LP} is the probability density function, F_{LP} is the cumulative distribution function, and α is the ratio of the true (but unknown) burst pressure to the calculated pressure at numerical instability, P_{NI}. The percentile function for the Log-Laplace distribution is

$$Q_{LP}(p\,|\,0,1.1057,11.45441)=$$

$$\alpha_p=\begin{cases}\exp\left[\ln(1.1057)+\dfrac{\ln(2p)}{11.45441}\right] & ;p\le 0.5\\[2ex] \exp\left[\ln(1.1057)-\dfrac{\ln\left[2(1-p)\right]}{11.45441}\right] & ;p>0.5\end{cases} \quad \text{for } (0<p<1) \quad (5)$$

The stochastic failure model may be applied to the Davis-Besse wastage area problem by noting that $\alpha\equiv P_{BP(\text{exp.})}/P_{NI}$; therefore, Eq. (4) can be scaled using the results of a finite-element model of the wastage area such that

$$\Pr\left[P_{BP(true)} \le SP\right] = \begin{cases} \dfrac{1}{2}\left[\left(\dfrac{\alpha}{1.1057}\right)\left(\dfrac{P_{NI}}{P_{NI}}\right)\right]^{11.45441} & ; 0 < \alpha < 1.1057 \\ 1-\dfrac{1}{2}\left[\left(\dfrac{\alpha}{1.1057}\right)\left(\dfrac{P_{NI}}{P_{NI}}\right)\right]^{-11.45441} & ; \alpha \ge 1.1057 \end{cases} \tag{6}$$

$$= \begin{cases} \dfrac{1}{2}\left(\dfrac{SP}{1.1057\times P_{NI}}\right)^{11.45441} & ; 0 < SP < \left(1.1057\times P_{NI}\right) \\ 1-\dfrac{1}{2}\left(\dfrac{SP}{1.1057\times P_{NI}}\right)^{-11.45441} & ; SP \ge \left(1.1057\times P_{NI}\right) \end{cases}$$

Given a computationally-determined *pressure at numerical instability*, P_{NI}, based on the results of a finite-element model of the wastage area and a required service pressure, *SP*, the model provides an estimate of the cumulative probability of *nonexceedance* of the true but unknown burst pressure, $P_{BP(true)}$, i.e., $\Pr\left\lfloor P_{BP(true)} \le SP \right\rfloor$, where $1.1057\times P_{NI}$ is the median burst pressure.

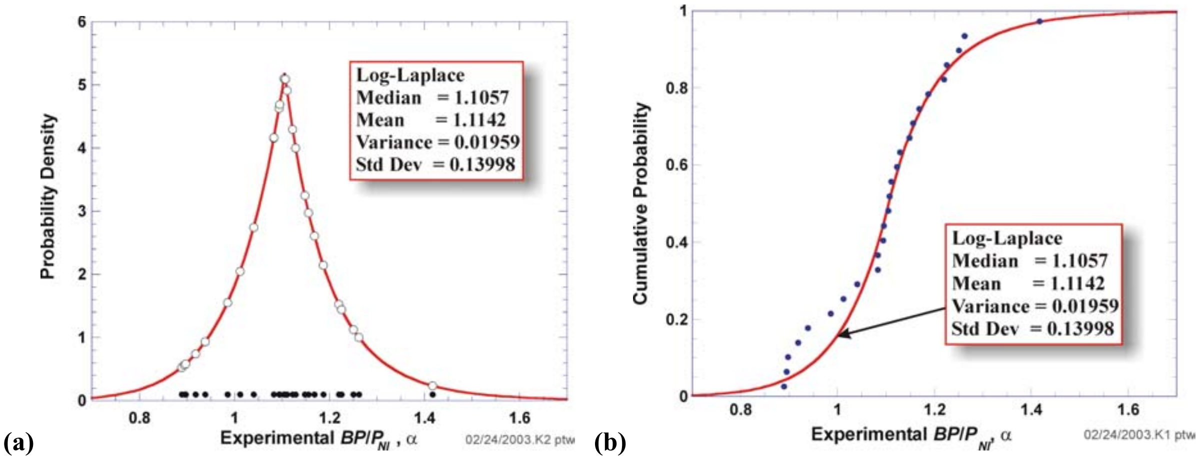

Fig. 3. Log-Laplace stochastic model characterizing the uncertainty in computational predictions of plastic collapse in disk burst tests.

SUMMARY

A stochastic model, derived from the estimated uncertainty of computational models in predicting failure by plastic collapse of circular disks under pressure loading, has been developed for application in risk-informed structural integrity assessments of a degraded nuclear power RPV head. This model employed the following technical bases:

(1) *experimental data* obtained during disk burst tests [3] with loadings, geometries, and materials relevant to the Davis-Besse pressure loading, wastage-area footprint, and cladding,
(2) nonlinear, large-deformation, elastic-plastic *discrete-element analyses* of the disk burst tests also reported in ref. [3] (GAPL-3 discrete-element code [4]),
(3) nonlinear, finite-strain, elastic-plastic *finite-element analyses* performed for the current study (ABAQUS finite-element code[5]) of the nine disk burst test specimens reported in ref. [3], and
(4) a *theoretical criterion* for plastic instability in a circular diaphragm under pressure loading, due to Hill [6] and Chakrabarty and Alexander [7], applied to the disk burst tests.

The transferability issue associated with applying this model to plastic-collapse failure predictions of a degraded RPV head is currently under active study, both computationally [10] and experimentally [13], at ORNL in support of NRC investigations of the Davis-Besse wastage area problem.

REFERENCES

1. USNRC Bulletin 2001–01, “Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles,” August 3, 2001.
2. *Recent Experience with Degradation of Reactor Pressure Vessel Head*, USNRC Information Notice 2002–11, United States Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, Washington, DC, March 12, 2002.
3. Riccardella, P. C., “Elasto-Plastic Analysis of Constrained Disk Burst Tests,” Paper No. 72-PVP-12, presented at the ASME *Pressure Vessels and Piping Conference*, New Orleans, LA, September 17–21, 1972
4. Thurman, A. L., *GAPL-3-A Computer Program for the Inelastic Large Deflection Stress Analysis of a Thin Plate or Axially Symmetric Shell with Pressure Loading and Deflection Restraints*, WAPD-TM-791, Bettis Atomic Power Laboratory, Pittsburgh, PA, June 1969.
5. *ABAQUS/Standard User’s Manual, v. 6.2*, Hibbit, Karlsson, and Sorensen, Inc., Pawtucket, RI, 2001.
6. Hill, R., “A Theory of the Plastic Bulging of a Metal Diaphragm by Lateral Pressure,” *Philos. Mag. (Ser. 7)*, Vol. 41, No. 322, 1950, pp. 1133–1142.
7. Chakrabarty, J. and Alexander, J. M., “Hydrostatic Bulging of Circular Diaphragms,” *J. Strain Anal.,* Vol. 5, No.3, 1970, pp. 155-161.
8. Ragab, A. R. and Bayoumi, S. E., *Engineering Solid Mechanics, Fundamentals and Applications*, CRC Press LLC, Boca Raton, FL, 1999.
9. Cooper, W. E., Kotteamp, E. H. and Spiering, G. A., “Experimental Effort on Bursting of Constrained Disks as Related to the Effective Utilization of Yield Strength,” Paper No. 71-PVP-49, ASME *Pressure Vessels and Piping Conference*, May 1971.
10. Williams, P. T. and Bass, B. R., “Analysis of the Davis-Besse RPV Head Wastage Area and Cavity,” ORNL/NRC/LTR-09, Oak Ridge National Laboratory, Oak Ridge, TN (under review).
11. Law, A. M., *Expert Fit© User’s Guide*, Averill M. Law & Associates, Tuscon, Arizona, May 2002.
12. Williams, P. T. and Bass, B. R., “Stochastic Failure Model for the Davis-Besse RPV Head,” ORNL/NRC/LTR-10, Oak Ridge National Laboratory, Oak Ridge, TN (under review).
13. McAfee, W. J., Bass, B. R., and Williams, P. T., *Outline of Proposed Test Plan for Performing Burst Disk Experiments at ORNL*, Heavy-Section-Steel Technology Program, October 9, 2002 (under review).