LASER ENTRANCE HOLE WINDOW BURST AND PRESSURE DEFLECTIONS AT CRYOGENIC TEMPERATURE

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Laser Entrance Hole (LEH) windows for hohlraums must have minimal thickness, yet must contain low temperature tamping gas in a reproducible envelope at 52 kPa. Given the high cost of a window failure, it is of interest to understand variability in the finished windows. The shape and magnitude of pressure deflections of LEH windows were well described at 18K using thin film elastic mechanics. Subsequently, 24 windows, with 3.9mm-apertures, were selected from several production lots to measure reproducibility in the windows. The windows were cooled to 18 K, and their leak rates, deflection at 52 kPa, and burst pressure were measured. Mean window deflection at 18K was 260 microns, with a standard deviation of 20 microns. Variability in window deflections at 52 kPa were well described by an anisotropic initial strain model. Window burst pressure was found to obey first-order Weibull statistics. The predicted failure rate for the use conditions was extrapolated to be less than 0.1%.

INTRODUCTION

Thin nonpermeable windows are needed for Laser Entrance Hole (LEH) windows used at the National Ignition Facility (NIF). The functions of the windows are to contain a medium-pressure (52 kPa) tamping gas, reduce radiative losses, and to provide a reproducible gas geometry for sequential laser shots. Polyimide has been selected as the window material due to its combined properties of strength and low permeability(1). As designed, the windows are expected to exhibit neglible leak rates and consistent pressure deflections, as well as an acceptable failure rate, at their operating temperature of 18K. Historically, tests to window failure had identified two potential failure mechanisms, "peel", in which the film delaminated from the washer, and "burst", in which the membrane ruptured while remaining adhered to the washer.

NIF operations goals include the need for >95% hohlraum yield, including cooldown and filling(2). Given the large number of components comprising a hohlraum, this flows down to a requirement for each of the components, including the LEH windows, have a failure rate less than 0.3% (2). The goals of the present study are to assess the reproducibility of the windows at cryogenic temperature, and to estimate the failure rate that might be expected in use.

EXPERIMENTAL DETAILS

The LEH windows were composed of aluminum washers, having an aperture of 3.3mm or 3.9mm, onto which a film was suspended with low-temperature epoxy. The film was composed of a 0.5 micron thick (+/-5%) polyimide membrane, coated with 25nm aluminum on the side opposite the washer(3,4).

For the statistical study, 24 3.9mm aperture LEH windows were assembled using standard fabrication procedures, tested at room temperature at 7 kPa for He leak rate and window center deflection. At 7 kPa, room temperature He leak rate for all washers was less than 1E-7 mbar-L/sec. The average center-of-window deflection was 139microns, with a standard deviation of 14 microns. The windows were selected from three different production lots. Subsequently, the windows were epoxy mounted to a low temperature cold head and cooled to 18K$\pm$0.5K. Center-of-window deflection was measured using a confocal microscope with an accuracy of 0.1 microns. Helium pressure was applied from the washer side. x-z deflection profiles were collected by scanning the microsope on an x-y-z stage, with an accuracy of 1 micron. Windows were initially deflected for three cycles from zero applied pressure to 52 kPa, and then pressurized to burst. Windows were then inspected for mode of failure, in particular, whether any delamination of the film from the washer had occurred, or whether any defect sites were apparent that could have initiated the failure.

WINDOW PRESSURE DEFLECTION

Figure 1 shows the x-z measured deflection profile across the face of a 3.3mm aperture washer, for various applied He pressures at 18K. The solid lines are best fits to a spheroidal cap shape, suitable for a model in which the film has no flextural strength and is in uniform biaxial stress. Such a model has been shown to provide good descriptions of membrane pressure deflections(5). For small elastic deflections, the deflection h at the center of the window is related to the pressure, p, the biaxial elastic modulus M, and the initial strain ε_0, as:

$$p / h \approx \begin{cases} 4Mt\left(\varepsilon_0 + \dfrac{2}{a^2}h^2\right) & h^2 \geq \dfrac{\varepsilon_0}{2}a^2 \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

where a is the aperture radius and t is the membrane thickness. Equation 1 provides a linear plot, the slope determining the modulus, and the intercept determining the initial strain(5). The two range cases in correspond to films which are "taut" (top case) and "baggy" (bottom case). For the "baggy" case with no applied pressure, the deflection can lie anywhere consistent with non-tensile stress in the film. For the LEH windows, neglecting the effect of the aluminum overcoat, typical 18K biaxial moduli from Equation (1) range from about 30GPa to 40GPa.

Window deflections were measured versus pressure for the 24 production windows. Figure 2 shows the cumulative number of center-of-window deflections at 18K for a 3.9mm aperture. The average window deflection at 52 kPa is 260 microns, with a standard deviation of 20 microns. While this is within the acceptable range for LEH window function, it is of interest to understand the cause for the observed variability. Some insight into the deflection variability can be gained by considering the deflection at 7kPa, also shown in Figure 2. The 31 micron standard deviation at 7kPa is considerably higher than the variability at 52 kPa (20 microns), and is also larger than the room temperature standard deviation (14 microns). The greater variation at low temperature is likely due to the thermal mismatch between the aluminum washer, with a CTE of 22 ppm/K, and high strength polyimide, with a CTE less than 10 ppm/K, resulting in greater "bagginess" of the film at low temperatures. With increasing pressure, the deflection asymptotically approaches the elastic deflection component independent of initial strain state, as can be seen in Equation (1).

While Equation 1 was found to be generally descriptive of the window deflection, large deviations from linear behavior occurred at low pressures, where much of the deflection variability originated. Also, for many of the windows, plots using Equation (1) did not yield a straight line even at relatively high applied pressures. The non-linearity was attributed to a biaxial initial strain state, rather than the Equation 1 assumption of an isotropic initial strain. Anisotropic initial strain was sometimes apparent as unidirectional wrinkles in the film at cryogenic temperature. The initial strain was divided into two components, a major axis ε_1 and a minor axis ε_2, where $\varepsilon_1 \geq \varepsilon_2$. Force balance between the window and applied pressure *p* yields

$$p = \frac{1}{2\pi}\int_0^{2\pi} p(\varphi)\,d\varphi$$

(2)

where ϕ is the angular position about the washer axis. $p(\phi)$ is the normalized force per unit angle exerted by the membrane on the washer. Assuming local biaxial stress, the normalized force is given by:

$$p(\varphi) = \begin{cases} 2Mt\left(\frac{\theta}{a} - \frac{1-\varepsilon_0(\varphi)}{R}\right) & \frac{\theta}{a} > \frac{1-\varepsilon_0}{R} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

The deflection profile is still assumed to be spherical, as observed by confocal microscopy. The membrane deflection is characterized by a radius R and an intersection angle with the washer θ, both uniquely related to the window deflection h by geometry(5). To carry out the integration in Equation (2), an ellipsoidal strain distribution was assumed for $\varepsilon_0(\phi)$, and a least-squares fit for the two strain axes was made to the deflection versus pressure data for each window. Representative fits, along with parenthetic values for ε_1 and ε_2, are shown in Figure 3. Negative strain values indicate excess film along an axis, while positive strain indicates tension. Of the 24 windows tested, LEH #16 showed the greatest deflection, LEH #20 showed the least deflection, and LEH #4 represented an intermediate case for which images were available. The inset photographs show LEH #4 at zero applied pressure and at 52 kPa. Visually, the initial shape of the window appears directionally wrinkled, which seems consistent with the existence of initial strain anisotropy, as indicated by the fit parameters for LEH #4. Upon pressurization to 52 kPa, the window appears spherical, as can be seen in the reflection of the microscope illumination ring on the window surface.

Figure 4 shows the best-fit initial strain values for the windows. Generally, the values show uniaxial initial strain averaging about 0.2% (tensile) on one axis and -1% (bagginess) on the second axis. The average elastic strain at 52 kPa is about 1%, which is of similar magnitude as the initial strain anisotropy for some of the windows. Thus, the initial strains are responsible for a large part of the observed deflection variation, particularly the variability attributable to the secondary initial strain axis.

WINDOW BURST

After initial deflection, the windows were pressure cycled from zero to 52 kPa an additional two times. For all windows, the He leak rates were below 1E-8 mbar-L/sec (the limit of our sensitivity) for both the initial and the third deflection. The windows were then pressurized to burst. Burst pressures for the 24 windows varied from 84 kPa to 317 kPa. Figure 5 shows a cumulative count of burst failures versus applied pressure, along with a best fit to a first-order cumulative Weibull distribution(Weibull, 1951)

$$F(p) = 1 - \exp(-p/\beta)^{1/w} \quad (4)$$

where β is the scale parameter and w is the distribution width, where β=205 kPa and w =18%. The strain at failure is typically about 2%, at a stress of about 1GPa. The width of the distribution is typical of ceramic membranes(7), suggesting a weakest-link failure at a defect site. An examination of the windows after burst showed the same failure mechanism for all 24 windows, namely rupture of the aperture. A typical failed window is shown in the inset to Figure 5. The film has remained adhered to the washer (e.g. no peel is observed) and the burst window is completely missing.

For extrapolating failure rates, the first order Weibull distribution is more conservative than a normal distribution(8). Based on the best-fit Weibull parameters, the extrapolated failure rate at 52 kPa is less than 0.1%. This appears to be a valid estimation of the expected failure rate for future production lots, as long as future windows are made with the same production process as the three lots tested here.

Conclusions

LEH window deflection variability and burst pressure fall within ranges that are acceptable for NIF LEH window requirements. For the process characterized by this study, the expected window failure rate for the NIF use conditions is less than 0.1%. The mean window deflection for a 3.9mm aperture is 260 microns, with a standard deviation of 20 microns. The primary source of deflection variability appears to be the initial strain state of the LEH window at 18K, which has a uniaxial component. The variability in burst pressure is typical of ceramic membranes, with an average burst pressure of about 205 kPa.

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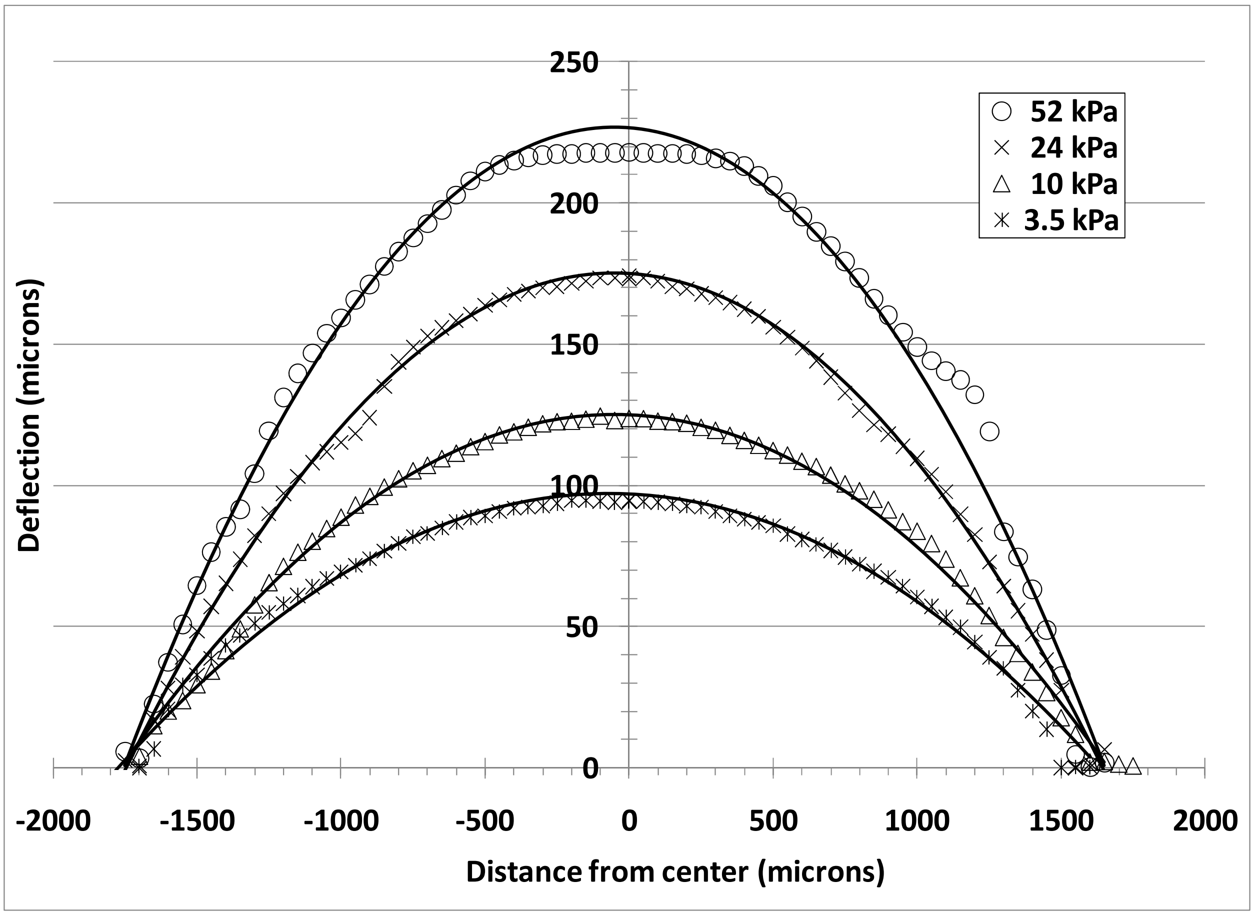

Figure 1: Deflection vs. distance from window center for a window aperture of 3.2mm. Solid lines are best fits to a spheroidal cap model.

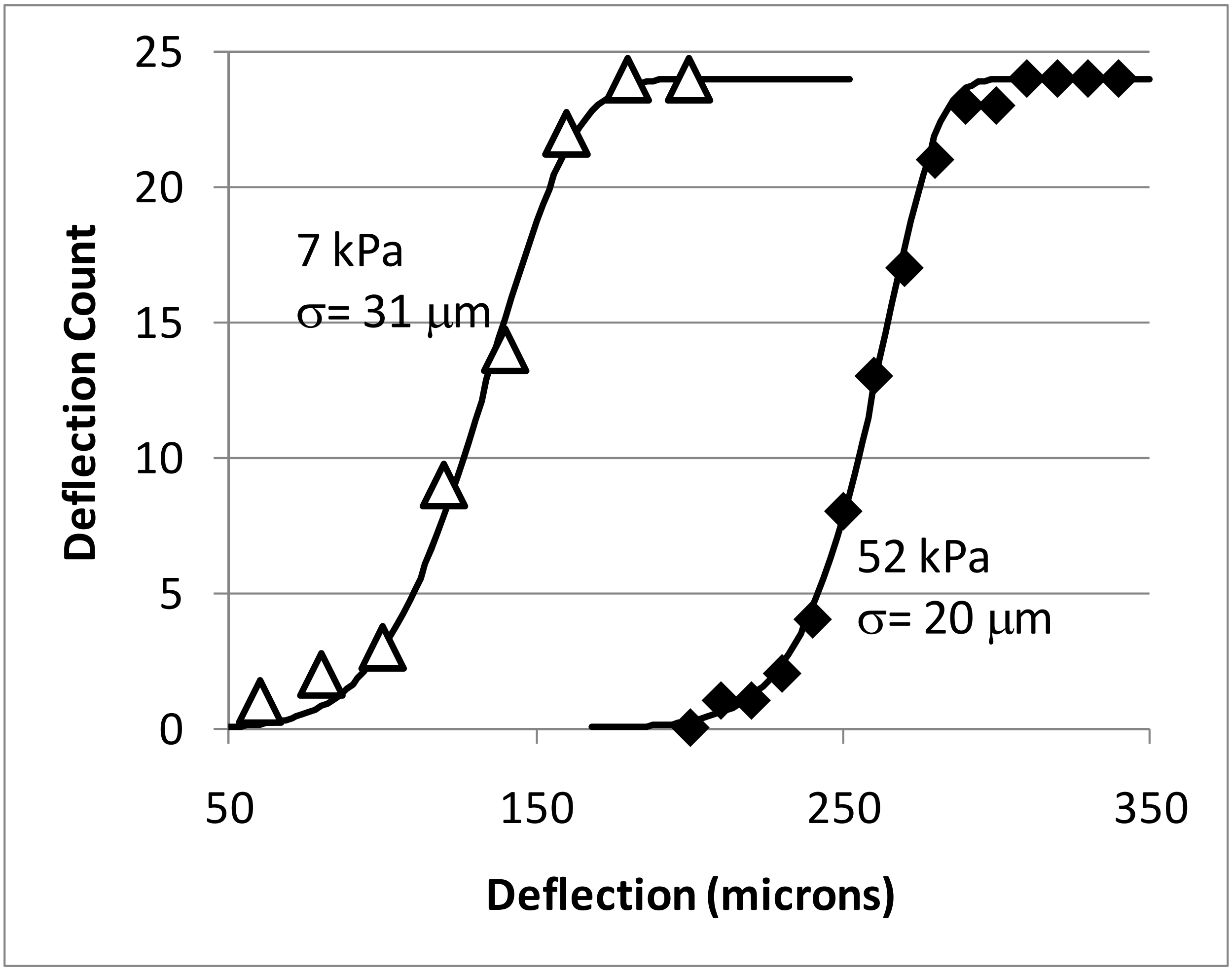

Figure 2: Cumulative deflection count for applied pressures of 7 kPa and 52 kPa. Median deflections are 140 microns at 7 kPa, and 260microns at 52 kPa.

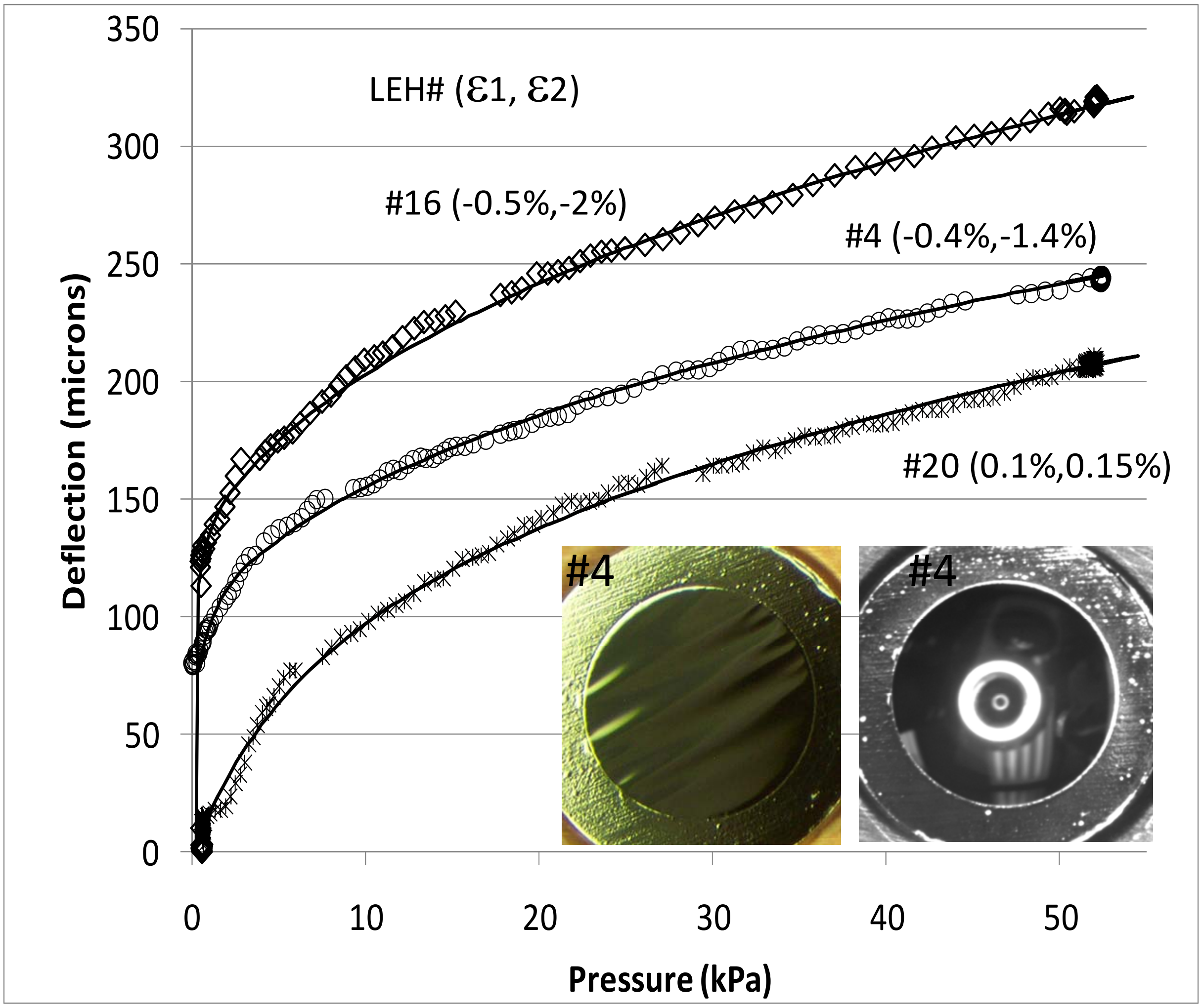

Figure 3: Deflection vs. pressure for various LEH windows at 18K. Solid lines are least-squares fits assuming various primary and secondary strain values (e1, e2). Labels show LEH window serial number and initial strain values. Photo inset: LEH#4 at 0 kPa and at 7.5kPa.

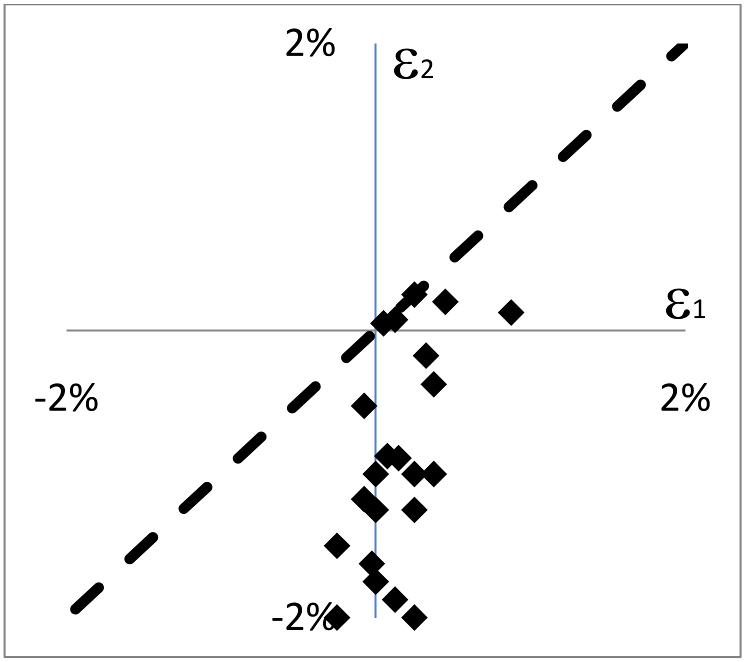

Figure 4: Secondary initial strain vs primary initial strain for population of 24 LEH windows.

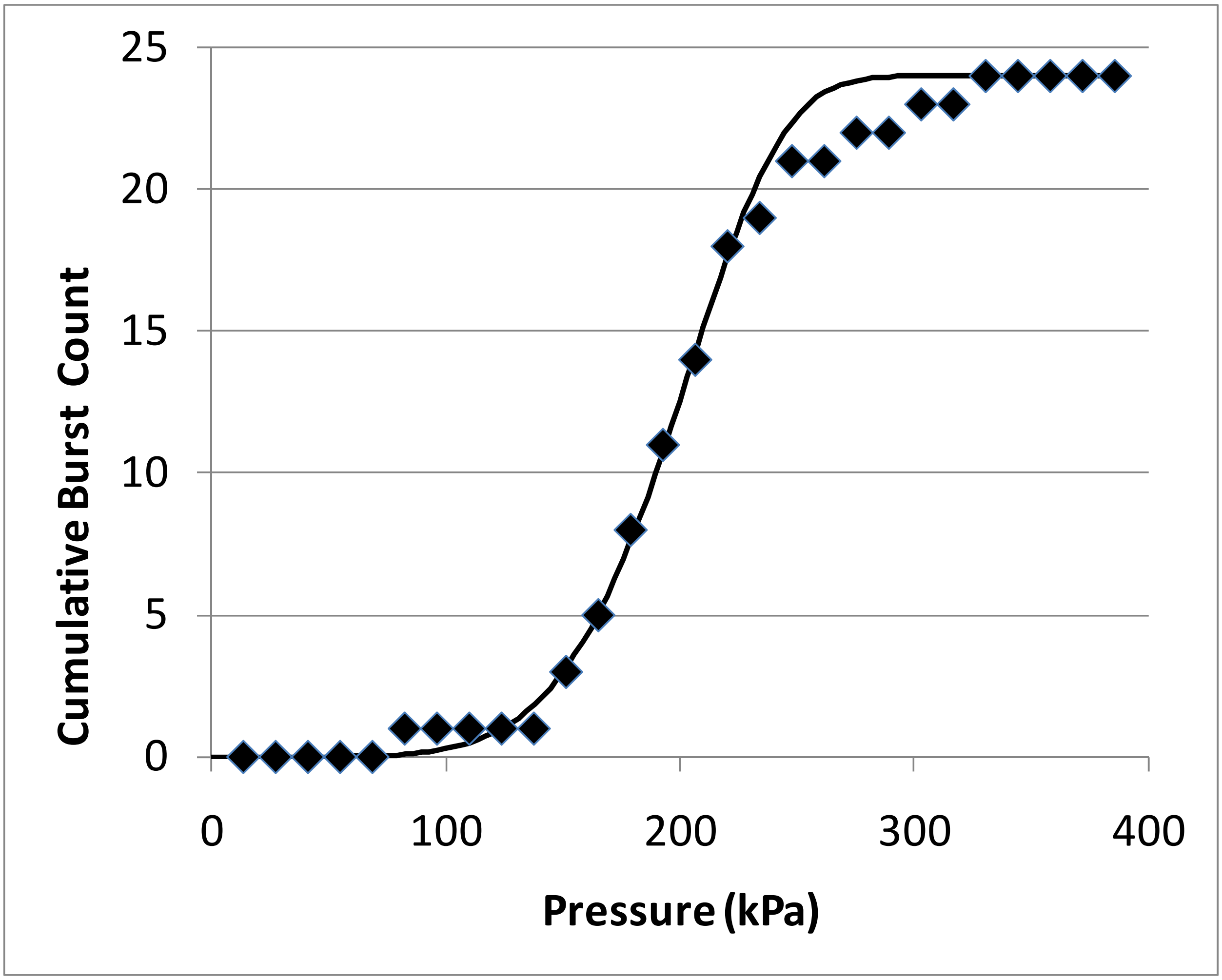

Figure 5: Cumulative burst count vs. applied pressure at 18K. Solid line is a first order Weibull distribution with a scale parameter β=205 kPa and a distribution width *w*=18%. Inset shows a typical burst window, with film adhered to the washer and window completely missing.