ANALYSIS OF A SCREW RETAINING RING CLOSURE MECHANISM FOR A TYPE B(U)F TRANSPORT PACKAGE

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ABSTRACT

A large cavity SAFKEG® has been developed by Croft Associates Ltd for the shipment of solid radioactive materials. Engineering challenges in ensuring O-ring compression, and hence leak tightness, of a screw retaining ring have been overcome as part of the design's substantiation.

Several statistical models have been developed as part of the effort to analyse the variation of the applied force developed by the screw retaining ring upon the O-ring seals and their compression. Parameters such as friction, geometry and O-ring property variations were assessed and consequently, the implications these factors have on the probability of achieving the desired O-ring seal compression were derived.

Each factor has been modelled as a triangular distribution with 100,000 datapoints with the minimum, maximum and most likely values being devised using manufacturers tolerances and a nomogram for the O-ring properties. The "Monte Carlo" simulation calculated a 98.55% probability that metal-to-metal contact would be achieved.

Newcastle University provided an independent review of the analysis, validating the results and providing further refinements. This included the use of truncated normal distributions, Bayesian analysis of the torque values and a more in-depth study of the effect of friction. This work was completed using Python software and confirmed metal-to-metal contact with a 99.27% probability.

Further improvements to the model are currently being carried out. Additional physical testing has been commissioned to acquire accurate, experimentally derived, friction values that can be inputted into the statistical model.

INTRODUCTION

The 4087A package has been developed as a new variant in the Croft SAFKEG® range, to meet a client's specification for a large cavity Type B(U) transport package for fissile contents. The design is typical of the existing Croft SAFKEG® range; however, several new features, notably a screw retaining ring, have been incorporated into the containment vessel (design no. 4086) to provide enhanced performance under Normal and Accident Conditions of Transport (NCT & ACT).

The 4086 Containment Vessel (CV) consists of a stainless-steel body and lid, where the lid is secured by a Nitronic-60 retaining ring. A set of double O-rings are fitted to the top flange in the 4086 CV body, together with an interspace test point within the lid to provide a verifiable leak tight closure system via a Croft Associates CALT leakage tester. See Figure 1 for a depiction of the 4086 CV.

The screw ring closure mechanism is key to the 4086 CV's structural and containment performance. This paper discusses how challenges have been resolved during the 4086 CV's development, using a combination of physical testing and statistical analysis.

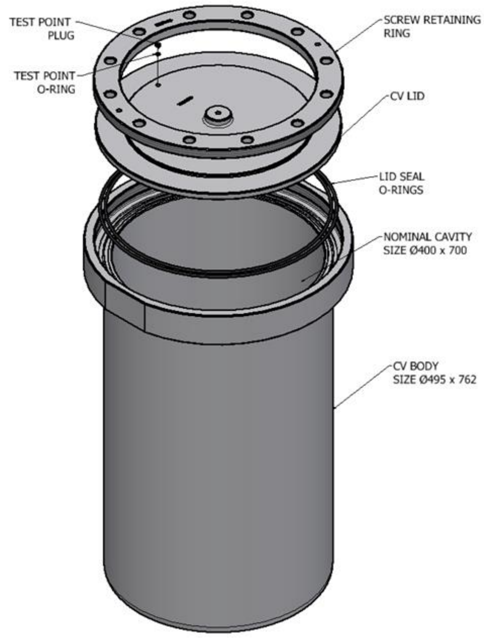

Figure 1. Design No. 4086 Containment Vessel

INITIAL MODELLING OF O-RING SEAL COMPRESSION

Several parameters such as friction, geometry and O-ring property variations were assessed. Consequently, the implications these factors have on the probability of achieving the desired O-ring seal compression has been modelled.

The aim of this analysis is to determine if the calculated required torque of 3,510 Nm is suitable in achieving metal-to-metal contact, ensuring leak tightness of the containment system. The probability of achieving leak tightness must be substantially high whilst ensuring the threads of the screw retaining ring do not fail due to excessive forces. The required torque of 3,510Nm has been calculated using British standards and assuming a friction factor of 0.2 [1] for steel-on-steel contact.

Triangular Distribution Methodology

Triangular distribution has been employed to analyse friction, geometry, O-ring property variations and the subsequent effect on achieving the applied load for achieving leak tightness of the 4086 CV. The triangular distribution is a continuous probability distribution that is particularly suitable for modelling uncertain quantities when limited sample data is available. It is defined by three values: the minimum, maximum, and most likely outcome, forming a shape that resembles a triangle.

The triangular distribution, for each of the assessed parameter's dataset, was generated using the following methodology in Excel:

i. The minimum (a), the maximum (b) and most likely (c) value which could occur within the dataset was obtained. This was determined using manufacturers data and tolerances.
ii. A Cumulative Distribution Function (CDF) was created, which is essentially a random number between 0 and 1. The accuracy of the model is dependent on how large the CDF is, which for this case 100,000 values were generated. This was an application of a "Monte Carlo" simulation to predict the probability of a variety of outcomes for random variables.
iii. Figure 2. Therefore, an "IF" statement was created in excel, giving a value of 1 if above, and 0 if below.

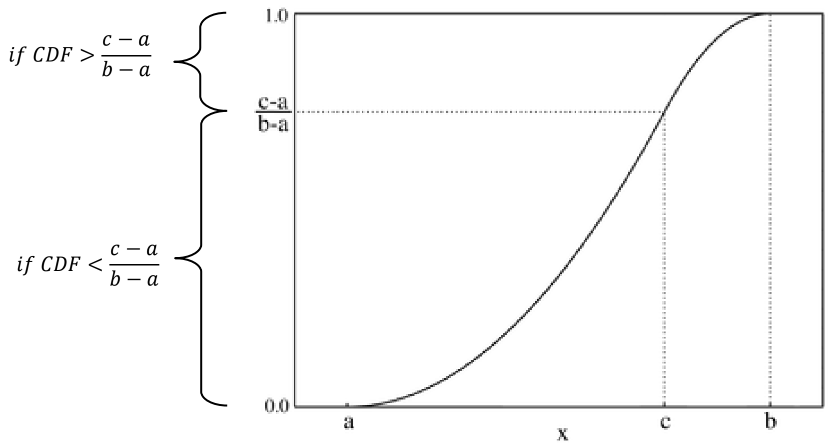

Figure 2. CDF for Triangular Distribution

$$CDF = \begin{cases} 0 & \text{for } x \le a, \\ \frac{(x-a)^2}{(b-a)(c-a)} & \text{for } a < x \le c, \\ 1 - \frac{(b-x)^2}{(b-a)(b-c)} & \text{for } c < x < b, \\ 1 & \text{for } b \le x. \end{cases} \quad (1)$$

iv. Figure 2 and Equation 1, for $a < x \le c$ or $c < x < b$ (depending on if the CDF is above or below $(c-a)/(b-a)$, the function of x was calculated.
v. Using the histogram function on excel, a pre-set number of ranges were determined. The count within these ranges were then graphed to display the resulting triangular distribution.

Calculated Applied Force

Each variable that affects the applied force on the screw retaining ring has a degree of uncertainty and a range of potential values. Variables include the variation of the 4086 CV's diameter, errors in the application of force through the torque wrench, torque multiplier, and friction.

For each of these factors, the minimum, maximum and most likely value were determined. Triangular distributions were then plotted using 100,000 randomly generated values as detailed in the methodology section.

Subsequently, the applied force was calculated and plotted using the entire data-spread (100,000 simulations) using equation 1 [2], see Figure 3 for the resulting applied force.

$$T = \mu \times P_o \times D \tag{2}$$

Where:

T= Torque (Nm), μ= Friction Factor, Po= Applied Force (N), D= Diameter (mm)

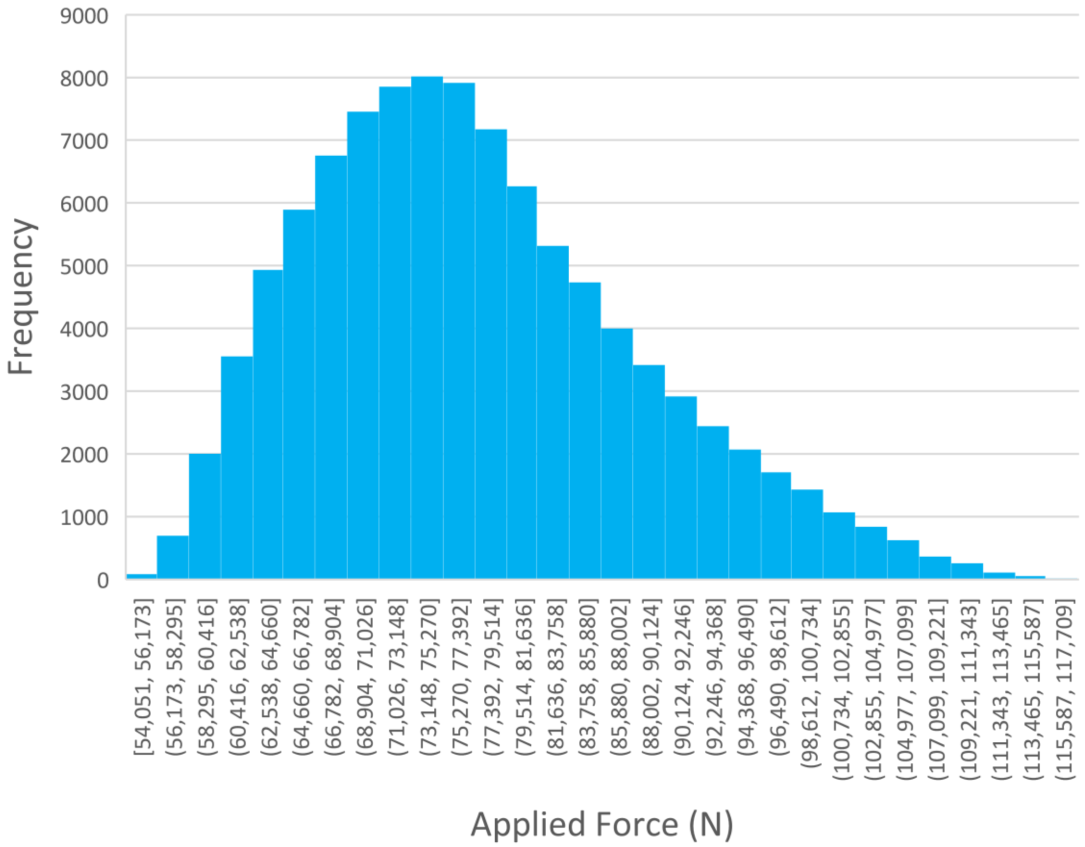

Figure 3. Distribution of the Calculated Applied Force

Required Force

The required force to compress the O-rings and achieve metal-to-metal contact was calculated with the use of a historical nomogram that was experimentally derived [3]. Extrapolating the nomogram provides the O-ring load (N/mm) required to compress the seals, when multiplied by the overall O-ring length (sum of inner and outer O-ring length), the force required to compress the O-ring to an associated percentage required for deflection can be determined.

The nomogram incorporates multiple variables including O-ring hardness, cross sectional diameter and O-ring deflection which have been assessed to determine the minimum, maximum and most likely values for the overall O-ring load.

The O-ring compressibility and length are then plotted into triangular distributions and multiplied together to plot the required force, see Figure 4.

__Results__

By comparing the data spread of achieved and required applied force, it was determined that 98,547 out of the 100,000 (98.55%) datapoints would result in the required force to achieve O-ring compressibility for metal-to-metal contact being satisfied or surpassed, demonstrating leak tightness of the 4086 CV.

The maximum achieved force across the dataset was up to 129,921 N. When comparing this value to the shear stresses in the 4086 CV, the safety factors for external male and female thread shear stress was 26.0 and 18.6 respectively. Therefore, in a '*worst case scenario*' according to the statistical analysis, it is assumed that the 4086 CV's threads will not yield.

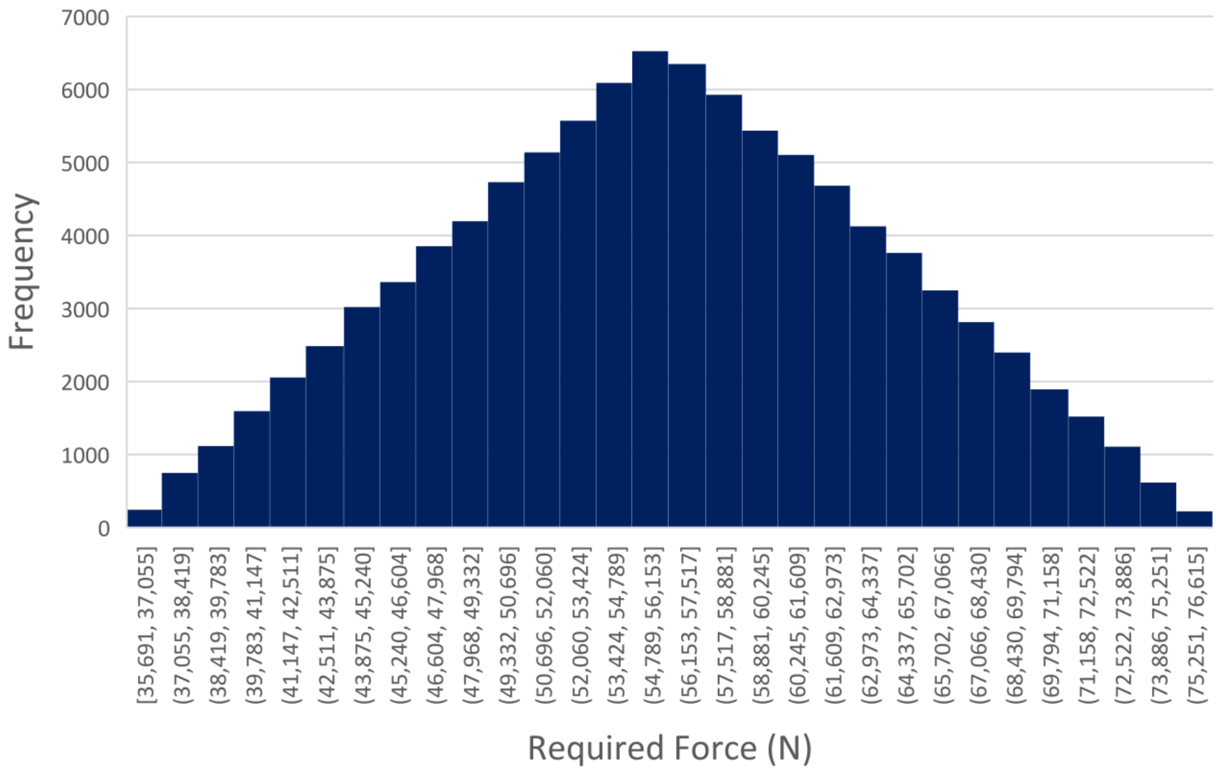

Figure 4. Distribution of the Calculated Required Force

NEWCASTLE UNIVERSITY MODEL

Newcastle University's School of Computing were instructed to create an additional analysis [4]. The aims of this analysis were to provide an independent review of Croft's model, before exploring whether a more appropriate model of the errors can be constructed. When recreating Croft's model, Python was selected as an alternative program to Excel. Figure 5 depicts the recreation of the nomogram [3] using Python.

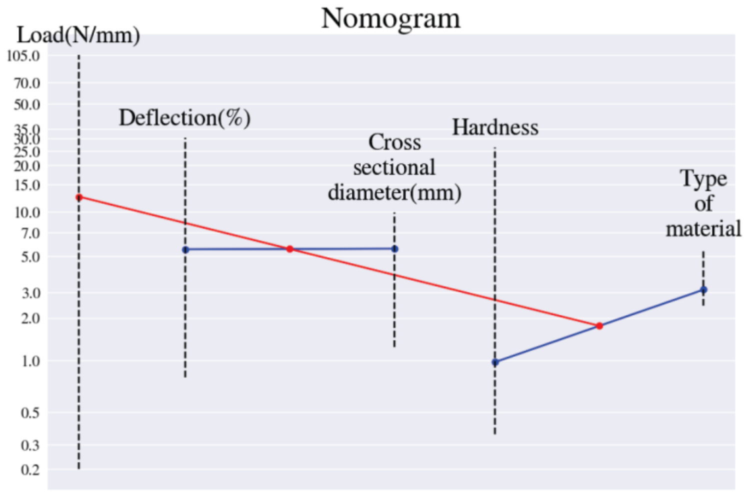

Figure 5. Nomogram Generated by Python

Improvement of the Original Model

The triangular distributions were replaced with truncated normal distributions, aiming to achieve a more accurate representation of the many small and independent sources of variation that occur during manufacture. According to the central limit theorem, the sum of these small independent errors often tends to be in a normal distribution. Furthermore, tolerance checks for parts ensure that parameters have specific minimum and maximum allowable values, therefore they are truncated. Figure 6 depicts the amended truncated normal distribution for torque.

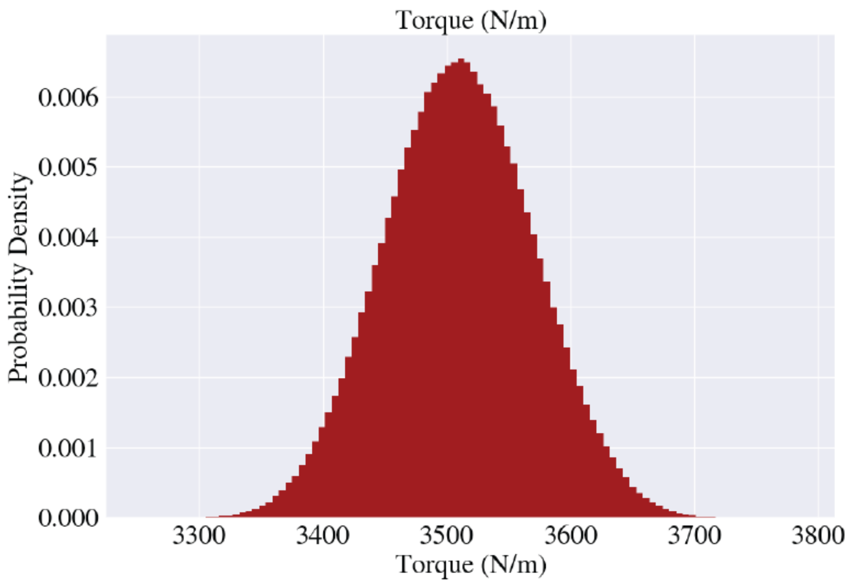

Figure 6 . Truncated Normal Distribution for Torque

A Bayesian analysis approach was introduced to handle the torque variability. Specific calibration data for the torque wrench was utilised to generate random torque sample data. These were combined with random samples from the torque multiplier, conforming to the truncated normal distribution. The analysis was formulated using a specific model to capture the relationship between the measured torque and the torque setting on the torque wrench, considering the multiplicative nature of the error. In this context, the error increases as the torque setting increases.

To explore the impact of the friction coefficient on the applied force a study was conducted on dry film lubricants from various brands. As part of this, a new torque formula was implemented [2]:

$$T = P_0 \left[0.159 \cdot p + 0.577 \cdot \mu_0 \cdot \ d + \frac{D_f}{2} \cdot \mu_0 \right] \tag{3}$$

where T is the torque (Nm), P_0 is Applied Load (N), μ_0 is the coefficient of friction, p is the thread pitch of the bolt (m), d is the pitch diameter of the bolt (m) and D_f is the nut friction diameter (m).

An analysis was conducted to understand the relationship between torque, diameter, and the sealing probability when using the selected lubricant for use on the 4086 CV, see Figure 7 for the results.

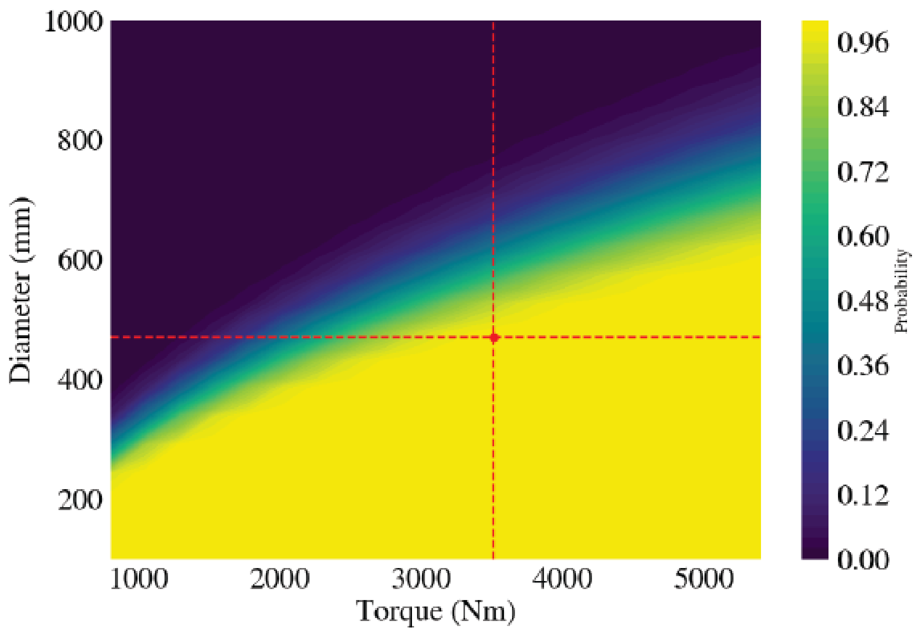

Figure 7. Surface Plot for Selected Lubricant

RESULTS

The initial triangular distribution models found that an applied torque of 3,510 Nm results in a 98.55% probability of the 4086 CV achieving metal-to-metal contact and hence, leak tightness. Newcastle University utilised additional methods to refine the model and calculated the sealing probability to be 99.27% [4]. This validated the original model and the high probability of the 4086 CV achieving leak tightness.

In addition to this statistical model, physical trials have shown that much lower values of applied torque can still provide sufficient leak tightness and metal-to-metal contact is not required. Furthermore, pre-shipment checks such as a leak test provide further assurance that the 4086 CV will be leak tight when in operation.

FUTURE ANALYSIS

Several assumptions were made in the statistical models that can be improved upon.

When using the truncated normal distribution to model the error, the confidence level for the of parameters was set at 99% due to the absence of industry standards for such values. Manufacture of large volumes of the 4087A SAFKEG® will provide the opportunity to prescribe a confidence level based on new primary data.

The friction coefficient of the lubricant was simulated based on values provided by the lubricant's manufacturer. These values may vary to those found within the 4086 CV because they have been derived assuming a different set of materials and dimensions.

A friction study has been commissioned to ISO 16047 [5]. The aim is to obtain experimental results based on the geometry and material combinations of the 4086 CV, integrating them to the current statistical model.

CONCLUSION

The results of the statistical analysis and validation provide evidence of a 98-99% likelihood that the O-rings of the 4086 CV will be fully compressed to provide metal-to-metal contact and therefore leak tight. Furthermore, physical testing and preshipment tests provide additional confidence on leak tightness of the 4086 CV.

Several improvements are being made to the model to obtain more primary data; this includes friction tests to ISO 16047 [5].

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