From: Edwin Hackett
To: DB LLTF
Date: 7/3/02 4:33PM
Subject: Fwd: Failure Model for DB

FYI - update on RES contractor efforts

ll

From: Mark Kirk , RES
To: Steven Long , NRR
Date: 7/3/02 4:13PM
Subject: Fwd: Failure Model for DB

Steve -

Attached please find a report from ORNL regarding the state of their model of DB in the "as found" condition. Paul is currently putting the finishing touches on this report (please consider the attached only a draft).

The short summary of this report is as follows:

1. If we use a Weibull cumulative probability function to represent the uncertainty associated with the failure criteria we arrive at a predicted lower bound burst pressure of 6.65 ksi. Because the 3 parameter Weibull function has a finite lower bound value there is - according to this model - zero probability of failure at pressures below 6.65 ksi

2. If instead we adopt a Normal cumulative probability function to represent the uncertainty associated with the failure criteria we arrive at a cumulative probability of failure of 8.4E-10 at the operating pressure of 2.165 ksi. At a slight overpressure (2.5 ksi) the probability of failure goes up by about an order of magnitude to 8.9E-9. In either event, these are very small numbers.

Next week we will begin calculations on larger footprints for the wastage area

Mark

CC: Bass, Richard - ORNL; Edwin Hackett; Nilesh Chokshi; Wallace Norris; Williams, Paul - ORNL

pol

From: "Paul T. Williams" <williamspt@ornl.gov>
To: mark Kirk <MTK@nrc.gov>
Date: 7/3/02 3:10PM
Subject: Failure Model for DB

Mark:

Attached is a summary with figures and tables of a letter report that I am still working on for the Davis-Besse failure criterion. I hope to have a draft of a more detailed report up to you by early next week.

Thanks

Paul

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DRAFT NOT FOR ATTRIBUTION 7/3/2002

ORNL/NRC/LTR-

Contract Program or Project Title: Heavy-Section Steel Technology (HSST) Program
Engineering Technology Division

Subject of this Document: Statistical Failure Model for the Davis-Besse RPV Head

Type of Document: Letter Report

Authors: P. T. Williams
B. R. Bass

Date of Document: July 2002

Responsible NRC Individual and NRC Office or Division: M. T. Kirk
Division of Engineering Technology
Office of Nuclear Regulatory Research

Prepared for the
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001
Under Interagency Agreement DOE 1886-N011-9B
NRC JCN No Y6533

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under Contract No. DE-AC05-00OR22725

ORNL/NRC/LTR -

Statistical Failure Model for the Davis-Besse RPV Head

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Oak Ridge, Tennessee

Manuscript Completed – July 2002
Date Published –

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Statistical Failure Model for the Davis-BesseRPV Head

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Summary

This report describes the development of a statistical model of failure for the cladding in the wastage area of the damaged head of the Davis-Besse reactor pressure vessel (RPV). The technical bases for the statistical model are (1) the experimental data developed during disk burst tests reported by Riccardella [1] with geometries and material properties relevant to the Davis-Besse cladding condition, (2) nonlinear finite-strain elastic-plastic finite-element analyses (performed for the current study) of the nine disk burst test specimens reported in [1], and (3) a theoretical continuum-mechanics treatment of plastic instability due to Hill [2] (as cited in [3]) applied to the disk burst tests.

In the early 1970s, constrained-disk burst tests were carried out under the sponsorship of the ASME *PVRC Subcommittee on Effective Utilization of Yield Strength* [4] This test program employed a range of materials and specimen geometries that were relevant to components in a nuclear power plant steam supply system. The geometries of the three test specimens analyzed in [1] are shown in Fig. 1, and the properties of the three materials are presented in Table 1. The nine disk burst tests produced three center failures and six edge failures over a range of burst pressures from 3.75 to 15 ksi as shown in Table 2. Also presented in Table 2 are the results of a computational study reported in [1] with a comparison to the experiments quantified by the parameter, , defined as the ratio of the experimental to predicted burst pressures for each test.

In the current study, three axisymmetric finite-element models (see Fig. 2) were developed to simulate the nine disk burst tests by applying the ABAQUS code with a nonlinear finite-strain elastic-plastic analysis of each test specimen geometry and material. The material properties provided in [1] were used to fit a power-law model for each material. The resulting power-law parameters are given in Table 1, and the true stress vs. true strain curves are shown in Fig. 3. Also shown in Fig. 3 is the stress-strain curve provided by Framatome for simulations of the SS308 cladding in the Davis-Besse head. Comparison of the curves in Fig. 3 indicates that the ABS-C carbon steel provides reasonably close agreement with the SS308 curve, although SS308 has a yield-strength lower than the three test materials.

Figure 4 presents effective plastic strain contours for the deformed condition of the Geometry A (ABS-C)

analysis at the point in the load path just before the onset of a state of numerical instability that aborted the ABAQUS execution. This state of numerical instability served as the condition for defining a predicted burst pressure for the test specimens. The highly localized plastic straining evident in the region near the fillet at the edge of the disk signals a necessary precondition for the onset of plastic collapse (in the form of a numerical breakdown of the solution procedure) in the specimen. This transition from uniform to localized plastic yielding is analogous to the onset of necking in a round-bar tensile specimen. Figure 5 provides a comparison of the predicted centerline vertical deflection histories with the experimental deflections at failure for the nine tests.

It is important to note that this analysis does not attempt to simulate the detailed continuum damage mechanics associated with this mode of failure. The goal of the analysis is to simulate the stress-strain state of the specimen along the load path up to the point of incipient tensile plastic instability. The material is assumed to be homogeneous with no significant defects, where its elastic-plastic deformation response to multiaxial stress states can be characterized by the application of incremental plasticity, J_2 flow theory with its associated flow rule, and isotropic strain hardening.

Table 3 compares the results of three sets of predicted burst pressures with the experimentally determined burst pressures. The parameter (= experimental burst pressure/predicted burst pressure) is shown as the third column for each group of predictions in the table. The predictions based on Hill's theory of plastic instability for pressurized circular diaphragms were developed by applying Hill's failure criterion [2,3] to the materials and geometries of the nine tests. Hill's criterion is valid only for failure at the centerline of the disk and assumes that the deformed geometry of the disk in this region can be treated analytically as a thin spherical shell under an equibiaxial state of stress. Moving away from the centerline towards the edge of the disk, the stress state becomes more complex (triaxial), and the assumptions of the theory no longer pertain. In Table 3, it can be observed that the predictions using Hill's instability criterion are in close agreement with the ABAQUS solutions, even for the cases with edge failures which are not addressed by the theory. This result suggests that, even though six of the nine disks failed at their edges, all of the disks were near a condition of the theoretical centerline plastic instability at the point of failure.

Table 4 provides descriptive statistics for the three sample sets of burst-pressure predictions, using the parameter as the relevant metric. The three samples are also collected together in Table 4 to provide a combined sample size of 26. The Normal and 3-parameter Weibull models were investigated to describe the statistical distributions of the FEM solutions (sample size equal to 9) and the combined sample (sample size equal to 26). The results of these analyses are presented in Tables 5 and 6 and Figs. 6 through 9. Given a computational failure prediction for a specific condition of the Davis-Besse wastage area, the resulting Normal and Weibull models can be scaled to provide a statistical distribution for the cumulative probability of failure as a function of pressure loading.

A bounding calculation was carried out for the "as-found" condition of the wastage area in the Davis-Besse head. The finite-element model used in the analysis is shown in Fig. 10. An adjusted stress-strain curve (see Fig. 11) was constructed to lower-bound the available data for the cladding material. The geometry of the wastage area footprint (taken from Fig. 13 in the *Root Cause Analysis Report* [5]) was extended by approximately 0.25 inches (see Fig. 12 and Table 7 for a geometric description of the adjusted footprint). A uniform cladding thickness of 0.24 inches (the minimum cladding thickness value shown in Fig. 14 of ref. [5]) was assumed in the model. The model was then loaded with increasing pressure until the point of numerical instability at an internal pressure of 6.65 ksi (see Fig. 13).

For the predicted burst pressure of 6.65 ksi, the Normal and Weibull statistical failure models can be scaled to provided estimates of cumulative probability of failure as a function of internal pressure for the specific condition of the wastage area simulated by the analysis. Examples of the scaled Weibull model are shown in Figs. 14 and 15 for normalized internal pressure and direct internal pressure, respectively.

As discussed above, the bounding calculation predicted a burst pressure of 6.65 ksi. For pressures below 5.486 ksi (at the position of the location parameter), the Weibull model predicts a zero probability of failure. The model based on a normal distribution estimates a cumulative probability of failure of $8.43 \cdot 10^{10}$ at the operating pressure of 2.165 ksi and $8.89 \cdot 10^{9}$ at 2.5 ksi. (See the table below for additional estimates).

Internal Pressure (ksi)	Normal Cumulative Probability of Failure	Weibull Cumulative Probability of Failure
2.155	7.84E-10	0
2.165	8.43E-10	0
2.200	1.09E-09	0
2.225	1.30E-09	0
2.250	1.55E-09	0
2.275	1.86E-09	0
2.300	2.22E-09	0
2.325	2.65E-09	0
2.350	3.15E-09	0
2.375	3.76E-09	0
2.400	4.47E-09	0
2.425	5.32E-09	0
2.450	6.32E-09	0
2.475	7.50E-09	0
2.500	8.89E-09	0

Table 1. Property Data for Materials in Disk Burst Tests

Material	Yield Strength 0.2% offset (ksi)	Ultimate Strength (ksi)	Strain at Ultimate (-)	True Stress 0.2% offset (ksi)	True Ultimate Stress (ksi)	Log Strain at Ultimate (-)	Power Law Parameters H (ksi)	n
Type 304 Stainless Steel	34	84	0.54	34.07	129.36	0.432	162.41	0.27
A-533B Low Alloy Steel	74	96	0.17	74.15	112.32	0.157	139.41	0.12
ABS-C Carbon Steel	39	64	0.31	39.08	83.84	0.270	105.20	0.17

Table 2. Comparison of Experimental to Predicted Failure Pressures in Ref. [1]

Material	Geometry	Experimental Burst Pressure (BP) (ksi)	Experimental Location of Failure	Riccardella's ASME Paper Predicted Burst Pressure (BP) (ksi)	Location of Failure	Exp. BP/ Predicted BP
SS 304	A	15	Edge	12.3	Edge	1.22
	B	6.8	Center	4.8	Edge	1.42
	C	7.7	Center	7.4	Center	1.04
A533B	A	11	Edge	9.8	Edge	1.12
	B	5.3	Edge	4.2	Edge	1.26
	C	6.7	Center	6.8	Center	0.99
ABS-C	A	9.8	Edge	8	Edge	1.23
	B	3.75	Edge	3	Edge	1.25
	C	4.94	Edge			

Table 3. Comparison of Experimental Burst Pressures to Three Predictions

Material	Geometry	Experimental		Riccardella's ASME Paper			Hill's Plastic Instability Theory			ABAQUS Solutions		
		Burst Pressure (BP) (ksi)	Location of Failure	Predicted Burst Pressure (BP) (ksi)	Location of Failure	Exp. BP/ Predicted BP	Predicted Burst Pressure (BP) (ksi)	Location of Failure	Exp. BP/ Predicted BP	Predicted Burst Pressure (BP) (ksi)	Location of Failure	Exp. BP/ Predicted BP
SS 304	A	15	Edge	12.3	Edge	1.22	12.98	Center	1.16	13.29	Edge	1.13
	B	6.8	Center	4.8	Edge	1.42	5.92	Center	1.15	6.22	Edge	1.09
	C	7.7	Center	7.4	Center	1.04	6.49	Center	1.19	6.59	Center	1.17
A533B	A	11	Edge	9.8	Edge	1.12	12.37	Center	0.89	12.26	Edge	0.90
	B	5.3	Edge	4.2	Edge	1.26	5.65	Center	0.94	5.24	Edge	1.01
	C	6.7	Center	6.8	Center	0.99	6.19	Center	1.08	6.03	Edge	1.11
ABS-C	A	9.8	Edge	8	Edge	1.23	8.95	Center	1.10	9.05	Edge	1.08
	B	3.75	Edge	3	Edge	1.25	4.08	Center	0.92	4.19	Edge	0.89
	C	4.94	Edge				4.47	Center	1.10	4.46	Edge/Center	1.11

Table 4. Descriptive Statistics for the Ratio of Experimental Burst Pressure to Predicted Burst Pressures

Descriptive Statistics	Riccardella (1972)	Hill's Theory	ABAQUS	Combined
Sample Size	8	9	9	26
Mean	1.1902	1.0576	1.0549	1.0975
Standard Error	0.0484	0.0374	0.0331	0.0251
Median	1.2223	1.0953	1.0939	1.1057
Standard Deviation	0.1368	0.1123	0.0993	0.1281
Sample Variance	0.0187	0.0126	0.0099	0.0164
Kurtosis	-0.0506	-1.4799	-0.4349	0.2593
Skewness	0.0007	-0.5892	-0.9683	0.1714
Range	0.4314	0.2979	0.2739	0.5277
Minimum	0.9853	0.8889	0.8943	0.8889
Maximum	1.4167	1.1868	1.1682	1.4167
Confidence Level(95.0%)	0.1144	0.0863	0.0764	0.0517

Table 5. Weibull Model Parameters and Median Rank Order Statistics for ABAQUS Predictions

Material	Geometry	Exp. BP/ Predicted BP	Rank	Order Statistic P
ABS-C	B	0.89427	1	0.074
A533B	A	0.89718	2	0.181
A533B	B	1.01186	3	0.287
ABS-C	A	1.08268	4	0.394
SS 304	B	1.09393	5	0.500
ABS-C	C	1.10722	6	0.606
A533B	C	1.11041	7	0.713
SS 304	A	1.12876	8	0.819
SS 304	C	1.16822	9	0.926

Weibull Parameters		K-S *p-value* Weibull	K-S *p-value* Normal
Location	0.848	0.2928	0.4236
Scale	0.232		
Shape	2.352		

	Model	Sample
Mean	1.0535	1.0549
Variance	0.0087	0.0099
Std. Dev.	0.0930	0.0993
Median	1.0464	1.0939

Table 6. Weibull Model Parameters and Median Rank Order Statistics for Combined Predictions

Rank	Method	Material	Geometry		Order Statistic
1	Hill's Theory	A533B	A	0.8889	0.0265
2	ABAQUS Soln.	ABS-C	B	0.8943	0.0644
3	ABAQUS Soln.	A533B	A	0.8972	0.1023
4	Hill's Theory	ABS-C	B	0.9180	0.1402
5	Hill's Theory	A533B	B	0.9382	0.1780
6	Ricarrdella (1972)	A533B	C	0.9853	0.2159
7	ABAQUS Soln.	A533B	B	1.0119	0.2538
8	Ricarrdella (1972)	SS 304	C	1.0405	0.2917
9	ABAQUS Soln.	ABS-C	A	1.0827	0.3295
10	Hill's Theory	A533B	C	1.0829	0.3674
11	ABAQUS Soln.	SS 304	B	1.0939	0.4053
12	Hill's Theory	ABS-C	A	1.0953	0.4432
13	Hill's Theory	ABS-C	C	1.1042	0.4811
14	ABAQUS Soln.	ABS-C	C	1.1072	0.5189
15	ABAQUS Soln.	A533B	C	1.1104	0.5568
16	Ricarrdella (1972)	A533B	A	1.1224	0.5947
17	ABAQUS Soln.	SS 304	A	1.1288	0.6326
18	Hill's Theory	SS 304	B	1.1479	0.6705
19	Hill's Theory	SS 304	A	1.1560	0.7083
20	ABAQUS Soln.	SS 304	C	1.1682	0.7462
21	Hill's Theory	SS 304	C	1.1868	0.7841
22	Ricarrdella (1972)	SS 304	A	1.2195	0.8220
23	Ricarrdella (1972)	ABS-C	A	1.2250	0.8598
24	Ricarrdella (1972)	ABS-C	B	1.2500	0.8977
25	Ricarrdella (1972)	A533B	B	1.2619	0.9356
26	Ricarrdella (1972)	SS 304	B	1.4167	0.9735

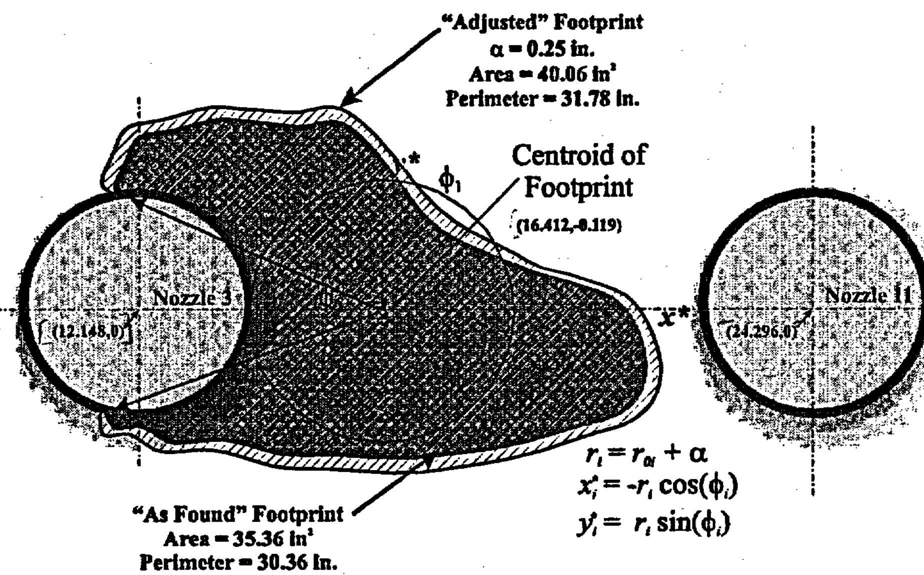
• = Experimental Burst Pressure/Predicted Burst Pressure

Weibull Parameters			2 Significance Test		
		Distr.	2	p-value	DOF
Location	0.825				
Scale	0.308	Normal	5.16240	0.07568	2
Shape	2.301	Weibull	1.69430	0.42864	2
	Model	Sample			
Mean	1.0975	1.0975			
Variance	0.0158	0.0164			
Std. Dev.	0.1256	0.1281			
Median	1.0876	1.1057			

Table 7. Wastage-Area-Footprint Geometry Data

Description	Scaling Factor	Area	Perimeter	Centroid of Wastage Area Footprint		Moments of Inertia About the Centroid			Eigenvalue Extraction for Principal Moments and Directions			
									Principal Moments		Principal Directions	
				x_c	y_c	I_{xx}	I_{yy}	I_{xy}	I_1	I_2	I_1	I_2
		(in^2)	(in.)	(in.)	(in.)	(in^4)	(in^4)	(in^4)	(in^4)	(in^4)	<n_x, n_y>	<n_x, n_y>
As-Found Footprint	1	35.36	30.36	16.4122	-0.1194	98.89	9699.33	-117.16	75.26	197.41	<0.9004, -0.4351>	<0.4351, 0.9004>
Adjusted Footprint for Bounding Calculation	0.25 in.	40.06	31.78	16.4301	-0.1255	129.02	11031.81	-141.35	99.00	245.71	<0.8943, -0.4476>	<0.4476, 0.8943>

Footprint centroid is in global coordinates.
Global coordinate system has its z-axis aligned with the vertical centerline of the vessel.
The x-y plane of the global coordinate system is a horizontal plane
with the x-axis along the line between the centerlines of Nozzles 3 and 11.



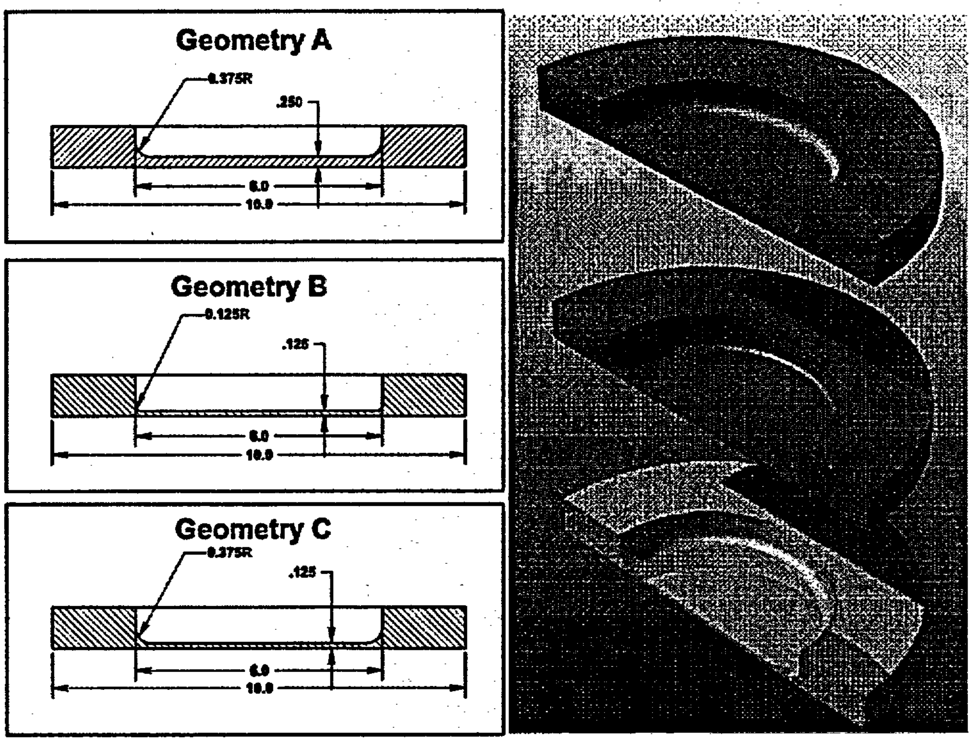


Fig. 1. Geometric descriptions of three burst disk specimens used in [1] (all dimensions are inches). Images on the right are Photoworks -rendered views of ½-symmetry solid models of the three specimens.

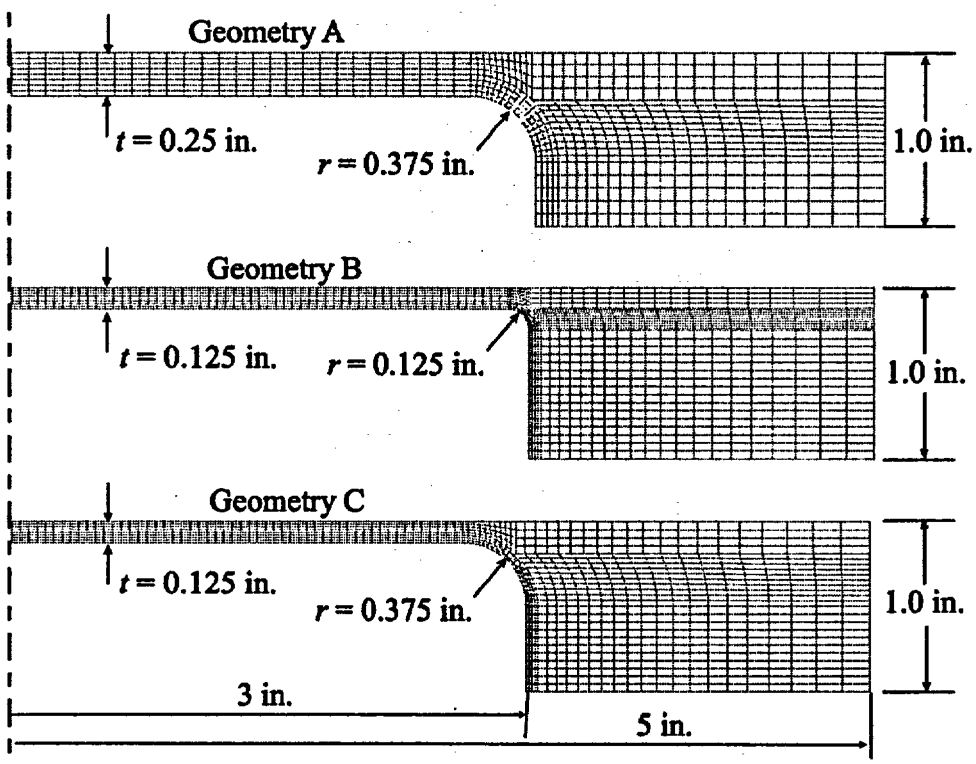


Fig. 2. Axisymmetric finite-element meshes used in the analyses of disk burst tests reported in [1]. Quadratic 8-node axisymmetric (CAX 8R) elements with reduced integration were used in a nonlinear finite-strain elastic-plastic analysis of the three burst disk geometries with three materials.

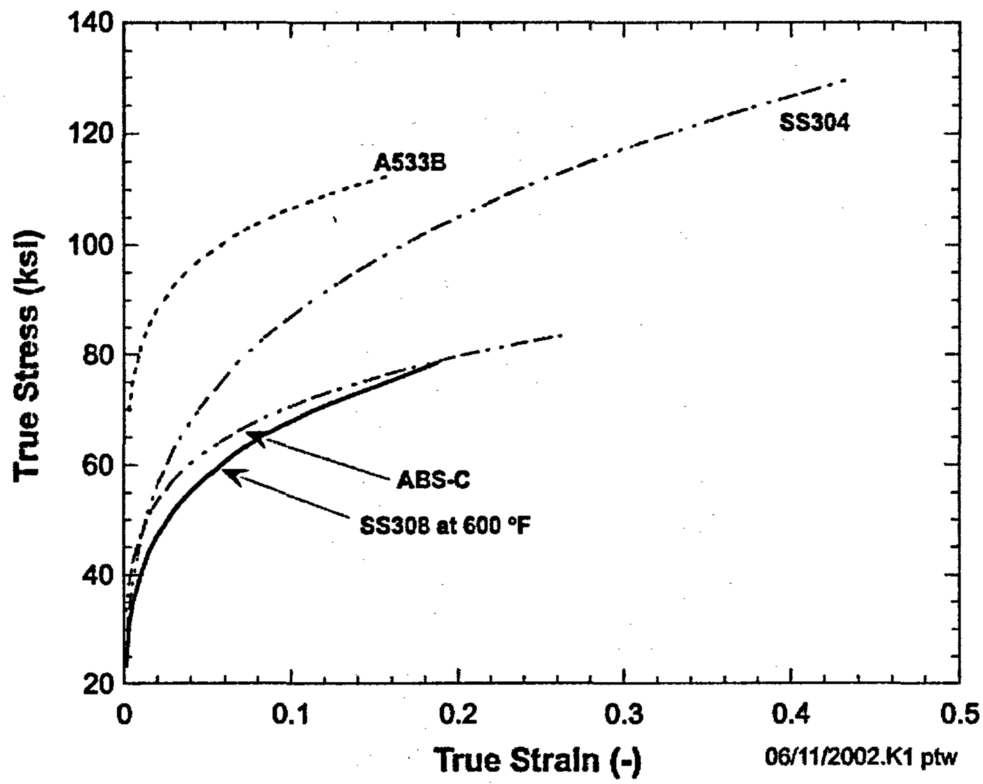
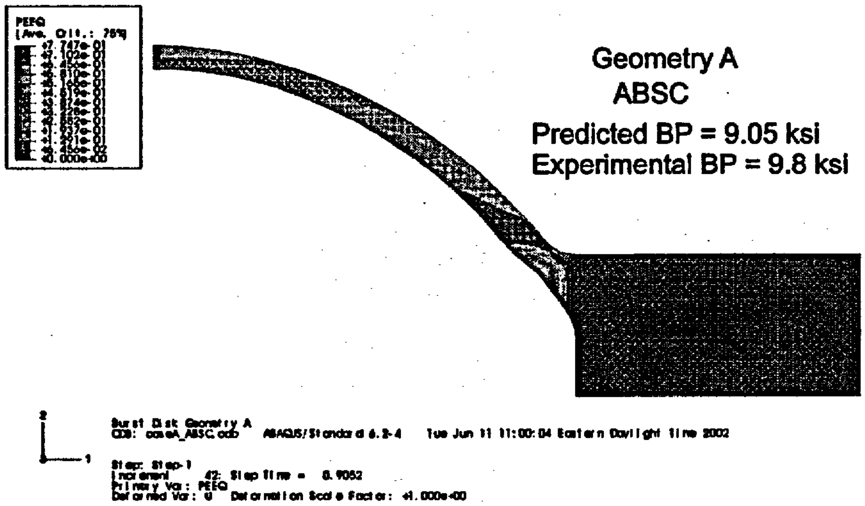
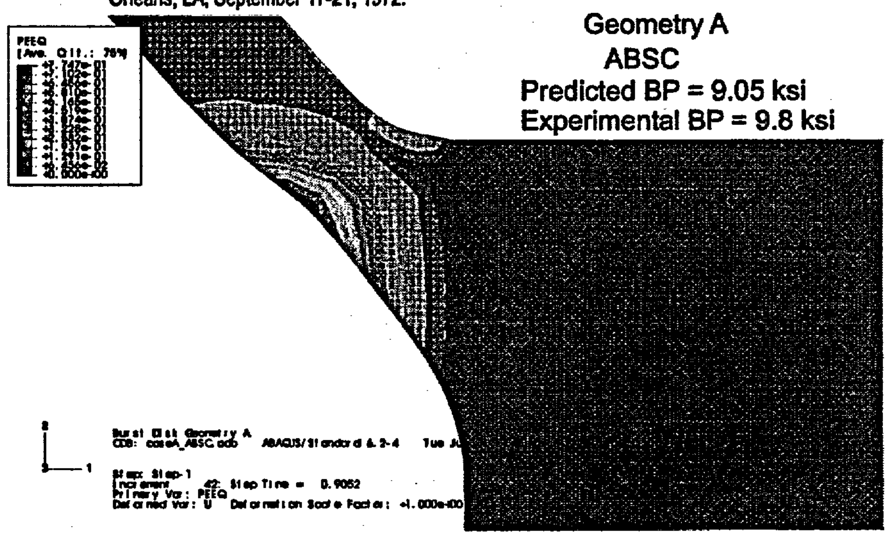


Fig. 3. True stress vs true strain curves of the three materials used in the disk burst tests compared to SS308 at 600 °F. These curves were developed using a power-law strain-hardening model fitted to yield and ultimate strength/strain data for each material.



Ref. P. C. Riccardella, "Elasto-Plastic Analysis of Constrained Disk Burst Tests," ASME Paper No. 72-PVP-12, *ASME Pressure Vessels and Piping Conference*, New Orleans, LA, September 17-21, 1972.

(a)



(b)

Fig. 4. Effective plastic strain contours for the Geometry A (ABS-C carbon steel) specimen at the point of numerical instability. Highly localized plastic straining provides a precondition for plastic collapseat the edge of the specimen.

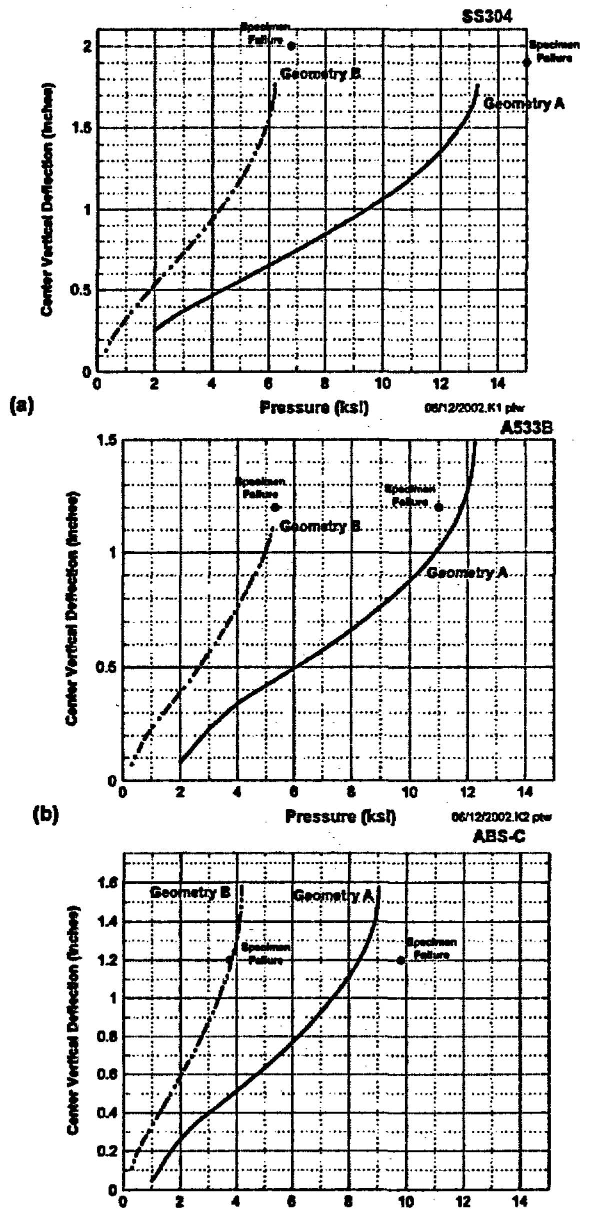
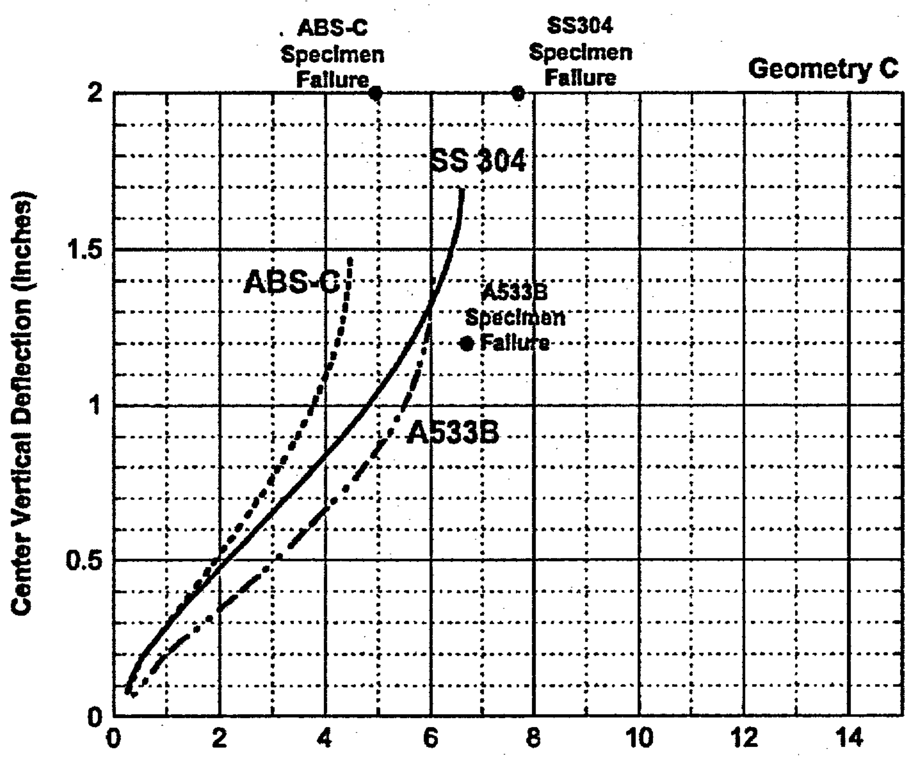


Fig. 5. Comparison of experimental centerline vertical deflections at failure to FEM vertical deflection histories at the center of the Geometry A and B specimens for (a) SS 304, (b) A533-B, and (c) ABS-C materials, and



(d)

Fig. 5. (continued) (d) vertical deflection histories at the center of Geometry C, all three materials.

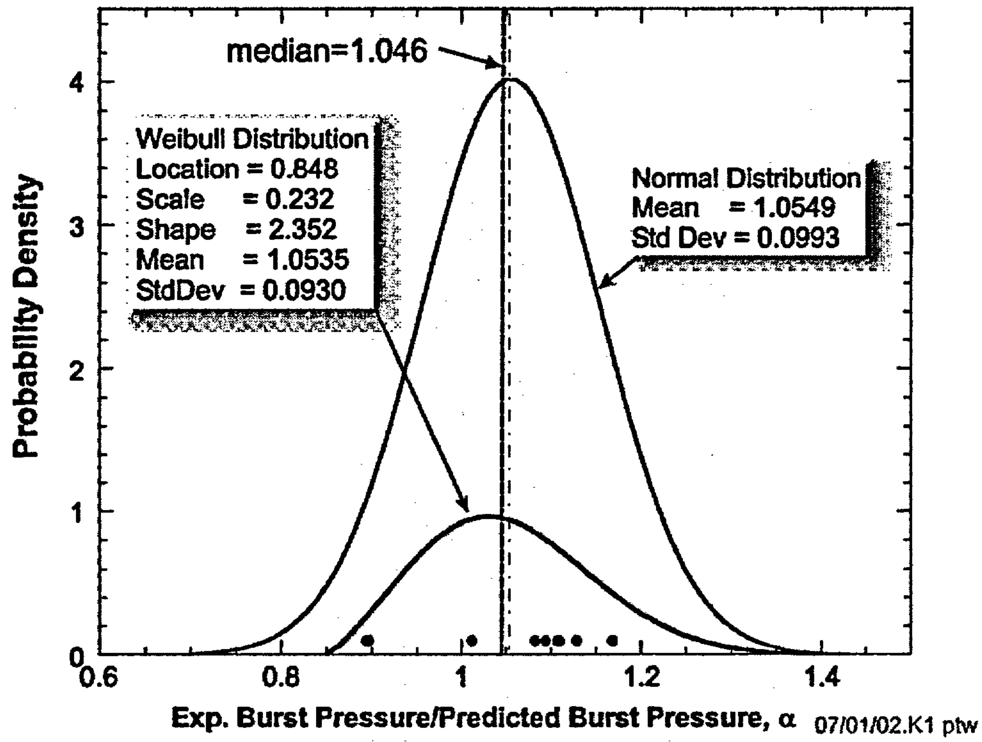


Fig. 6. Probability densitiesfor two continuous statistical distributions fitted to the sample of 9 data points for = experimental burst pressure/FEM predicted burst pressure.

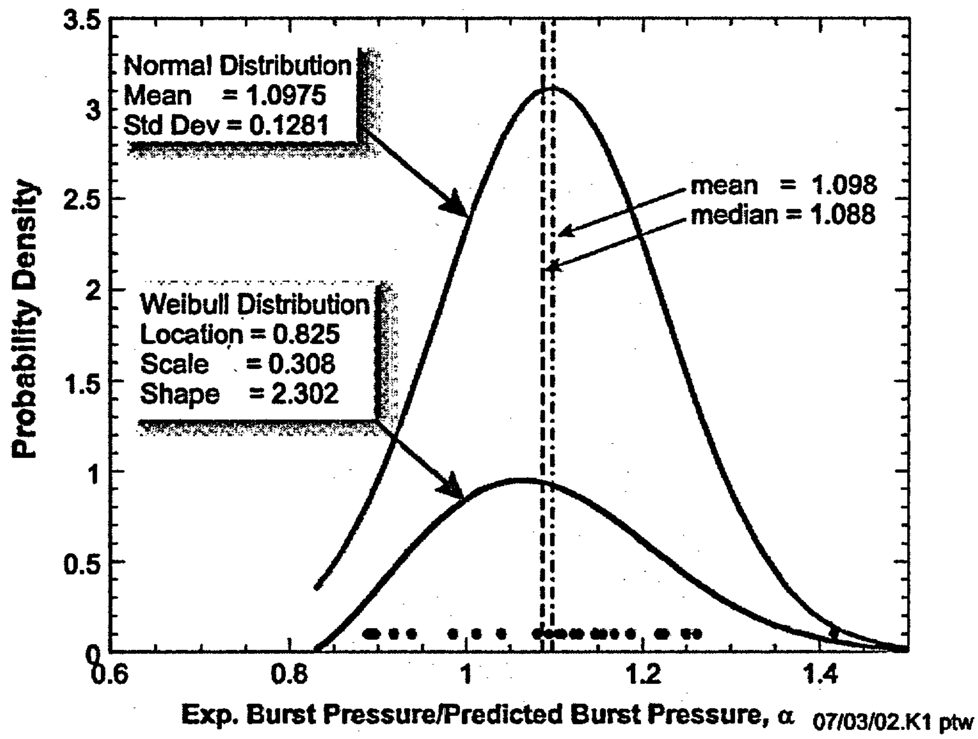


Fig. 7 Probability densitiesfor two continuous statistical distributions fitted to the combined sample of 26 data points for = experimental burst pressure / predicted burst pressure.

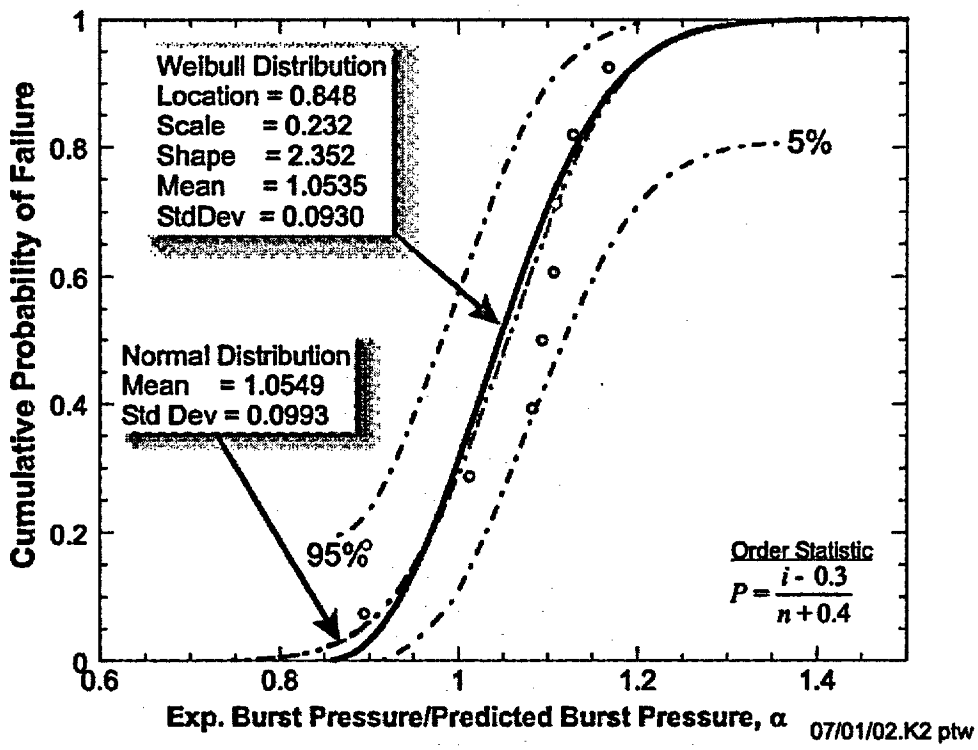


Fig. 8. Weibull statistical failure model ($n = 9$) compared to a normal cumulative distribution function, median rank order statistic, and the 90% confidence interval on the order statistic. ABAQUS FEM solutions were used to develop the models. N.B.: The order statistics and their 90% confidence intervals are shown here for comparative purposes only and were not used in the point-estimate procedures for the parameters of either the Weibull or Normal distributions.

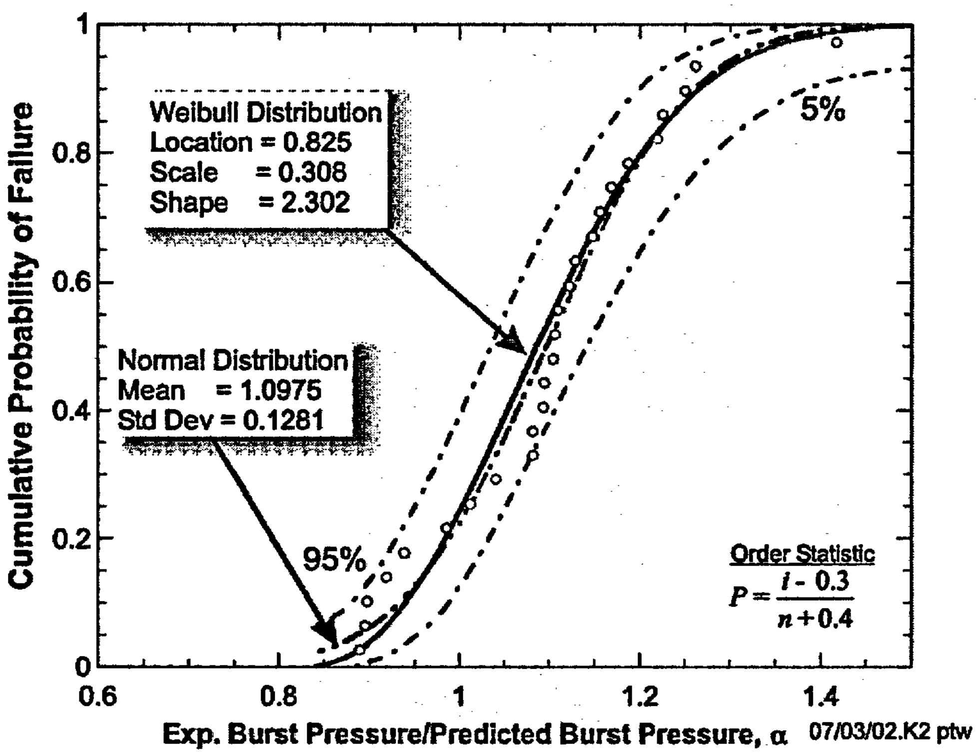
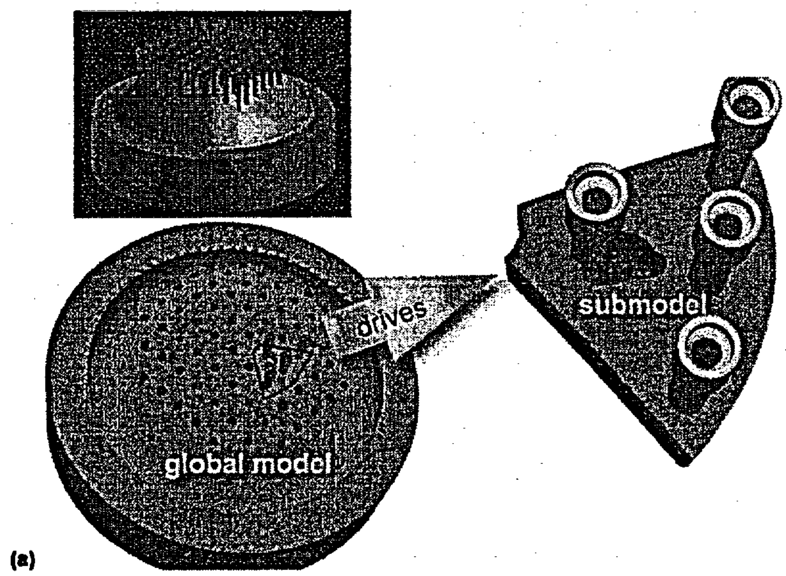


Fig. 9. Weibull statistical failure model (n = 26) compared to a normal cumulative distribution function, median rank order statistic, and the 90% confidence interval on the order statistic. Models developed with combined sample. N.B.: The order statistics and their 90% confidence intervals are shown here for comparative purposes only and were not used in the point-estimate procedures for the parameters of either the Weibull or Normal distributions.



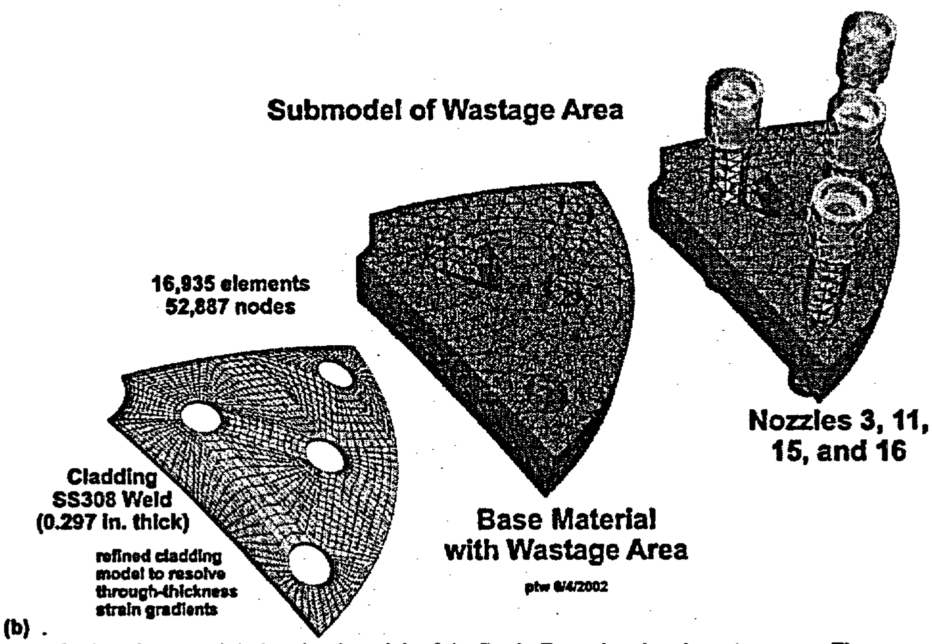


Fig. 10. Finite-element global and submodels of the Davis-Bessehead and wastage area. The displacements at the vertical side boundaries of the submodel are driven by the global model. Both models are exposed to the same internal pressure loading.

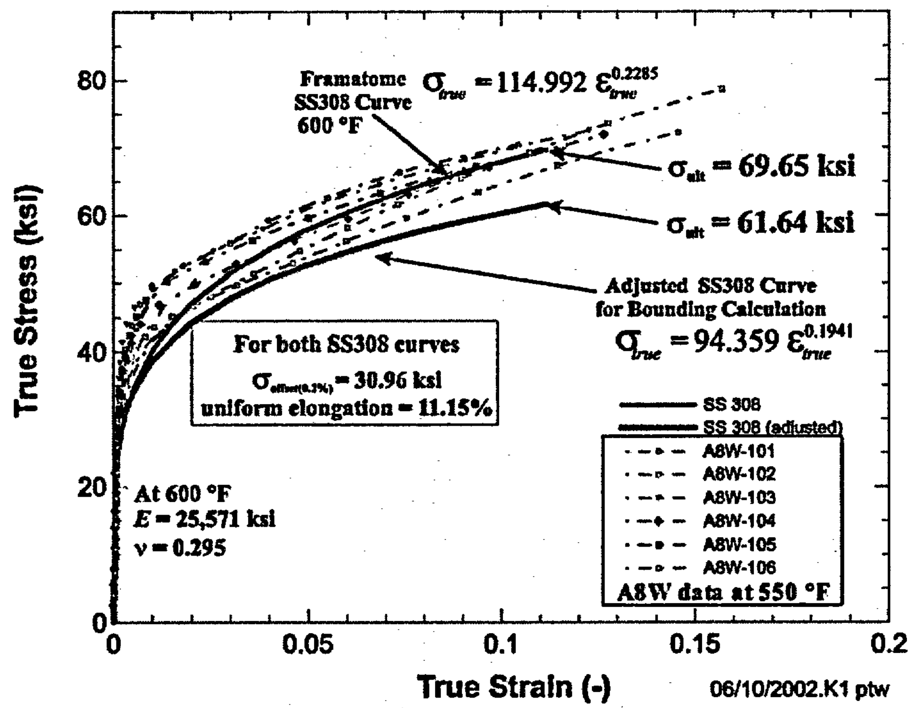


Fig. 11. Adjusted SS308 stress vs strain curve used in the bounding-case calculations compared to curves from a range of A8W heats. Strain hardening in the adjusted curve was reduced to lower-bound all of the data. The offset yield strength and strain at ultimate strength were retained from the unadjusted SS304 curve received from Framatome.

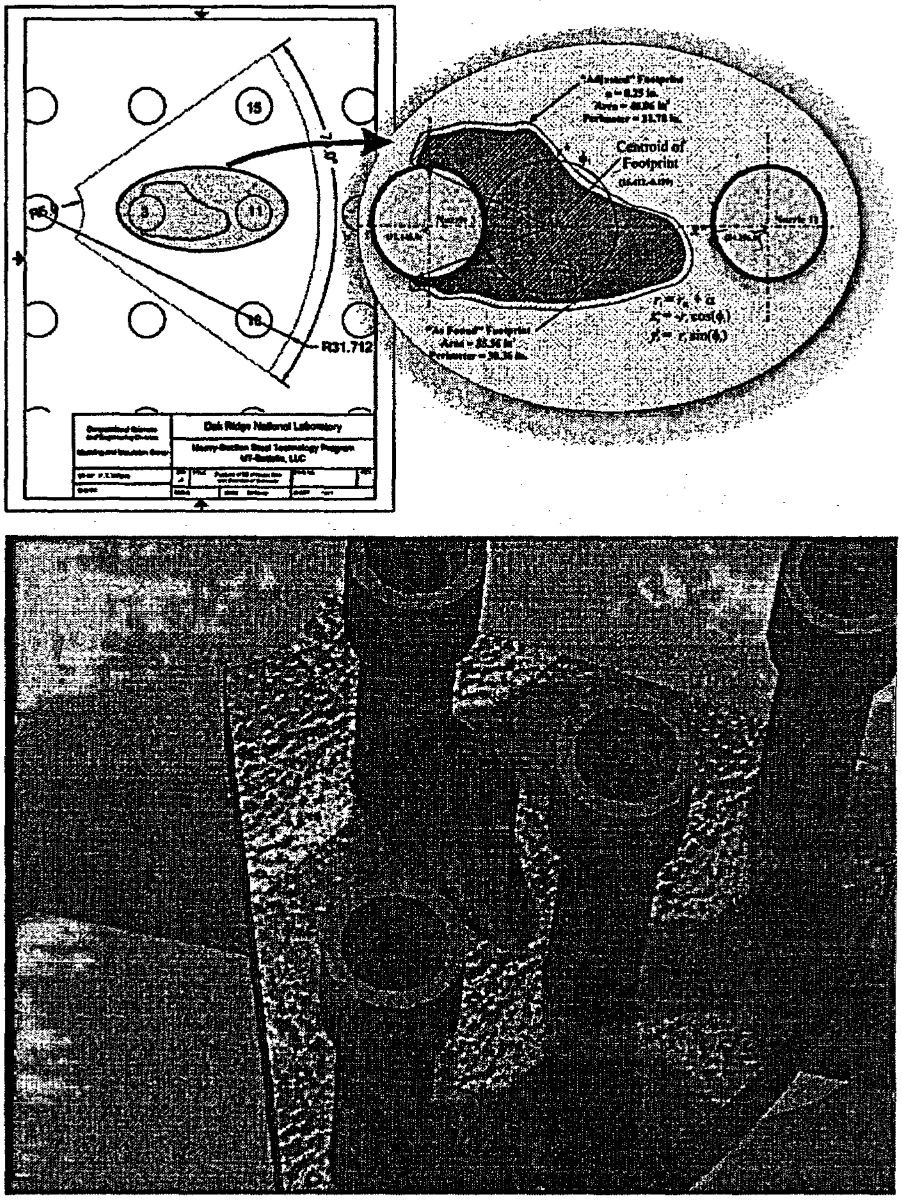
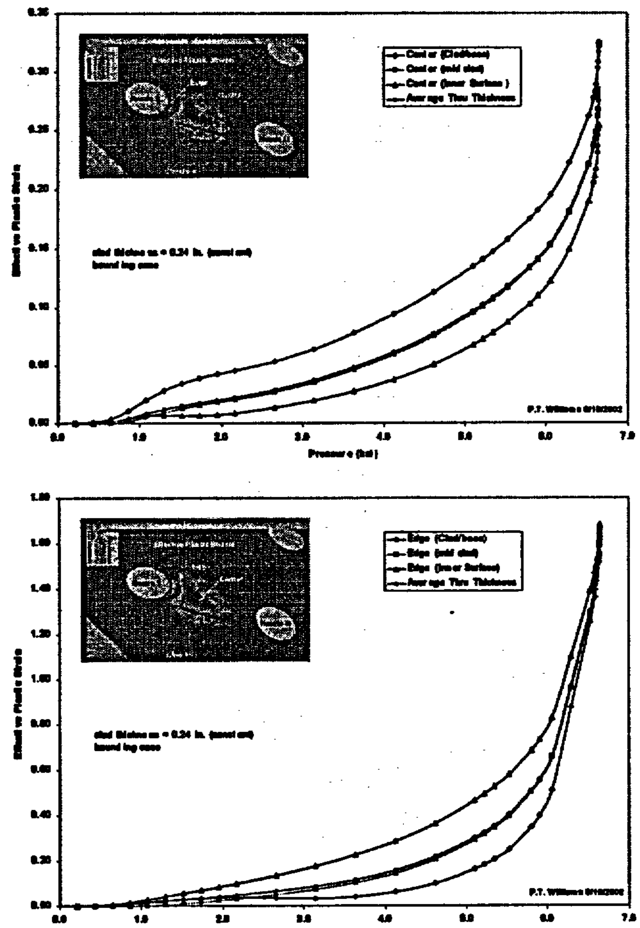


Fig. 12. Geometry of adjusted wastage area footprint. Lower figure is a Photoworks -rendered image of the submodel with the adjusted "as-found" footprint.



(a)

(b)

Fig. 13. Effective plastic-strain histories at two high-strain locations in the wastage area: (a) near the center and (b) near Nozzle 3.

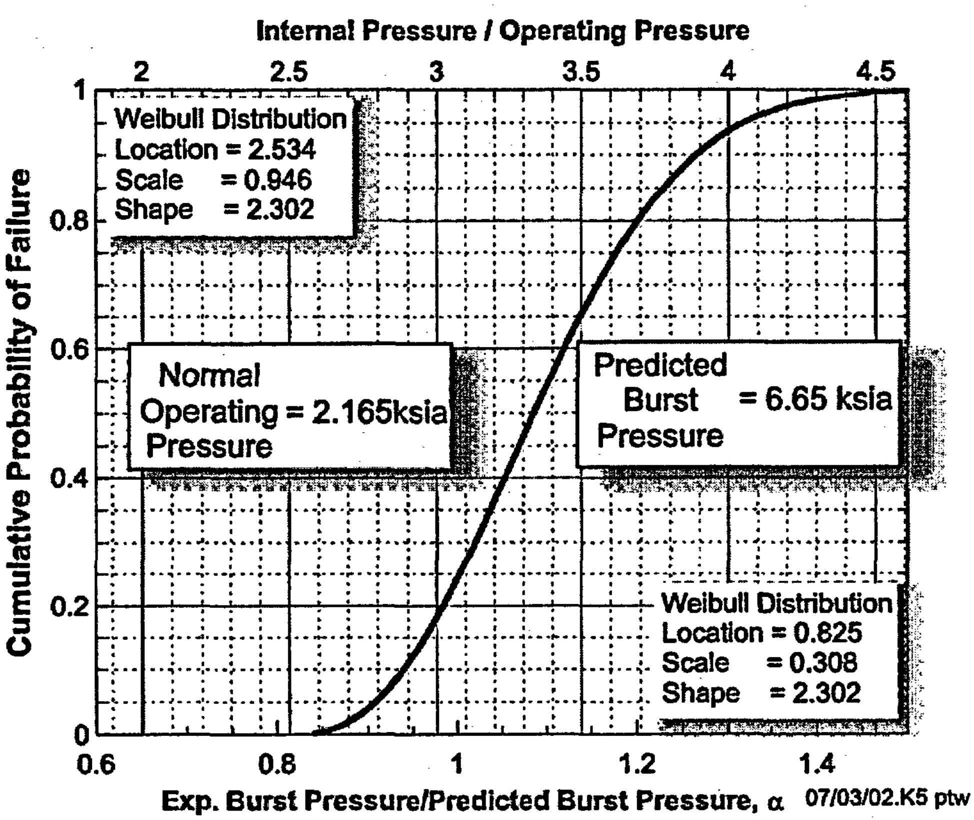


Fig. 14. Application of the failure statistical criterion produces a cumulative probability of failure (based on a Weibull distribution) curve for the Bounding Case condition. Cumulative probability of failure as a function of normalized internal pressure.

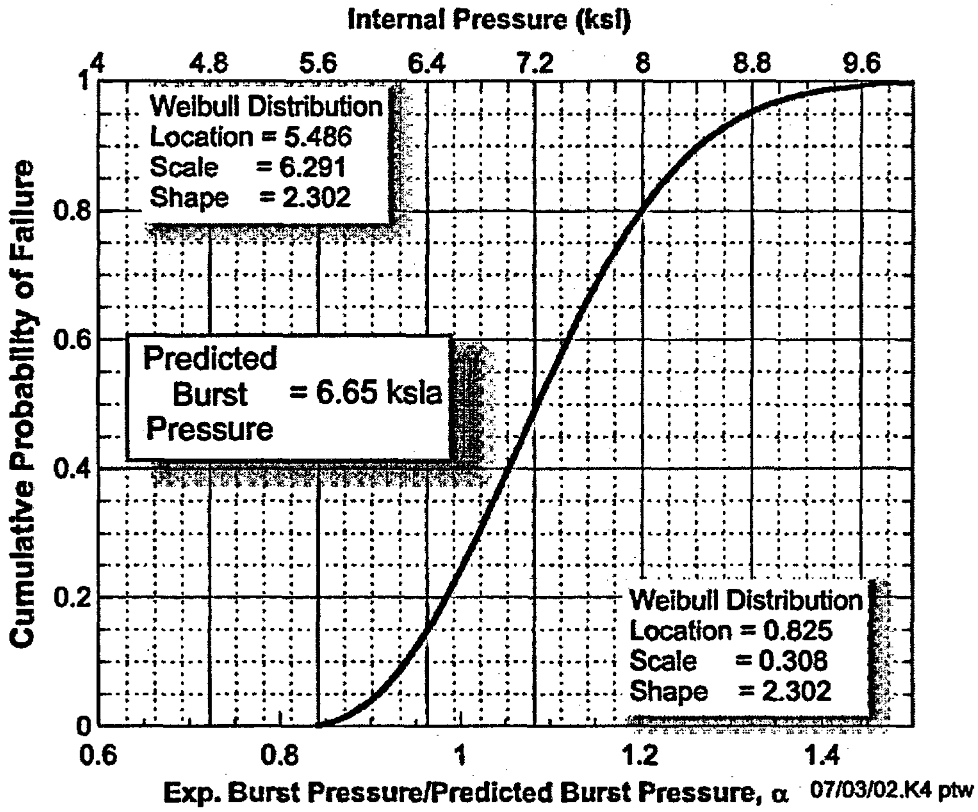


Fig. 16. Application of the failure statistical criterion produces a cumulative probability of failure (based on a Weibull distribution) curve for the Bounding Case condition. Cumulative probability of failure as a function of internal pressure.

References

1. P. C. Riccardella, "Elasto- Plastic Analysis of Constrained Disk Burst Tests," Paper No. 72-PVP-12, presented at the ASME *Pressure Vessels and Piping Conference*, September 17-21, 1972, New Orleans, LA.
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Mark:

Attached is a summary with figures and tables of a letter report that I am still working on for the Davis-Besse failure criterion. I hope to have a draft of a more detailed report up to you by early next week.

Thanks

Paul

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