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ABSTRACT

The question of whether ligament rupture pressure or unstable burst pressure may vary significantly with pressurization rate at room temperature arose from the results of pressure tests by industry on tubes with machined part–throughwall notches. Slow (quasi–static) and fast 14 MPa/s (2000 psi/s) pressurization rate tests on specimens with nominally the same notch geometry appeared to show a significant effect of the rate of pressurization on the unstable burst pressure. Unfortunately, the slow and fast loading rate tests were conducted following two different test procedures, which could confound the results. The current series of tests were conducted on a variety of specimen geometries using a consistent test procedure to better establish the effect of pressurization rate on ligament rupture and burst pressures.

1. Introduction

The flow stress of a typical mill annealed (MA) or thermally treated (TT) Alloy 600 or TT Alloy 690 tube material at temperatures ≤ 300°C is not expected to show a strong dependence on strain rate or stress rate. Consequently, the ligament rupture pressure or unstable burst pressure of a steam generator (SG) tube with a part–throughwall axial crack is not expected to depend significantly on the rate of pressurization at these temperatures. However, an industry vendor conducted a series of room temperature (RT) tests with slow (quasi–static) and fast 14 MPa/s (2000 psi/s) pressurization rates tests that appeared to show a significant effect of the rate of pressurization on the unstable burst pressure. The tests were conducted on tubes with machined part–throughwall notches with a complex shape, the so–called Type 14 notch shown in Fig. 1.[1] These notches were machined nominally to the same nominal depth profile (as measured by an eddy current technique) as that of a stress corrosion crack in a SG tube removed from a domestic SG. Slow (quasi–static) and fast 14 MPa/s (2000 psi/s) pressurization rate tests on these specimens with nominally the same notch appeared to show a significant effect of the rate of pressurization on the unstable burst pressure. Unfortunately, the two types of tests at the two strain rates were conducted following two different test procedures. The slow rate tests were conducted in two steps – first, the specimen was pressurized without bladder and foil until ligament rupture occurred (but not burst); next, a bladder and foil was inserted and the specimen pressurized until unstable burst. The unstable burst pressure during the second step was found to be significantly less than the ligament rupture pressure observed during the initial portion of the test, which indicated that the specimens would have burst unstably during the initial testing if the pump had sufficient flow capacity to maintain pressure after the initial ligament rupture. The

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fast rate 14 MPa/s (2000 psi/s) tests were conducted with bladder and foil from the beginning of the tests. The average ligament rupture (burst) pressure increased was 30% higher in the tests with a pressurization rate 14 MPa/s (2000 psi/s) than in the quasi–static case. Subsequent analyses suggested that differences in notch profiles between the slow and the fast rate test specimens could account for some of the observed "rate effect" but not all of it.

An earlier series of tests on EDM notch specimens at ANL showed relatively small rate effects. A second series of tests was conducted on a variety of specimen geometries to clearly determine the effect of pressurization rate on ligament rupture and burst pressures.

2. Factors Influencing Tests to Determine Pressurization Rate Effect

It is known that ligament rupture pressure is more likely to display a pressurization rate effect than unstable burst pressure.[2] In order to be able to predict ligament rupture pressures reliably, we need crack length, the geometry of the crack tip ligament and the flow stress of the material. For a given crack geometry, a true pressurization rate effect on ligament rupture pressure can occur only if the flow stress of the material is a function of strain rate. Flow stress of Alloy 600 (mill-annealed or thermally-treated) at room or normal operating temperature (~300°C) is not expected to vary significantly with the range of strain rates that occur in conventional tensile testing. However, the effective strain rates in narrow crack tip ligaments at high pressurization rates may be significantly higher than what is achievable under conventional tensile testing. The effect of pressurization rate can be masked by spurious factors that need to be understood and accounted for before the true pressurization rate effect on ligament rupture pressure can be established. Key factors other than the effect of strain rate on the flow stress that could affect the pressurization rate effect tests are:

a) Artificial elevation (or reduction) of ligament rupture and burst pressures due to the use of bladder and foil in the test specimens.

b) Specimen-to-specimen variation in as-fabricated ligament geometry and crack length for a given nominal crack geometry.

Tests were conducted with and without bladder and foil to determine the effect of the bladder and foil on the ligament rupture and burst pressure. The typical response time of the pressure transducer used in our RT test facility is 5 ms. The rise time to 2500 psi at a rate of 2000 psi/s is 1.25 s. Because this is much greater than the transducer response time, the response time should have negligible effect on the measured pressurization rate. Also, in order to assess the true effect of pressurization rate, the variability in the test data due to geometric variation from specimen-to-specimen has to be reduced. This was done by first computing the ligament rupture pressures of the specimens with the ANL model[3] using the as-fabricated flaw geometry and the flow stress of the material as determined from conventional tensile tests. If the ligament rupture pressures of the tests conducted with various pressurization rates could be predicted within the 95% confidence limits of the ANL model and showed no systematic bias with respect to the predicted values, we concluded that there was no significant effect of pressurization rate on the ligament rupture pressure. It is more difficult to directly establish a rate effect for SCCs, because the complex SCC flaw geometry varies from specimen to specimen in an arbitrary manner. Thus, any conclusion regarding pressurization rate effect in SCC specimens would have to be drawn on a statistical basis from a relatively large number of tests. Such a determination has not been made under the current study.

3. Test Results

All tests were conducted at room temperature on tubes that were 22 mm (0.875 in.) in diameter, a 1.3 mm (0.050 in.) wall thickness and had nominal yield and ultimate tensile strengths of 290 and 630 MPa (42 and 91 ksi), respectively. All the flaws in the test specimens were fabricated by electro discharge machining (EDM). The test facility had the capability to maintain a flow rate of 46 L/min (12 gpm) at 52 MPa (7500 psi) indefinitely.

The tests were divided into two series. The first series of tests were conducted at various pressurization rates on specimens with single < 25.4 mm (1 in.) long rectangular part-throughwall (PTW) flaws with various combinations of bladder and foil to determine the acceptable dimensions of the bladder and foil.

The second series of tests were conducted at various pressurization rates on specimens with single PTW rectangular and trapezoidal flaws, and two PTW rectangular flaws. To minimize the effects of bladder and foil on the results, all of the specimens in the second test series were tested in two stages. First, the specimens were pressurized without any bladder or foil at a controlled pressurization rate to ligament rupture. Pressurization then was continued until the pump ran out of flow or pressure capability. For the specimens that did not undergo unstable burst, a bladder and foil was inserted inside the specimens, and the specimens were repressurized at the desired rate until unstable burst occurred. The bladder used was a hard Tygon tubing with a 3.2–mm (1/8–in)–thick wall and a diameter slightly smaller than the specimen ID. Brass foils of thickness 0.13 mm (0.005 in.) were used, and they extended 6.35 mm (0.25 in.) beyond the flaw extremities. The foil and bladder were sprayed with a lubricant to reduce friction between the foil and SG tube.

3.1 First Test Series

Test results for the initial series of tests on the effect of bladder and foil on ligament rupture pressure and unstable burst pressure at different pressurization rates are presented in Tables 1 and 2, respectively. Because these were standard rectangular EDM notches, the as-fabricated geometries of the specimens were close to the nominal values shown in the tables. Table 1 shows that at comparable pressurization rates, the ligament rupture pressures for tests using a bladder but without any foil are close to those using neither bladder nor foil. The 100% TW, 12.7 mm (0.5 in.) long notch tests of Table 2 show no significant effect of foil and bladder thickness on burst pressures. The 100% TW 6.3 mm (0.25 in.) long notch tests in the same table show no significant difference in burst pressures for tests conducted with or without foil and bladder. Similarly, no systematic differences were detected in the burst pressures for tests using bladder with a 0.13 mm (0.005 in.) brass foil or with bladder but no foil. Although the comparison testing with and without bladder and foil has not been exhaustive, the industry vendor has also concluded that the use of bladder and foil of the same sizes as used here does not affect the ligament rupture or burst pressure significantly.[a]

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[a] Private Communication R. Keating (deceased) to S. Majumdar, Argonne National Laboratory, 2000.

3.2 Second Test Series

Four types of EDM notched specimens, shown in Figs 2–3, were used for additional pressurization rate effect tests. The total flaw length of each specimen was fixed nominally at 1 in. (25 mm). An additional series of rectangular EDM flaws with shorter lengths were tested to determine if pressurization rate effects are more pronounced in such specimens. Also, two tests were conducted on specimens with SCC.

Four pressurization rates were used: quasi–static (stepwise pressure increases with intermittent hold), 7 MPa/s (1000 psi/s), 14 MPa/s (2000 psi/s), 41 MPa/s (6000 psi/s), and, for some tests, >70 MPa/s (>10,000 psi/s). The quasi–static tests were used as controls/references. Because all the flaws after ligament rupture were 25.4–mm (1–in.) long, they were expected to exhibit nominally the same burst pressure, and hence only a representative number were tested to unstable burst.

3.2.1 Tests on 25 mm (1 in.) Long EDM Flaws

Table 3 summarizes the data from the ligament rupture tests on rectangular and non-rectangular flaws 25 mm (1 in.) long. The raw data are somewhat misleading because the as–received EDM flaws varied somewhat from the specified dimensions which has a significant influence on ligament rupture pressure. As noted previously, these results have to be compared with predictions of ligament rupture pressures based on the as–fabricated flaw geometry before the effect of pressurization rate can be assessed.

Results from the unstable burst testing are summarized in Table 4. All of the unstable burst pressures varied between 14–16 MPa (2000–2300 psi), as expected because all of the flaws had an overall length of 25 mm (1 in.). Consequently, the rest of the specimens were not tested.

3.2.2 Tests on Short EDM Flaws

Three 6.35–mm– (1/4–in.)–long, 90% TW flaws, OM232, OM234, and OM250, were tested at a nominal pressurization rate of 41 MPa/s (6000 psi/s). The observed ligament rupture pressures are 40.0, 40.7, and 40.1 MPa (5800, 5900, and 5810 psi), respectively.

Two 19.05–mm (3/4–in.)–long, 80% TW flaws OM235 and OM236, tested at a nominal rate of 50.3 MPa/s (7300 psi/s), yielded ligament rupture pressures of 24.8 and 26.8 MPa (3600 and 3885 psi), respectively.

3.2.3 Tests on Stress Corrosion Cracks

Limited tests at various pressurization rates were initiated on 22.2–mm (7/8–in.)–diameter tubes containing laboratory–produced ODSCC axial flaws of nominally 12.7– and 19.05–mm (1/2– and 3/4–in.) length and ≥80% PTW. The two pressure tests conducted on SCC specimens to date were inconclusive because, unlike EDM notches, no abrupt ligament rupture event occurred in these tests. The specimens displayed time-dependent leak rate increase.

4. Analysis of Test Results

4.1 Predicted Failure Pressures

As noted, to minimize the uncertainties due to specimen-to-specimen variation in flaw geometry, the observed ligament rupture pressures should be compared with ligament rupture pressures predicted using the as-fabricated geometry. For the tests on the 25 mm (1 in.) flaws, this comparison is shown in Fig. 4 where the predicted values are based on a constant rate-independent yield stress=290 MPa (41.6 ksi), a rate-independent constant ultimate tensile strength = 630 MPa (91.4 ksi), and a flow stress factor k=0.55. The predicted test ligament rupture pressures are within the ± 95% confidence limits of the test predicted ligament rupture pressures and no strong bias about the predicted value is observed. Thus, there is no statistical evidence of a systematic pressurization rate effect on the ligament rupture pressure for rates up to 14 MPa/s (2 ksi/s) for 25 mm (1 in.) long notches.

For a 25 mm (1 in.) throughwall crack, the predicted unstable burst pressure is 17 MPa (2.4 ksi), which is within 10% of all the observed unstable burst pressures. Thus, there is no significant pressurization rate effect on the unstable burst pressures for rates up to 14 MPa/s (2 ksi/s) for 25 mm (1 in.) TW flaws.

The ligament rupture pressure data for flaws < 25 mm (1 in.) are plotted in Figs. 5a as a function of pressurization rate. Figs. 5a also includes Type 14 test data from the vendor.[1] The Type 14 data appear to exhibit a larger pressurization rate effect than the ANL tests; 30% increase for the Type 14 specimens compared to 10% increase for the ANL tests due to an increase in pressurization rate from quasi–static to 13.8 MPa/s (2 ksi/s).

Much of the variability in the ligament rupture data (particularly the Type 14 data) can be traced to the variability in the as–built notch geometry from the nominal geometry.[1] As mentioned earlier, a better estimate of the true effect of pressurization rate can be obtained by normalizing the test results by the predicted ligament rupture pressures using the as–fabricated geometry of the notches and the ANL ligament rupture model. The variation of the normalized ligament rupture pressures with pressurization rate is shown in Fig. 5b. The scatter band at 138 kPa/s [20 psi/s (quasi-static)] is estimated from a database on ligament rupture pressure on rectangular EDM notches conducted at ANL.[2-4] Note that most of the type 14 data fall within the ANL data scatter. The plot suggests no significant pressurization rate effect between quasi–static and 7 MPa/s (1 ksi/s). Beyond 7 MPa/s (1 ksi/s), there is a slight increase in the normalized ligament rupture pressure with pressurization rate that varies approximately as pressurization rate raised to an exponent 0.129. The shorter notches tend to show a slightly larger rate effect than the longer notches. However, if the pressurization rate is limited to 13.8 MPa/s (2 ksi/s), the increase in ligament rupture pressure compared to quasi–static is about 10%, which is within the scatter band of the quasi–static test data.

4.2 Post-Test Observations of Specimens

Post–test observations of the 6.35–, 19.05–, and 25.4–mm (1/4–, 3/4–, and 1–in.)–long notches indicated large radial bulging deformation occurring locally around the flaw for all the flaws. However, the < 25–mm (1–in.)–long flaws also experience significant bulk plastic strain away from the flaw location because the nominal stress in these specimens exceeded the yield strength. The general level of plastic deformation diminishes with increasing flaw size, because the larger flaws undergo ligament rupture at lower pressures in a regime where the bulk of the tube away from the flaws remains elastic. The observed pressurization rate effect for the shorter flaws may be a result of a strain rate effects associated with the more extensive plastic deformation.

5. Conclusions

The 25 mm (1 in.) long rectangular as well as trapezoidal notches and two notches separated by axial and circumferential ligament do not show any pressurization rate effect on the ligament rupture or unstable burst pressure. Rectangular notches < 25 mm (1 in.) long show a small pressurization rate effect on ligament rupture pressure for rates > 7 MPa/s (1000 psi/s), with shorter notches experiencing a slightly greater rate effect than longer notches. However the increase in ligament rupture pressure at 13.8 MPa/s (2000 psi/s), which is the upper limit for most laboratory and field pressure tests[5], compared to quasi–static loading is only 10%, which is within the scatter of the data for quasi–static loading. From this study, no conclusions can be drawn regarding the effect of pressurization rate on unstable burst pressure of initially 100% throughwall notches < 25 mm (1 in.) long.

The pressurization rate effect observed in the specimens with shorter part-throughwall flaws may be associated with the significant plastic deformation in the bulk of the tubes away from the flaws. Plastic deformation is more localized in specimens with longer flaws.

The use of tygon bladder ≤ 3 mm (1/8 in.) thick, with or without standard size 0.13-mm (0.005 in.) thick brass foils, does not influence the ligament rupture or unstable burst pressures of part-throughwall notches. For initially throughwall notches, the change of tygon bladder thickness from 2 to 3 mm (3/32 to 1/8 in.) does not affect the unstable burst pressure if it is used together with standard size 0.13-mm (0.005 in.) thick brass foils.

Because of the difficulty of controlling the geometry of actual SCCs, pressurization rate effects in SCC specimens would have to be investigated by testing a large number of specimens with "similar" SCCs at several pressurization rates and comparing the pressure vs. leak rate data on a statistical basis. Such a program is not planned.

Although the current series of tests have been conducted at RT on MA Alloy 600 tubes, the conclusions relative to pressurization rate effect are expected to be applicable to TT tubes at RT as well as at operating temperatures (~300°C). The plastic deformation mechanisms and behavior of the MA and TT materials are similar and strain rate effects due to thermal creep are not expected to be significant at ≤ 300°C. The conclusions should also be applicable to TT Alloy 690 for the same reason. The grain boundary carbides associated with TT materials may have significant effects on the long–term deformation of grain boundaries, but the failure processes of interest involve primarily plastic deformations in the bulk of the grain.

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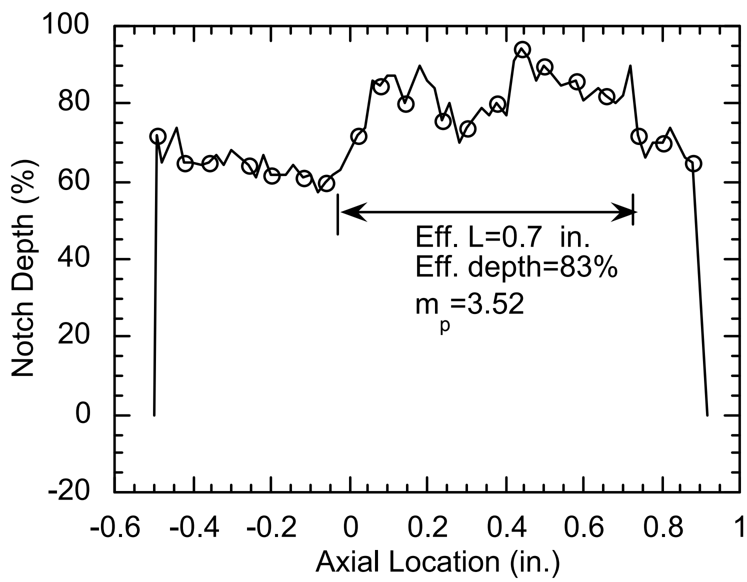


Figure 1. Notch depth profile for Type 14 specimen. m_p denotes radial ligament stress magnification factor.

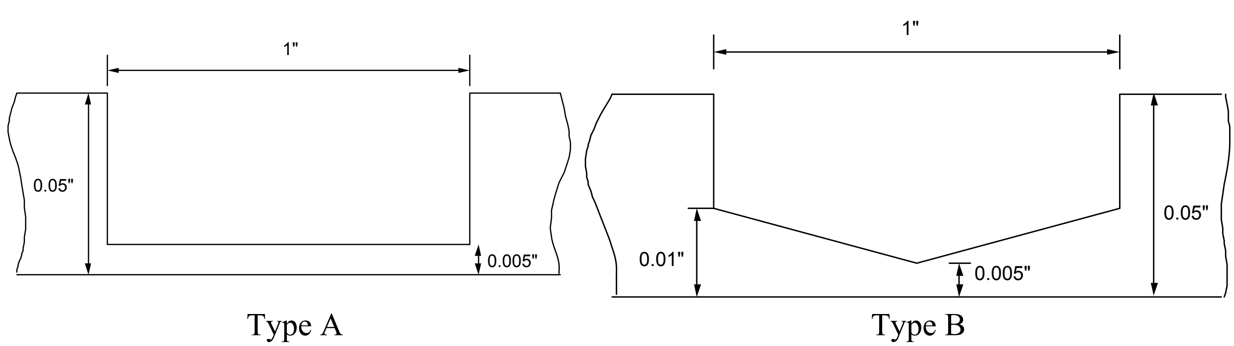
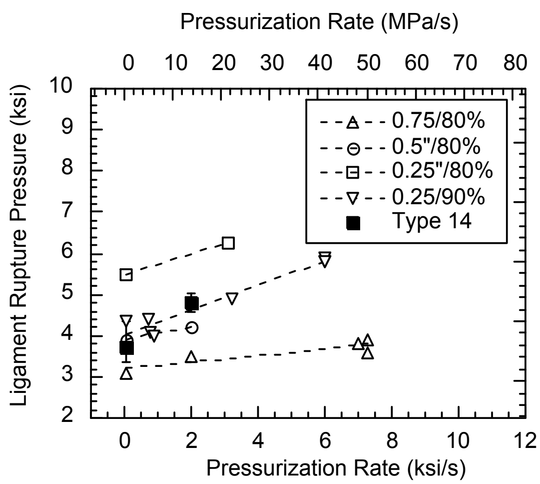
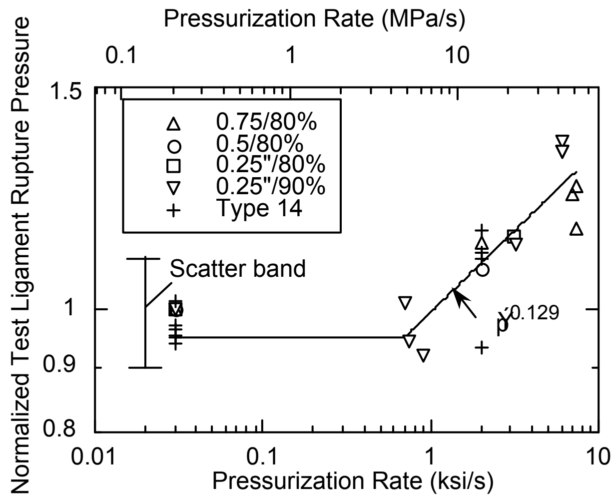


Figure 2. Type A: single rectangular flaw and Type B: single trapezoidal flaw.



(a)



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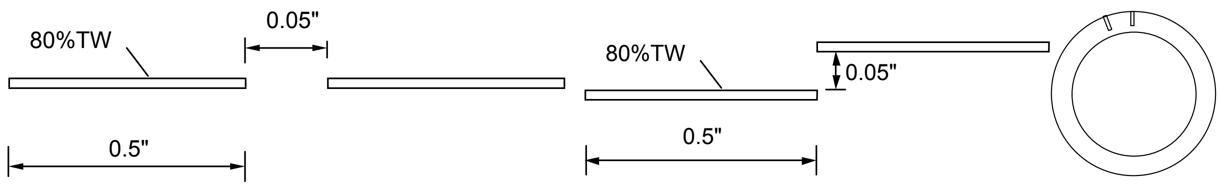

Type C Type D

Figure 3. Type C: 2–collinear flaws (axial ligament) and Type D: 2–offset flaws (circumferential ligament)

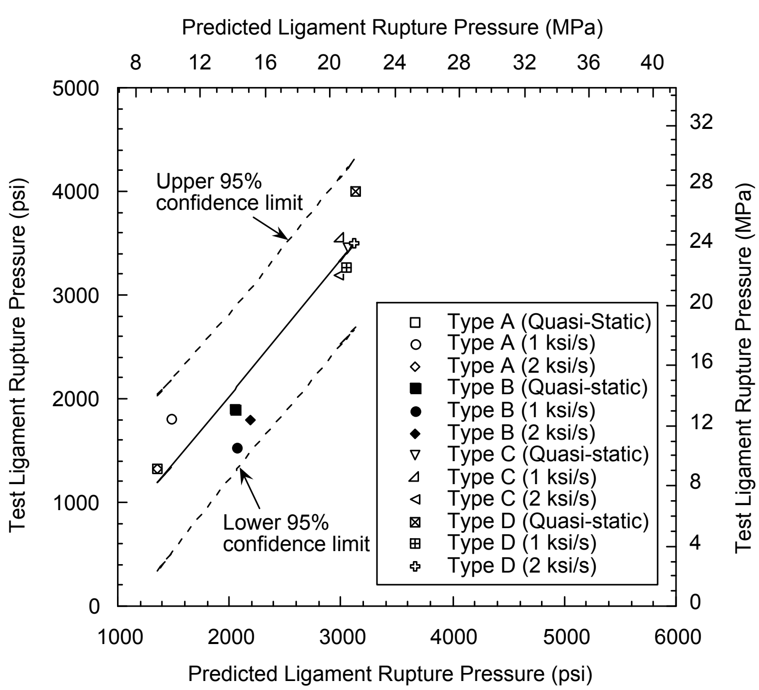

Figure 4. Predicted vs. observed ligament rupture pressure for quasi–static to 14 MPa /s (2 ksi/s) tests.

Figure 5. Variation of (a) test ligament rupture pressures and (b) normalized test ligament rupture pressures with pressurization rate.

Table 1 Ligament rupture pressures for < 25 mm (1 in.) long, part–throughwall rectangular EDM flaws with and without bladder

Flaw Length mm (in.)	Flaw Depth (%)	Foil	Bladder	Pressurization Rate MPa/s (psi/s)	Ligament Rupture Pressure MPa (psi)
19.0 (0.75)	80	No	No	Quasi–static	21.4 (3100)
				13.8 (2000)	24.1 (3500)
				48.3 (7000)	26.2(3800)
6.3 (0.25)	90	No	No	Quasi–static	30.0 (4350)
				5.2 (750)	28.3(4100)
				22.0 (3200)	33.8(4900)
12.7 (0.5)	60	No	No	13.8 (2000)	40.7 (5900)[a]
			3/32 in. Tygon	13.8 (2000)	41.4 (6000)[a]
6.3 (0.25)	80	No	No	Quasi–static	37.9 (5500)
			3/32 in. Tygon	20.7 (3000)	43.1 (6250)[a]
6.3 (0.25)	60	No	No	13.8 (2000)	49.60(7200)
			3/32 in. Tygon	20.7 (3000)	47.60(6900)[a]

[a] Specimen burst with fishmouth flaw opening

Table 2 Unstable burst pressures (Stage 2) for < 25 mm (1 in.) long, part–throughwall and throughwall rectangular EDM flaws with and without bladder and foil.

Flaw Length mm (in.)	Flaw Initial Depth (%)	Foil	Bladder	Pressurization Rate MPa/s (psi/s)	Unstable Burst Pressure MPa (psi)[a]
12.7 (0.5)	100	Standard 0.005 in.	3/32 in. Tygon	13.8 (2000)	30.3 (4400)
		Standard 0.005 in.	1/8 in. Tygon		29.6 (4300)
		Standard 0.005 in.	1/8 in. Tygon		30.0 (4350)
		Oversize 0.005 in.	1/8 in. Tygon		30.7 (4450)
6.3 (0.25)	90	No	No	22.1 (3200)	44.8 (6500)[b]
		No	1/8 in. Tygon	4.80(700)	44.8 (6500)
		Standard 0.005 in.	1/8 in. Tygon	6.2 (900)	41.4 (6000)
6.3 (0.25)	90	No	No	Quasi–static	42.7 (6200)[b]
				5.2 (750)	44.1 (6400)[b]
				22.0 (3200)	44.8 (6500)[b]

[a] Nominal burst pressure of a 13 mm (0.5 in.), 100% throughwall notch is 30 MPa (4400 psi)
[b] Specimen did not burst with fishmouth flaw opening

Table 3 EDM flaw ligament rupture pressure (Stage 1) for four flaw types (Types A, B, C, and D in Figs. 2–3) and five different pressurization rates.

Pressurization Rate, MPa/s (psi/s)	Observed Failure Pressures, MPa (psi) [Specimen No.] For Flaw Types Indicated in Figs 2–3: A	B	C	D
Stage 1 Testing; Radial Ligament Rupture (no foil or bladder)				
Quasi–steady–state	9.1 (1320) [OM201]	13.1 (1900) [OM207]	23.9 (3460) [OM214[b]]	27.6 (4000) [OM219[c]] 21.7 (3150) [OM223[c]]
7 (1000)	12.5 (1815) [OM202] 11.5 (1675) [OM204]	10.6 (1535) [OM224]	24.4 (3540) [OM215[b]]	22.5 (3264) [OM220[c]]

14 (2000)	9.1 (1325) [OM203]	12.4 (1800) [OM210]	22.0 (3190) [OM216[b]]	24.1 (3500) [OM222[c]]
41 (6000)	11.7 (1690) [OM205]	13.4 (1950) [OM211]	21.6 (3135) (OM217[b]]	24.3 (3520) [OM225[c]]
> 69(>10,000)	13.0 (1885) [OM206]	51.0 (7400) [OM209[a]] 12.9 (1875) [OM212]	23.7 (3440) [OM213[b]] 23.1 (3350) [OM218[b]]	–

[a] Flaw much shallower than specified dimensions.
[b] Both radial and axial ligaments ruptured.
[c] Both radial and circumferential ligaments ruptured.

Table 4 EDM flaw unstable burst pressure (Stage 2) for four flaw types (Types A, B, C, and D in Figs. 2–3) and five different pressurization rates.

Pressurization Rate, MPa/s (psi/s)	Observed Failure Pressures, MPa (psi) [Specimen No.] For Flaw Types Indicated in Figs 2–3			
	A	B	C	D
Stage 2 Testing; Unstable Burst (with foil and bladder)				
7 (1000)	–	–	14.1 (2050) [OM215]	–
14 (2000)	15.8 (2295) [OM203]	–	14.3 (2075) [OM216]	–
41 (6000)	14.7 (2130) [OM205]	–	13.9 (2020) [OM217]	–
> 69(>10,000)	15.6 (2265) [OM206]	–	15.0 (2175) [OM218]	–