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Dresden Unit 2
Vessel Head Stud Flaw Evaluation

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Table of Contents

Executive Summary iv
1.0 Introduction 1
1.1 Background *1*
1.2 Scope *1*
2.0 Applied Stresses 2
2.1 Boltup and Normal Operation *2*
2.2 Emergency/Faulted Conditions *3*
3.0 Head Stud Fracture Toughness 4
3.1 Charpy Data *4*
3.2 Available Fracture Toughness *5*
3.2.1 Leak Test 5
3.2.2 Startup Condition 5
4.0 Allowable Flaw Size 8
4.1 Allowable Fracture Toughness *8*
4.2 LEFM Model *8*
4.3 Results *9*
5.0 Structural Assessment 13
5.1 One Stud Failed *13*
5.2 Allowance for Postulated Flaws *13*
6.0 Conclusions 15
7.0 References 16

Executive Summary

In the 15th refueling outage for Dresden 2, D2R15, conducted in the spring of 1998, the UT inspection detected two more vessel head studs with indications. One stud was replaced and one stud was inadvertently left in place while an acceptable stud was replaced. This condition was discovered just prior to restart and the NRC was notified. In reviewing the issue, the NRC raised questions regarding the use of the tensioning load as the limiting condition in the prior evaluations. As a result, a flaw evaluation of the Dresden 2 vessel head studs has been done considering all loading cases presented in the closure flange stress report.

The following points summarize the conclusions of the analyses presented in this report:

1. The tensioning stress is the maximum membrane stress, but leak test and startup have large bending stresses, such that flaw evaluations for these conditions are needed to establish the limiting allowable flaw sizes.
2. The emergency and faulted conditions are bounded by normal and upset conditions.
3. Given the combination of J-R curve testing done and the Charpy data available, K_{IC} fracture toughness values could be estimated for the temperatures associated with the leak test and startup conditions.
4. Section XI provides requirements for calculating postulated flaws (IWB-3730). The smallest postulated flaw size of 0.39 inches is conservative for the D2R15 outage where a postulated flaw equal to the calibration standard depth, 0.157 inches, may have grown 0.05 inches.
5. The structural capability of the studs in the closure flange has substantial margin for the scenario per Section XI where one stud with a known crack is assumed to fail completely. If, beyond Section XI requirements, an edge flaw is conservatively added to each of the 91 remaining studs, the acceptable edge flaw is 1.1 inches, considerably larger than the postulated flaw size of 0.39 inches.

The overall conclusion from the analysis is that continued operation of Dresden 2 with a cracked vessel head stud in place is justified.

1.0 Introduction

As a result of further cracking found in Dresden 2 vessel head studs and questions raised by the NRC regarding prior evaluations, GE Nuclear Energy (GENE) has, at ComEd's request, performed a flaw evaluation of the Dresden 2 vessel head studs considering all loading cases presented in the closure flange stress report.

1.1 Background

Cracking of vessel head studs was first detected at Dresden 2 in 1989, when two studs were found cracked and replaced. This event led to two evaluations by GENE for ComEd. The first [1] was an evaluation of allowable flaw size and structural margin based on available Charpy data and correlations between Charpy data and fracture toughness, K_{IC}. For the second evaluation [2], material from a cracked stud was tested to determine K_{IC} from J-R curves. The K_{IC} values, taken at 80°F to 150°F, were used to refine the allowable flaw size determination. The results in [2] also reflected an improved detection capability in the UT inspection technique.

In the 15th refueling outage for Dresden 2, D2R15, conducted in the spring of 1998, the UT inspection detected two more vessel head studs with indications. One stud was replaced and one stud was inadvertently left in place while an acceptable stud was replaced. This condition was discovered just prior to restart and the NRC was notified. In evaluating the situation, the NRC took another look at the flaw evaluation and structural assessment in [2]. One of the statements made in [2] was that the stud tensioning step was the most limiting condition for brittle fracture, because the stresses are high and the temperatures, and associated K_{IC}, are relatively low. The NRC asked that ComEd quantitatively demonstrate the validity of this statement, which has led to the subject evaluation.

1.2 Scope

This report documents an evaluation of the Dresden 2 vessel head studs, considering the applied stresses for all conditions analyzed in the design stress report for the closure flange [4]. The scope of the evaluation includes the following steps:

a. Stresses for stud tensioning, leak test and heatup/cooldown were extracted from the design stress report. Since each condition occurs at a different temperature, each was taken through the process of determining the allowable flaw size. Emergency and faulted transients were determined in [4] to be bounded by the normal/upset events for the closure flange. The evaluations in the LaSalle 1 and 2 stress reports were reviewed to confirm this.

b. K_{IC} results from J-R curve testing cover a temperature range of 80°F to 150°F. The leak test and normal operating conditions occur at higher temperatures. For the leak test and normal operating conditions, Charpy data are used to estimate an upper shelf K_{IC}.

c. The cracked stud is assumed to be failed. ASME Code Section XI, IWB-3730 [5], which references nonmandatory Appendix G, is used to evaluate postulated flaws in the remaining studs. Allowable depths for the postulated flaw are determined for tensioning, leak test and startup, when the limiting operating stresses occur.

d. IWB-3610 of Section XI requires that the primary stress limits be met while taking no credit for the area of the crack. For the closure flange, these limits are measured in terms of the stud area required to maintain closure. Technically, only the area of the known crack need be addressed, and it is. In addition, a more conservative scenario is discussed to show the substantial margins present.

2.0 Applied Stresses

In the prior head stud analysis [2], the tensioning load was evaluated as the limiting load because "the stresses in the studs do not change significantly after the initial bolt up. Also, the temperature (correspondingly, the material fracture toughness) is lowest during the bolt up compared to any other plant operating condition." In its recent review, the NRC requested a quantitative demonstration of the validity of this statement.

The Dresden 2 design stress report [4] was reviewed to compare analyzed operating stresses with the tensioning stress. The review showed that the tensioning stress used in [2] was larger than any stud membrane stresses in [4], but some of the operating stress states include large bending stresses which make the overall stresses larger than the tensioning stress. Much of the bending stress is in reality relieved by the tensioner boltup method, as discussed in the LaSalle 2 closure flange stress report [6]. In fact, after describing the progression of tensioner lifts and flange rotations, the LaSalle 2 report states,

> "The net result is that the stud moments are greatly reduced. Experience and strain gage tests show that almost all of the moment is released."

In contrast to this statement, the Dresden 2 bolt preload condition shows 38.5 ksi of bending , because the studs were treated as cantilever beams with the tops of the studs rotated the same amount as the head flange. This approach resulted in large bending stresses in the studs for the bolt preload condition, and correspondingly larger bending stresses for other operational conditions.

2.1 Boltup and Normal Operation

The membrane and bending stresses were extracted from [4] for the leak test condition and for the startup/normal operation/shutdown condition causing the largest stresses. These were the only operating conditions where stresses were calculated, because after reviewing the other normal/upset transients, B&W concluded that their effects were too remote from the closure flange to be significant. The LaSalle 1 [7] and LaSalle 2 [6] stress reports addressed other normal and upset transients such as turbine trip, loss of feedwater pumps and scram. In both cases, bolt preload or startup/shutdown conditions were most limiting, confirming the conclusion made in [4].

The tensioning stress reported in [2] was based on a tensioner load of 1,442,000 lbs. The stress, taken as membrane stress, is

$$\sigma_m = 55.6 \text{ ksi}$$

Since the stud evaluation [2] was performed, Dresden has provided a new tensioning load of 1.43×10^6 lbs [8], so the stress above is slightly conservative.

The leak test stress was determined for a leak test of 1000 psig. This required interpolation of the stresses for the bolt preload case (pressure = 0 psig) and the hydrotest case (pressure = 1563 psig). The resulting membrane and bending stresses are

$$\sigma_m = 35.1 \text{ ksi}$$
$$\sigma_b = 44.0 \text{ ksi}$$

The maximum startup/normal operation/shutdown stresses occurred toward the end of the heatup phase of startup. The membrane and bending stresses are

$$\sigma_m = 31.4 \text{ ksi}$$
$$\sigma_b = 64.3 \text{ ksi}$$

While the overall operating stresses are higher than the tensioning stress, it is true, as stated in [2], that the available K_{IC} for these higher temperature conditions is higher than that used for the tensioning event. As a result, the combination of stresses and available K_{IC} is evaluated for each operating condition to determine the allowable flaw size.

2.2 Emergency/Faulted Conditions

The Dresden 2 stress report states that, "Transients which affect other parts of the vessel and are more severe than heatup/cooldown are too far removed from the flanges to affect them. The one exception is the rapid depressurization." The report then describes that the heat transfer coefficients are low for the rapid depressurization and the pressure drops rapidly, so the stresses will be between steady state and boltup conditions.

As a check on this discussion, the LaSalle 1 [7] stress report, done by Combustion Engineering, and LaSalle 2 [9] stress report, done by CBIN, were consulted. For LaSalle 1, the Vessel Overpressure event and Blowdown event are analyzed. Both are bounded by the stresses for the preload case. In LaSalle 2, stresses are not documented, but the statement is made that ".. no more severe stresses have been encountered in the emergency and faulted conditions than had previously been calculated for the normal and upset category.." These checks confirm the conclusion in the Dresden 2 stress report.

3.0 Head Stud Fracture Toughness

Based on the J-R curve testing documented in [2], a K_{IC} value was established of 130 ksi-√in for the stud tensioning event. The J-R curve tests were done to a maximum temperature of 150°F, because of the focus on the tensioning condition. Therefore, K_{IC} estimates for higher temperatures must be developed for the leak test and startup evaluations.

There are correlations which provide estimates of K_{IC} as a function of Charpy data, which is typically much more available. Such correlations were listed in Table 3-3 of [1]. For upper shelf conditions, the Rolfe-Novak-Barsom correlation gives K_{IC} as a function of Charpy energy and yield strength.

3.1 Charpy Data

One of the two studs removed in 1989, specifically stud #47, provided the material for Charpy and J-R curve testing. Test specimens were taken from the near OD, ½ radius and near bore locations. The impact energy results up to 150°F were presented in [1]. Other data such as percent shear were provided by ComEd [10], but not documented in [1]. The overall assessment of the stud material [11] completed in 1993 included Charpy impact energy data for stud #47 at 200°F. The Charpy test results for the stud #47 material from these various sources are in Table 3-1.

The Charpy data in Table 3-1 show that the stud material is not at upper shelf at 150°F. The percent shear values range from 50% to 70%. Therefore, the K_{IC} values reported in [2], which were in excess of 130 ksi-√in at 150°F, were for material in the Charpy transition region. The upper shelf K_{IC} is expected to be considerably higher.

In order to estimate an upper shelf K_{IC}, the upper shelf energy (USE) for the stud material is needed. The Charpy impact energy data from Table 3-1 for the ½ radius location are plotted in Figure 3-1. As seen there, the results for stud #47 at 200°F are about the same as at 150°F. The percent shear data at 200°F are not available, so the exact onset of upper shelf may be at 200°F or it may be higher. In either case, a USE of 47 ft-lb based on the average data at 150°F and 200°F is expected to be conservative for determination of the upper shelf K_{IC}. It is noted that Charpy data for stud #70 removed in 1989 is also presented in [11], and the stud #47 impact energies at 150°F and 200°F are lower by 2-3 ft-lbs.

3.2 Available Fracture Toughness

3.2.1 Leak Test

The leak test for D2R15 in April 1998 was conducted in the temperature range from 193°F to 219°F [8]. At these temperatures, the stud material may be at the upper shelf, but the percent shear data is not available to confirm this. Therefore, a conservative value is taken for leak test as the maximum K_{IC} recorded from the J-R testing of the stud #47 material, which is shown in Table 2-1 of [2] to be 141 ksi-$\sqrt{in}$ at 100°F.

A K_{IC} of 140 ksi-$\sqrt{in}$ is used for the leak test flaw evaluation in Section 4.

3.2.2 Startup Condition

The limiting stresses occur late in the heatup phase of startup, when stud temperatures are certainly in the upper shelf range. The Rolfe-Novak-Barsom correlation gives K_{IC} for upper shelf conditions as a function of Charpy energy and yield strength:

$$(K_{IC}/S_y)^2 = 5*(CVN/\ S_y - 0.05) \tag{3-1}$$

(K_{IC} in ksi-$\sqrt{in}$, S_y in ksi and CVN in ft-lbs)

The S_y for stud #47 at the ½ radius location is given in Table 3-2 of [1] as 155.2 ksi. With the conservative CVN=47 ft-lbs from Section 3.1, the available K_{IC} at upper shelf is:

$$K_{IC} = 174 \text{ ksi-}\sqrt{in}.$$

Table 3-1
Charpy Data for Stud #47

Specimen Location	Test Temperature, °F	Impact Energy, ft-lbs	Lateral Expansion, mils	Percent Shear, %
½ Radius	-50	14,15		
Near OD	10	22,18	13,6	20,10
½ Radius	10	21,20	10,10	10,10
Near Bore	10	20,20	10,11	10,10
Near OD	RT	31,32	7,15	30,30
½ Radius	RT	22,25	10,9	50,45
Near Bore	RT	25,23	6,10	35,30
Near OD	80	39,31	23,18	40,45
½ Radius	80	28,27	13,10	45,45
Near Bore	80	22,26	13,16	15,20
½ Radius	125	30,33		
Near OD	150	47,47	18,28	50,50
½ Radius	150	47,46	27,31	65,70
Near Bore	150	44,46	28,20	70,55
½ Radius	200	46,48		

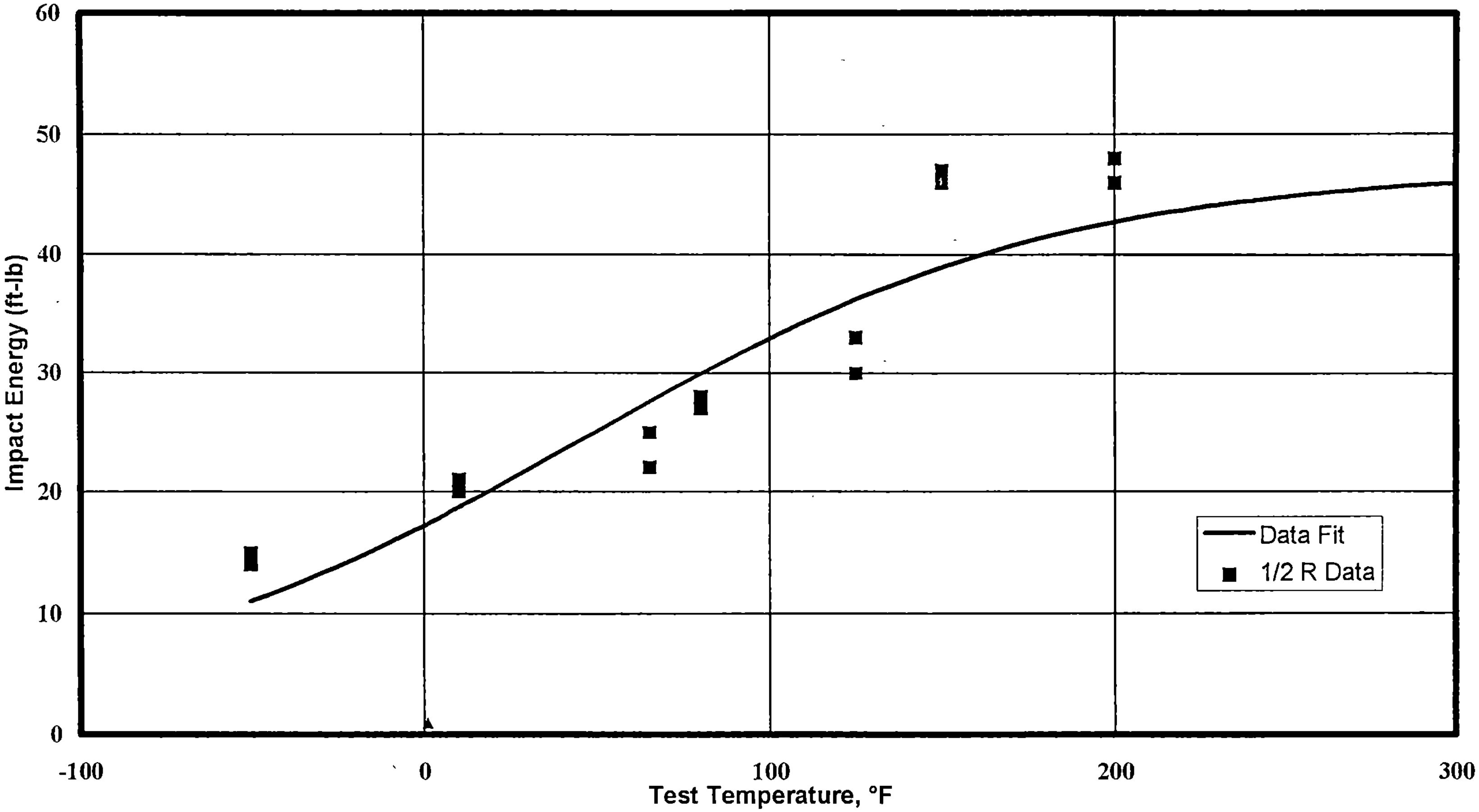


Figure 3-1. Charpy Impact Energy Data for Stud #47, ½ Radius Location (USE = 47 ft-lb)

4.0 Allowable Flaw Size

ASME Code Section XI provides criteria for postulated flaws in IWB-3730. These criteria are used here to establish the allowable postulated flaw size for studs which pass the UT inspection. Allowable flaw sizes are determined for the tensioning, leak test and startup conditions.

4.1 Allowable Fracture Toughness

The allowable fracture toughness is the available fracture toughness divided by the appropriate safety factor (SF). The safety factors for postulated flaws from Appendix G, referenced in IWB-3730, are summarized below:

Operating Condition	Safety Factor - Postulated Flaws [a]
Tensioning	1.5
Leak Test	1.5
Startup	2.0

Appendix G, Article G-4000 references WRC Bulletin 175 [12] for evaluating toughness levels in bolting material. Bulletin 175 has the following discussion on bolting toughness in Section 7C:

> "The applicable toughness property for bolts should be the static fracture toughness value, K_{IC}. Dynamic loading would not be expected to occur in bolting. Also, these higher strength steels generally exhibit very little influence of loading rate on fracture toughness."

Based on this discussion, the allowable fracture toughness is K_{IC}/SF.

4.2 LEFM Model

The applied stress intensity is determined with the same model as was used in [2] for an edge crack in the stud, which matches the cracking characteristics found in the removed studs. The equations are summarized below.

$$K = \sigma^*(F)^*\sqrt{(\pi a)} \qquad (4\text{-}1)$$

For bending stresses,

$$F = (\sqrt{\pi}/8)[3.75-10.93(a/D)+20.05(a/D)^2-19.93(a/D)^3+7.56(a/D)^4]/(1-a/D)^2 \qquad (4\text{-}2)$$

[a] Appendix G, G-4000 specifies no safety factors for bolting, so the safety factors for the vessel are used. The implied safety factor for bolt tensioning in G-2222(c) is 1.0 (full bolt preload at initial RT_{NDT}). A safety factor of 1.5 is conservative.

For tensile stresses,

$$F_{tensile} = F_{bending} \times R \quad (4\text{-}3)$$

$$\text{where } R = K_{p,t}/K_{p,b} \quad (4\text{-}4)$$

$K_{p,t}$ and $K_{p,b}$ are stress intensity factors, equivalent to F, for an edge cracked plate in tension and in bending, respectively, as discussed in [2].

This model was used in [2] to calculate K for the tensioning load, which was taken as a tensile stress. The model here is used to calculate K's for both tensile and bending stress, as both are present in the other operating conditions.

4.3 Results

Tables 4-1 through 4-3 show the K calculated for tensioning, leak test and startup, respectively. The allowable flaw sizes are determined by comparing the applied K with K_{IC}/SF. The resulting allowable flaw sizes are summarized below.

Operating Condition	Available K_{IC}	Allowable Postulated Flaws
Tensioning	130 ksi√in	0.82 in
Leak Test	140 ksi√in	0.62 in
Startup	174 ksi√in	0.39 in

Because of the different safety factors, the startup condition is most limiting. The limiting postulated flaw is 0.39 inches. In preparation for the D2R15 leak test, during which flange temperatures exceeded 212°F, the studs were preloaded and in water for approximately 3 days. At the stress corrosion crack (SCC) growth rate of 6.6×10^{-4} in/hr determined in [1] and [2], the postulated crack growth would be 0.05 inches. Assuming an initial flaw at the depth of the calibration flaw, 0.157 inches [8], the flaw depth at the next inspection would be 0.21 inches. The limiting postulated flaw size is conservative, with a margin of 0.18 inches.

Table 4-1
Dresden 2 Flaw Evaluation for Tensioning

Variables:

Outside Diameter (D)	5.85	in
Inside Diameter (d)	1.1	in
Tensile Stress (σt)	55620	psi
Bending Stress (σb)	0	psi
Crack increment (Δa)	0.02	in

a	a/D	Kp,b	Kp,t	R	F	Kb	Kt	Ktotal
0.1	0.017	1.094	1.121	1.024	0.818	0.0	26.1	26.1
0.12	0.021	1.089	1.122	1.030	0.816	0.0	28.7	28.7
0.14	0.024	1.084	1.122	1.035	0.814	0.0	31.1	31.1
0.16	0.027	1.079	1.123	1.041	0.812	0.0	33.3	33.3
0.18	0.031	1.075	1.124	1.046	0.809	0.0	35.4	35.4
0.2	0.034	1.070	1.126	1.052	0.807	0.0	37.4	37.4
0.22	0.038	1.066	1.127	1.058	0.805	0.0	39.4	39.4
0.24	0.041	1.061	1.129	1.064	0.803	0.0	41.3	41.3
0.26	0.044	1.057	1.131	1.070	0.801	0.0	43.1	43.1
0.28	0.048	1.053	1.133	1.076	0.799	0.0	44.9	44.9
0.3	0.051	1.049	1.135	1.082	0.797	0.0	46.6	46.6
0.32	0.055	1.046	1.138	1.088	0.796	0.0	48.3	48.3
0.34	0.058	1.042	1.140	1.094	0.794	0.0	49.9	49.9
0.36	0.062	1.038	1.143	1.101	0.792	0.0	51.6	51.6
0.38	0.065	1.035	1.146	1.107	0.790	0.0	53.2	53.2
0.4	0.068	1.032	1.149	1.114	0.789	0.0	54.8	54.8
0.42	0.072	1.029	1.153	1.120	0.787	0.0	56.4	56.4
0.44	0.075	1.026	1.156	1.127	0.786	0.0	57.9	57.9
0.46	0.079	1.023	1.160	1.134	0.784	0.0	59.5	59.5
0.48	0.082	1.020	1.163	1.141	0.783	0.0	61.0	61.0
0.5	0.085	1.017	1.167	1.147	0.782	0.0	62.5	62.5
0.52	0.089	1.015	1.171	1.154	0.780	0.0	64.0	64.0
0.54	0.092	1.012	1.176	1.161	0.779	0.0	65.5	65.5
0.56	0.096	1.010	1.180	1.168	0.778	0.0	67.0	67.0
0.58	0.099	1.008	1.185	1.175	0.777	0.0	68.5	68.5
0.6	0.103	1.006	1.189	1.182	0.776	0.0	70.0	70.0
0.62	0.106	1.004	1.194	1.189	0.775	0.0	71.5	71.5
0.64	0.109	1.002	1.199	1.197	0.774	0.0	73.0	73.0
0.66	0.113	1.000	1.204	1.204	0.773	0.0	74.5	74.5
0.68	0.116	0.999	1.209	1.211	0.772	0.0	76.0	76.0
0.7	0.120	0.997	1.214	1.218	0.771	0.0	77.5	77.5
0.72	0.123	0.996	1.220	1.225	0.770	0.0	78.9	78.9
0.74	0.126	0.994	1.225	1.233	0.769	0.0	80.4	80.4
0.76	0.130	0.993	1.231	1.240	0.769	0.0	81.9	81.9
0.78	0.133	0.992	1.237	1.247	0.768	0.0	83.4	83.4
0.8	0.137	0.991	1.243	1.254	0.768	0.0	84.9	84.9
0.82	0.140	0.990	1.249	1.262	0.767	0.0	86.4	86.4
0.84	0.144	0.989	1.255	1.269	0.767	0.0	87.9	87.9
0.86	0.147	0.988	1.261	1.276	0.766	0.0	89.4	89.4
0.88	0.150	0.988	1.268	1.284	0.766	0.0	90.9	90.9
0.9	0.154	0.987	1.274	1.291	0.766	0.0	92.5	92.5

Table 4-2
Dresden 2 Flaw Evaluation for Leak Test

Variables:

Outside Diameter (D)	5.85	in
Inside Diameter (d)	1.1	in
Tensile Stress (σt)	35100	psi
Bending Stress (σb)	44000	psi
Crack increment (Δa)	0.01	in

a	a/D	Kp,b	Kp,t	R	F	Kb	Kt	Ktotal
0.1	0.017	1.094	1.121	1.024	0.818	20.2	16.5	36.7
0.11	0.019	1.092	1.121	1.027	0.817	21.1	17.3	38.5
0.12	0.021	1.089	1.122	1.030	0.816	22.0	18.1	40.2
0.13	0.022	1.087	1.122	1.032	0.815	22.9	18.9	41.8
0.14	0.024	1.084	1.122	1.035	0.814	23.7	19.6	43.4
0.15	0.026	1.082	1.123	1.038	0.813	24.5	20.3	44.9
0.16	0.027	1.079	1.123	1.041	0.812	25.3	21.0	46.3
0.17	0.029	1.077	1.124	1.043	0.811	26.1	21.7	47.8
0.18	0.031	1.075	1.124	1.046	0.809	26.8	22.4	49.1
0.19	0.032	1.072	1.125	1.049	0.808	27.5	23.0	50.5
0.2	0.034	1.070	1.126	1.052	0.807	28.2	23.6	51.8
0.21	0.036	1.068	1.126	1.055	0.806	28.8	24.2	53.1
0.22	0.038	1.066	1.127	1.058	0.805	29.5	24.9	54.3
0.23	0.039	1.063	1.128	1.061	0.804	30.1	25.5	55.5
0.24	0.041	1.061	1.129	1.064	0.803	30.7	26.0	56.7
0.25	0.043	1.059	1.130	1.067	0.802	31.3	26.6	57.9
0.26	0.044	1.057	1.131	1.070	0.801	31.9	27.2	59.0
0.27	0.046	1.055	1.132	1.073	0.800	32.4	27.7	60.2
0.28	0.048	1.053	1.133	1.076	0.799	33.0	28.3	61.3
0.29	0.050	1.051	1.134	1.079	0.798	33.5	28.9	62.4
0.3	0.051	1.049	1.135	1.082	0.797	34.1	29.4	63.5
:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:
0.5	0.085	1.017	1.167	1.147	0.782	43.1	39.5	82.5
0.51	0.087	1.016	1.169	1.151	0.781	43.5	39.9	83.4
0.52	0.089	1.015	1.171	1.154	0.780	43.9	40.4	84.3
0.53	0.091	1.014	1.174	1.158	0.780	44.3	40.9	85.1
0.54	0.092	1.012	1.176	1.161	0.779	44.6	41.4	86.0
0.55	0.094	1.011	1.178	1.165	0.778	45.0	41.8	86.8
0.56	0.096	1.010	1.180	1.168	0.778	45.4	42.3	87.7
0.57	0.097	1.009	1.182	1.172	0.777	45.8	42.8	88.5
0.58	0.099	1.008	1.185	1.175	0.777	46.1	43.2	89.4
0.59	0.101	1.007	1.187	1.179	0.776	46.5	43.7	90.2
0.6	0.103	1.006	1.189	1.182	0.776	46.9	44.2	91.0
0.61	0.104	1.005	1.192	1.186	0.775	47.2	44.7	91.9
0.62	0.106	1.004	1.194	1.189	0.775	47.6	45.1	92.7
0.63	0.108	1.003	1.196	1.193	0.774	47.9	45.6	93.5
0.64	0.109	1.002	1.199	1.197	0.774	48.3	46.1	94.3
0.65	0.111	1.001	1.201	1.200	0.773	48.6	46.5	95.1
0.66	0.113	1.000	1.204	1.204	0.773	49.0	47.0	96.0
0.67	0.115	0.999	1.207	1.207	0.772	49.3	47.5	96.8
0.68	0.116	0.999	1.209	1.211	0.772	49.6	47.9	97.6
0.69	0.118	0.998	1.212	1.214	0.771	50.0	48.4	98.4
0.7	0.120	0.997	1.214	1.218	0.771	50.3	48.9	99.2

Table 4-3
Dresden 2 Flaw Evaluation for Startup

Variables:

Outside Diameter (D)	5.85 in
Inside Diameter (d)	1.1 in
Tensile Stress (σt)	31400 psi
Bending Stress (σb)	64300 psi
Crack increment (Δa)	0.01 in

a	a/D	Kp,b	Kp,t	R	F	Kb	Kt	Ktotal
0.1	0.017	1.094	1.121	1.024	0.818	29.5	14.8	44.3
0.11	0.019	1.092	1.121	1.027	0.817	30.9	15.5	46.4
0.12	0.021	1.089	1.122	1.030	0.816	32.2	16.2	48.4
0.13	0.022	1.087	1.122	1.032	0.815	33.5	16.9	50.4
0.14	0.024	1.084	1.122	1.035	0.814	34.7	17.5	52.2
0.15	0.026	1.082	1.123	1.038	0.813	35.9	18.2	54.1
0.16	0.027	1.079	1.123	1.041	0.812	37.0	18.8	55.8
0.17	0.029	1.077	1.124	1.043	0.811	38.1	19.4	57.5
0.18	0.031	1.075	1.124	1.046	0.809	39.1	20.0	59.1
0.19	0.032	1.072	1.125	1.049	0.808	40.2	20.6	60.7
0.2	0.034	1.070	1.126	1.052	0.807	41.1	21.1	62.3
0.21	0.036	1.068	1.126	1.055	0.806	42.1	21.7	63.8
0.22	0.038	1.066	1.127	1.058	0.805	43.0	22.2	65.3
0.23	0.039	1.063	1.128	1.061	0.804	44.0	22.8	66.7
0.24	0.041	1.061	1.129	1.064	0.803	44.8	23.3	68.1
0.25	0.043	1.059	1.130	1.067	0.802	45.7	23.8	69.5
0.26	0.044	1.057	1.131	1.070	0.801	46.6	24.3	70.9
0.27	0.046	1.055	1.132	1.073	0.800	47.4	24.8	72.2
0.28	0.048	1.053	1.133	1.076	0.799	48.2	25.3	73.5
0.29	0.050	1.051	1.134	1.079	0.798	49.0	25.8	74.8
0.3	0.051	1.049	1.135	1.082	0.797	49.8	26.3	76.1
0.31	0.053	1.047	1.136	1.085	0.797	50.5	26.8	77.3
0.32	0.055	1.046	1.138	1.088	0.796	51.3	27.3	78.5
0.33	0.056	1.044	1.139	1.091	0.795	52.0	27.7	79.8
0.34	0.058	1.042	1.140	1.094	0.794	52.8	28.2	80.9
0.35	0.060	1.040	1.142	1.098	0.793	53.5	28.7	82.1
0.36	0.062	1.038	1.143	1.101	0.792	54.2	29.1	83.3
0.37	0.063	1.037	1.145	1.104	0.791	54.9	29.6	84.4
0.38	0.065	1.035	1.146	1.107	0.790	55.5	30.0	85.6
0.39	0.067	1.033	1.148	1.111	0.790	56.2	30.5	86.7
0.4	0.068	1.032	1.149	1.114	0.789	56.9	30.9	87.8
0.41	0.070	1.030	1.151	1.117	0.788	57.5	31.4	88.9
0.42	0.072	1.029	1.153	1.120	0.787	58.1	31.8	90.0
0.43	0.074	1.027	1.154	1.124	0.787	58.8	32.3	91.0
0.44	0.075	1.026	1.156	1.127	0.786	59.4	32.7	92.1
0.45	0.077	1.024	1.158	1.130	0.785	60.0	33.1	93.1
0.46	0.079	1.023	1.160	1.134	0.784	60.6	33.6	94.2
0.47	0.080	1.021	1.162	1.137	0.784	61.2	34.0	95.2
0.48	0.082	1.020	1.163	1.141	0.783	61.8	34.4	96.2
0.49	0.084	1.019	1.165	1.144	0.782	62.4	34.9	97.3
0.5	0.085	1.017	1.167	1.147	0.782	63.0	35.3	98.3

5.0 Structural Assessment

Given that a stud with a detected flaw was inadvertently left in operation, a structural assessment of the closure flange bolting is done assuming the subject stud is completely failed. ASME Code Section XI, IWB-3610(d)(2) requires that the primary stress limits be met while discounting any area associated with a crack. For the redundant flange bolting, this assessment is made below, assuming one of the 92 studs is failed.

5.1 One Stud Failed

The methodology for determining the design required stud area is described in Section 5 of [1]. The stud required area is based on the design pressure and the S_m of the bolting material. Maintaining the stud required area is the equivalent of meeting the requirement of Section XI, IWB-3610(d)(2).

The required area was conservatively calculated in [1] as 2030.3 in^2. The available area, for 92 studs, is 2382 in^2 [2], with the area per stud being 25.89 in^2. With one stud failed, the available area is 2356.1 in^2.

$$2356.1 \text{ in}^2 \text{ available} > 2030.3 \text{ in}^2 \text{ required}$$

Therefore, continued operation assuming complete failure of the cracked stud is acceptable.

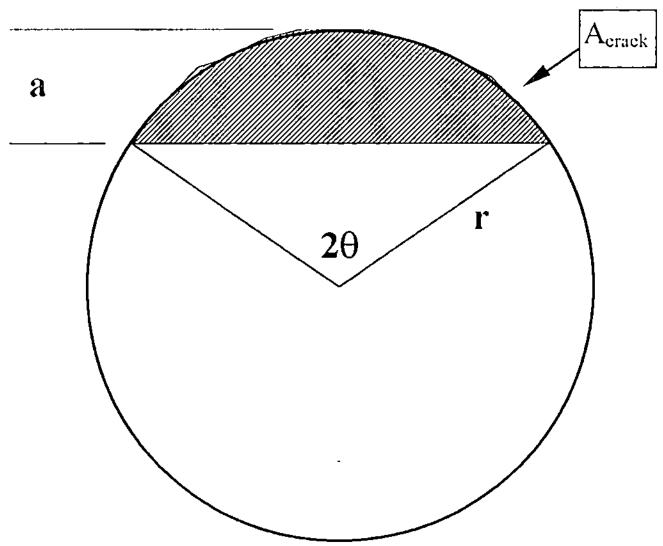
5.2 Allowance for Postulated Flaws

Section XI requires that area be removed corresponding to only the known cracking, in this case taken to be the entire area of the one stud with a known crack. To demonstrate the redundancy in the Dresden 2 closure assembly, a beyond-Section XI area calculation is done to determine the maximum edge crack that can be tolerated if the cracked stud is completely failed and the other 91 studs each have the same edge crack.

The area of an edge crack of maximum depth a in a round bar of radius r is expressed as [13]

$$A_{crack} = \frac{1}{2} r^2 (2\theta - \sin 2\theta) \quad (5\text{-}1)$$

where 2θ is the angle between the radii which form the triangle including the crack front.



The acceptable value of A_{crack} is determined from the difference between available and required area:

$$(2356.1 - 2030.3)\ in^2 / 91\ studs = 3.58\ in^2/stud$$

For a = 1.1 inches, $A_{crack} = 3.51\ in^2/stud$.

Therefore, the primary stress requirements of IWB-3610(d)(2) are met for an edge flaw of up to 1.1 inches. This is larger than the limiting postulated flaw of 0.39 inches, and much larger than the calibration flaw depth of 0.157 inches.

Therefore, there is margin in the stud preload capacity even assuming continued operation with a failed stud and cracks in each remaining stud equal to the postulated flaw size.

6.0 Conclusions

The following points summarize the conclusions of the analyses presented in this report:

1. The tensioning stress is the maximum membrane stress, but leak test and startup have large bending stresses, such that flaw evaluations for these conditions are needed to establish the limiting allowable flaw sizes.
2. The emergency and faulted conditions are bounded by normal and upset conditions.
3. Given the combination of J-R curve testing done and the Charpy data available, K_{IC} fracture toughness values could be estimated for the temperatures associated with the leak test and startup conditions.
4. Section XI provides requirements for calculating postulated flaws (IWB-3730). The smallest postulated flaw size of 0.39 inches is conservative for the D2R15 outage where a postulated flaw equal to the calibration standard depth, 0.157 inches, may have grown 0.05 inches.
5. The structural capability of the studs in the closure flange has substantial margin for the scenario per Section XI where one stud with a known crack is assumed to fail completely. If, beyond Section XI requirements, an edge flaw is conservatively added to each of the 91 remaining studs, the acceptable edge flaw is 1.1 inches, considerably larger than the postulated flaw size of 0.39 inches.

The overall conclusion from the analysis is that continued operation of Dresden 2 with a cracked vessel head stud in place is justified.

7.0 References

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[5] "Rules for Inservice Inspection of Nuclear Power Plant Components," Section XI of ASME Boiler & Pressure Vessel Code, 1989 Edition.

[6] "Section S1, Main Closure Flange Stress Analysis - 251" BWR LaSalle II Vessel," GE VPF 3073-230(1)-1, June 1973.

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[8] "Unit 2 Reactor Closure Studs Flaw Evaluation," ComEd Nuclear Design Information Transmittal (NDIT) SEC-DR-98-098 Rev. 0, May 19, 1998.

[9] "Section E1, Main Closure Flange Special Report - 251" BWR LaSalle II Vessel," GE VPF 3073-230(25)-1, November 1974.

[10] Fax, dated 1/14/90, J. Chynoweth of ComEd to T Caine of GENE, "Charpy Lateral Expansion and Percent Shear Data."

[11] "Evaluation of Material from Dresden Unit 2 Reactor Head Closure Studs (SMAD Report M-03166-93, Dated 05/24/93," NDIT MSD-98-029, 5/22/98.

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[13] Avallone and Baumeister, "Marks' Standard Handbook for Mechanical Engineers," 9th Edition, 1987, pg. 2-9.