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DESIGN AND ANALYSIS OF A LARGE CAVITY TYPE B(U)F SAFKEG®

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ABSTRACT

Croft Associates Ltd has recently completed the design and development of a new, large cavity (Ø400 mm x 700mm), Type B(U)F transport package. The design is typical of proven transport containers; however, several novel features are incorporated to provide enhanced performance under Normal and Accident Conditions of Transport (NCT & ACT). In particular, a large screw ring closure mechanism has been developed to provide the structural and containment performance of the Containment Vessel (CV) closure.

This paper focuses on the design, development, and substantiation of the new SAFKEG® design, with particular emphasis on the novel features utilised to enhance the package performance. The paper describes the design development from the initial preliminary design through to post-test reference design, regulatory impact testing and underpinning Finite Element Analyses (FEA).

The screw ring closure mechanism is key to the CV structural and containment performance. This paper discusses the benefits of this type of closure design along with the challenges faced during design development, not least with respect to preload, consistency of torque application and determination of the acceptable torque range for O-ring seal compression within the CV closure system.

As part of the new package performance substantiation, in-depth analyses of the impact performance were undertaken. A verification strategy was derived utilising a benchmarking/decision matrix approach, this considered experience gained upon the successful licensing of previous SAFKEG® designs.

The verification strategy prescribed a combination of physical testing and FEA to validate the impact performance of the package. High speed photography and Faro Arm metrology measurements were used to analyse the resulting deformations from the impact tests.

Once benchmarked, the detailed FEA model accurately demonstrated the performance of the package under impact conditions. Furthermore, the model was used to examine package behaviour under conditions not feasible to undertake within the physical test program, including further sensitivity studies, e.g., upon increased drop height to explore whether “cliff edges” existed in the impact performance verification.

This paper presents a summary of the packages’ design development, regulatory testing, and performance validation with an emphasis on modelling, test strategy, analysis, and evaluation.

INTRODUCTION

The design is a new variant of the Croft SAFKEG® range, introduced to meet a customer requirement for a new larger Type B(U)F package to transport fissile contents.

This new SAFKEG® design is based upon an optimised approach which utilises the existing Croft SAFKEG® range of Type B transport packages as the principal source of reference. Noting the similarity of contents and the present licensing status, the SAFKEG® 2816 was utilised as the most applicable basis for the new package design, with the package design further incorporating some of the proven features developed upon the SAFKEG® 4085, 3977 HS and 3979 LS packages.

The design has been subjected to a full series of regulatory impact tests and thermal analyses, as defined within the 2018 IAEA SSR-6 [1] regulations for both Normal and Accident Conditions of Transport (NCT & ACT) respectively. The deformation and distortions resulting from these tests subsequently formed the basis of the validation of FEA impact and thermal assessment for the ACT conditions discussed within this report.

The resealable CV is fitted with a separate closure lid, fastened, and secured by a large screw retaining ring that requires a bespoke torque tool to operate, this type of design closure cannot be opened unintentionally. Further development and analysis has been untaken upon this novel feature, including a statistical model. The model utilised triangular probability distributions to analyse the potential variance in applied seal compression force, that could arise from variations due to tolerance in system parameters.

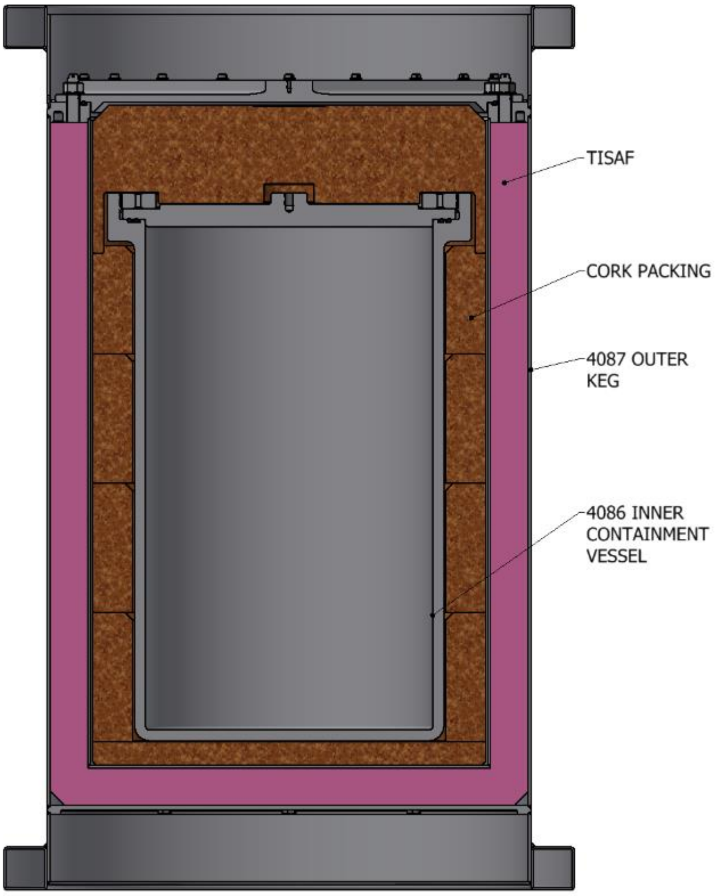

Figure 1. Cross Section View of SAFKEG®

DESIGN DEVELOPMENT

To optimise the cost, schedule, and minimise the risk of the project, the design development process utilised proven features from existing licenced Croft SAFKEG® packages. The package design utilised the proven concept of an outer stainless steel welded keg, providing impact and thermal protection under ACT of the inner CV. The keg incorporates TISAF (Thermal insulating shock absorbing foam) which is manufactured by Croft using a proprietary process and formulation. TISAF has been used extensively within Croft Type B packaging designs for over 40 years and has been subject to extensive testing and evaluation, including physical impact and pool fire testing within Type B transport packages. Typically, within Croft SAFKEG® designs, further thermal and impact protection is provided by a cork packing set surrounding the CV.

This form of keg structure and construction has been proven to provide a corrosion resistant, deformable structure with progressive and predictable impact performance.

To commence the preliminary design phase, an optioneering review was undertaken upon the proposed package features. The design features evaluated included:

- Overall package shape and form
- Outer keg fabrication
- Outer keg material
- Keg lid closure
- CV body design and fabrication
- CV Material
- CV Closure
- CV seal design
- CV seal material
- CV lifting and handling
- Features for impact and accident performance
- Package tie down

At this preliminary design stage, scoping calculations were completed to provide initial validation and verification of the preliminary package design, to substantiate the performance against the functional specification requirements.

Upon acceptance of the preliminary design, the project was progressed to a detailed design development stage. In this phase of design, initial scoping FEA was undertaken upon the impact performance of the package in line with IAEA SSR-6 regulations [1]. The intent of the scoping analysis was to identify areas of potential weakness within the impact performance of the package. This informed modifications to the design to optimise areas of concern. For example, the optimisation of the stiffening ribs on the keg lid to minimise deflection, and hence provide further confidence in the impact performance ahead of the physical prototype testing (Figure 2).

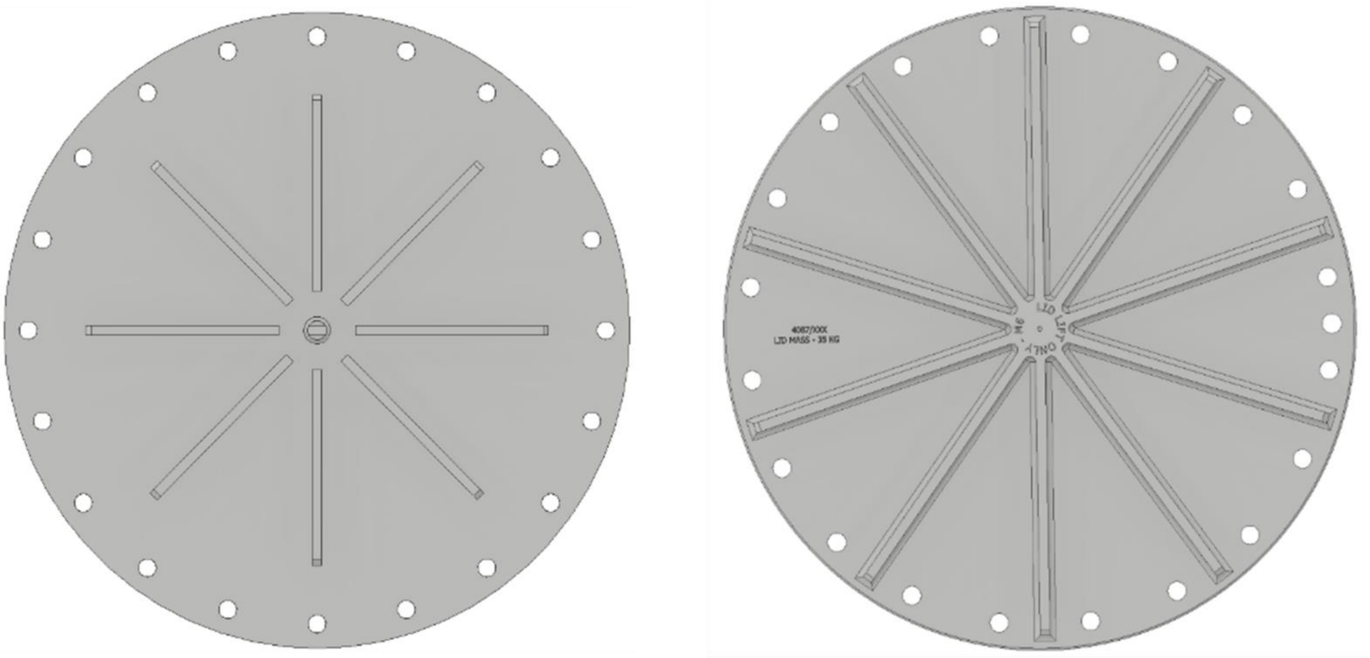

Figure 2. Stiffening Ribs on Keg Lid (LHS before and RHS after FEA Optimisation)

A key feature of the design which required significant development was the novel screw ring closure mechanism for the CV. This vital component provides a key safety function, which ultimately prevents the loss or dispersal of the radioactive contents into the environment. The safety of the package design is therefore clearly dependent upon achieving the required sealing performance of the CV. The screw-ring closure mechanism was selected over a more traditional bolting arrangement due its superior performance in an impact scenario, as demonstrated upon other Croft SAFKEG® products.

This screw-ring closure mechanism ensures that O-ring seals remain compressed during accident conditions of transport (ACT), with minimal transient seal gaps. However, due to the novel nature of the screw-ring of this size, significantly larger than other packages within the SAFKEG® range, Croft opted to undertake further development and analysis to provide confidence in the design. This is discussed in detail further in the paper.

FEA ANALYSIS

SAFKEG® Physical Drop Test Performance

This new SAFKEG® design has successfully completed a cumulative series of NCT and ACT impact tests. The test series strategy was derived utilising a benchmarking/decision matrix approach, using evidence and professional experience from previous drop tests on existing SAFKEG® designs.

Two prototype SAFKEG®s were used, one was orientated to impact upon the lid edge and the other on the side impact zone for maximum deformation and knockback respectively. Extensive metrology points were identified and marked upon each of the keg body, keg rims, lid, lid studs and base to allow measurement of point displacements using a Faro Arm, which were fed back into the regulatory FEA to accurately model impact damage [2].

SAFKEG® Thermal and Impact FEA Performance

The impact FEA assessment was used throughout the design development to assess the impact performance against the prescribed damage criteria.

The regulatory impact assessment [3] aligned very closely with the test evidence from the physical impact test program. The physical testing was used to benchmark the FEA model and the model then used to perform a full series of regulatory impact scenarios, including several beyond design basis impacts to demonstrate the absence of cliff edge effects. The largest transient CV lid gap opening of the closure reported in the impact FEA analysis was 0.055mm, with no residual gap remaining post impact. This is comfortably within the design intent and considered to be an enhancement over perceived performance, when compared to an equivalent bolted closure.

The impact analysis additionally assessed several alternative drop test orientations in a sensitivity study, these were certain orientations that would prove difficult to control and complete in physical tests but would provide bounding deformations for the thermal FEA assessments (Figure 3).

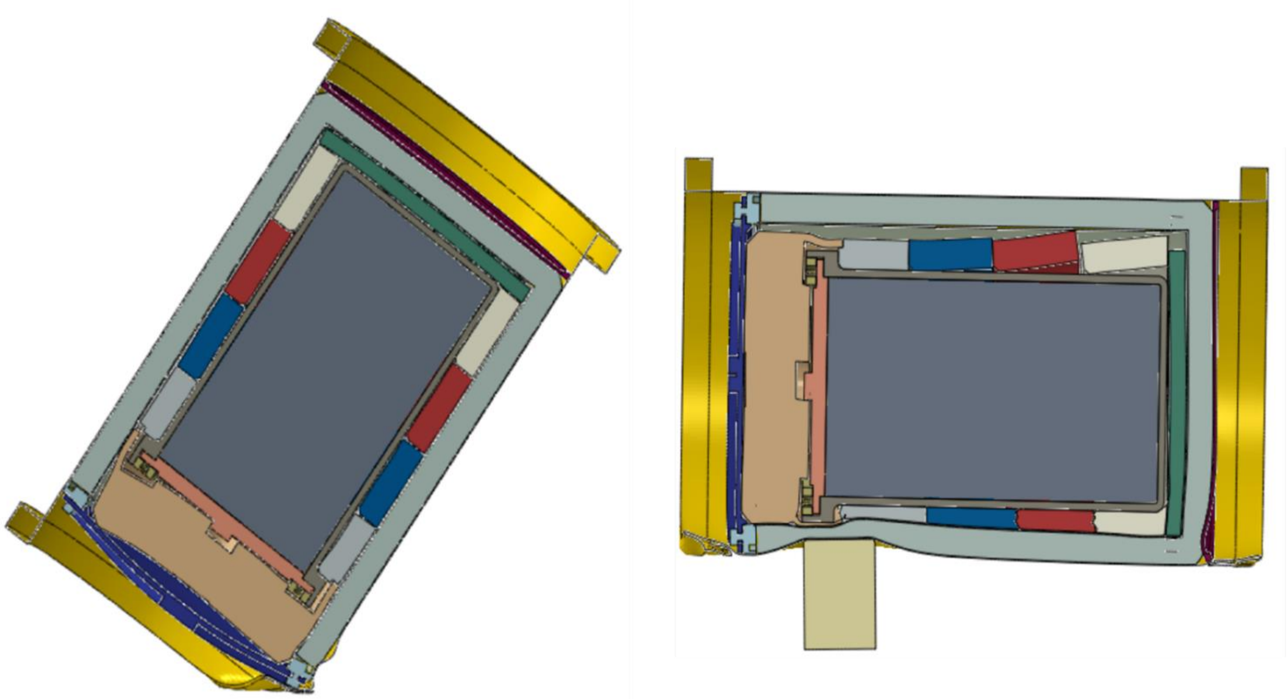

Figure 3. SAFKEG® FEA Impact Analysis (LHS Lid Edge 9m Drop and RHS Punch Test)

A series of NCT and ACT thermal FEA assessments [4] were undertaken in accordance with SSG-26:2018 guidance [5]. The thermal assessments used initially undamaged (NCT) and then damaged (ACT) models resulting from the physical drop tests with worst case pessimistic assumptions in terms of initial conditions, material properties and applied heat loads (Figure 4). All results were shown to be within the SSR-6 2018 regulation [1] requirements for Type B(U)F transport packages, as described within the Design Safety Report (DSR).

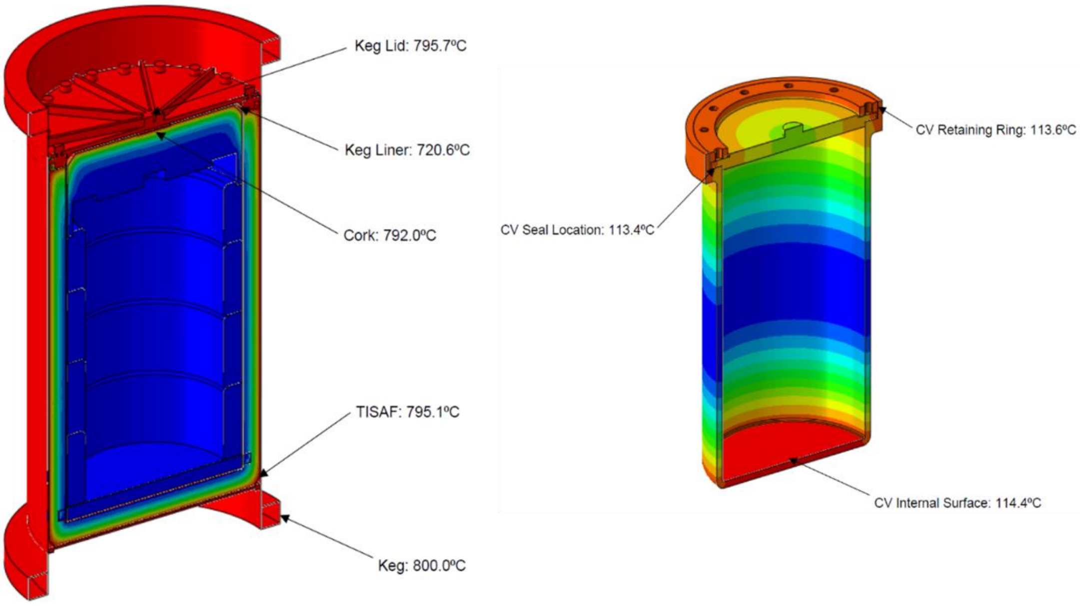

Figure 4. SAFKEG® FEA Thermal Analysis

SAFKEG® Benchmarking

Comparing the deformed benchmark FEA model geometry with photographs of the damaged impact test specimen (Figure 5), shows that the FEA model accurately reflects the nature and distribution of the damage seen in the physical impact tests, as reported in [3].

Figure 5. SAFKEG® FEA Benchmarking

CV SCREW RING CLOSURE DEVELOPMENT AND ANALYSIS

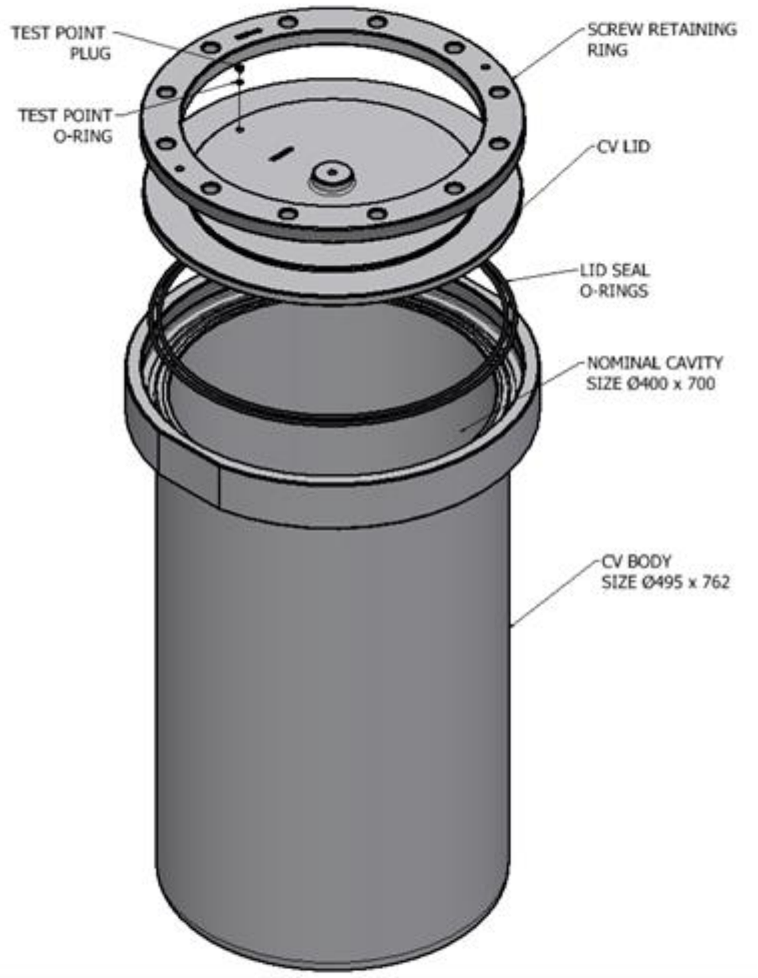

Figure 6. CV Components

As discussed earlier in this paper, although screw ring closure mechanisms have been used previously upon the SAFKEG® range, this developed design was considered novel due to its diameter and required torque input, both values being significantly larger than other designs within the SAFKEG® range. This required development of torque input tooling, and detailed consideration of the accuracy and repeatability of torque application, to ensure the design intent of metal-to-metal seal face contact for optimum containment performance.

The CV (Figure 6) consists of an anti-galling Nitronic 60 screw retaining ring, which is used to secure the stainless-steel lid onto the body and compress the seals to provide a leak tight containment boundary. A set of double O-rings are fitted to the top flange in the CV body, with an interspace test point located on the lid to provide a verifiable leak-tight closure. This is verified by a pressure drop test using a Croft Associates Leakage Tester (CALT).

A closure torque of 3,500 Nm was calculated as the required input to achieve the desired O-ring seal compression. This torque value was derived using hand calculations and a series of physical trials. This resulted in a closure system that satisfied the design intent of metal-to-metal contact between the CV lid and body at the seal interface, ensuring full seal compression. An in- depth design study was completed to analyse the feasibility, repeatability, and accuracy of the system, as described below.

Feasibility

Various challenges were presented during the design of the closure mechanism. In particular, the consideration of how to apply the magnitude of closure torque required (3,500 Nm) in a practical, safe and ergonomic manner. A bespoke CV closure tooling system and method was developed (Figure 7), using a torque frame along with a 27:1 torque multiplier which reduced operator input torque to circa 130 Nm, and was confirmed compliant with typical manual handling limits.

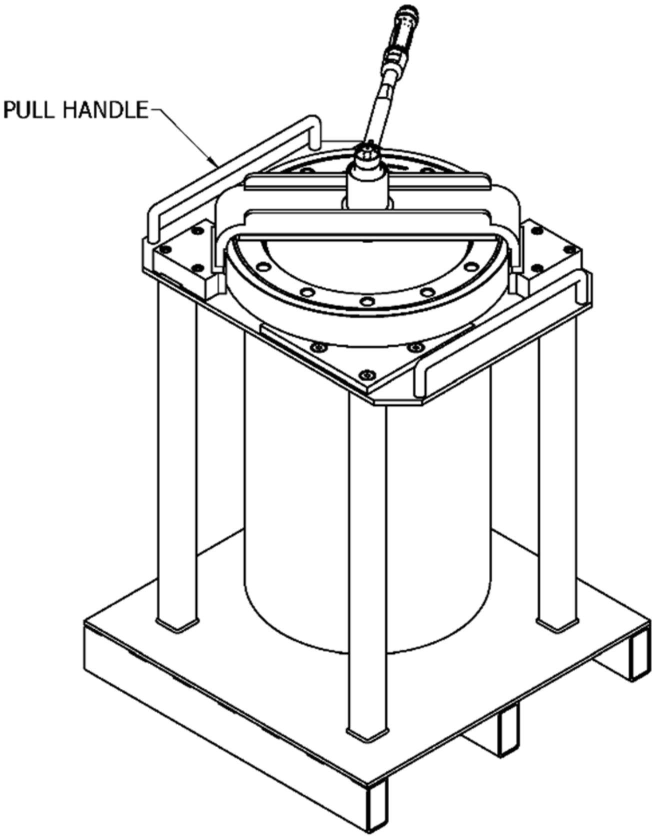

Figure 7. CV Torque Tightening Tooling

Repeatability

A statistical analysis was undertaken upon the closure system to better understand how the variables of the system affect the accuracy and repeatability of the compressive load applied to the seals, and subsequently determine the relationship between input torque and seal compression.

The aim of this analysis was to understand that if the required input torque of 130 Nm is applied to the torque multiplier, what is the probability that the applied load acting on the O-ring seals is both repeatable and achieves the design intent of full seal compression, i.e., metal-to-metal contact, thereby ensuring leak tightness of the containment system.

The statistical methodology is based upon the torque formula from BS 4518-1982 [6], namely:

$$\mathrm{T} = \mu \times \mathrm{P_o} \times \mathrm{D}$$

Where:

T = Torque (Nm)

$\mu =$ Friction Factor

$P_o =$ Applied Load (N)

$D =$ Diameter (mm)

The model inputs were determined by the following parameters:

- Variation in friction factor from application of dry molybdenum to the screw retaining ring threads.
- Dimensional tolerances in screw ring basic major thread diameter.
- Errors in torque wrench and multiplier when tightening the CV screw retaining ring based upon the published accuracy of the equipment.
- Resulting applied compressive force acting on the O-ring seals.

A cumulative distribution function formula was used to generate a dataset of 100,000 randomly generated scenarios using the input parameters, effectively running a Monte Carlo style simulation. This provided a distribution of resulting applied loads.

Accuracy

A second analysis was then run using the variables within the O-ring nomogram [7] used to determine the variance in load per linear length (N/mm) required to compress seals, based on the following parameters:

$H =$ tolerance on seal hardness

$d =$ tolerance on the cross-sectional diameter of seals

$\Delta =$ variation of % deflection calculated from design tolerances on the machined O-ring grooves

Again, a cumulative distribution function was used to generate 100,000 scenarios using the tolerances on the input parameters. This resulted in a triangular probability distribution of load required to achieve the desired seal compression (Figure 8), depending on the variation in the O-ring hardness, cross sectional diameter and deflection.

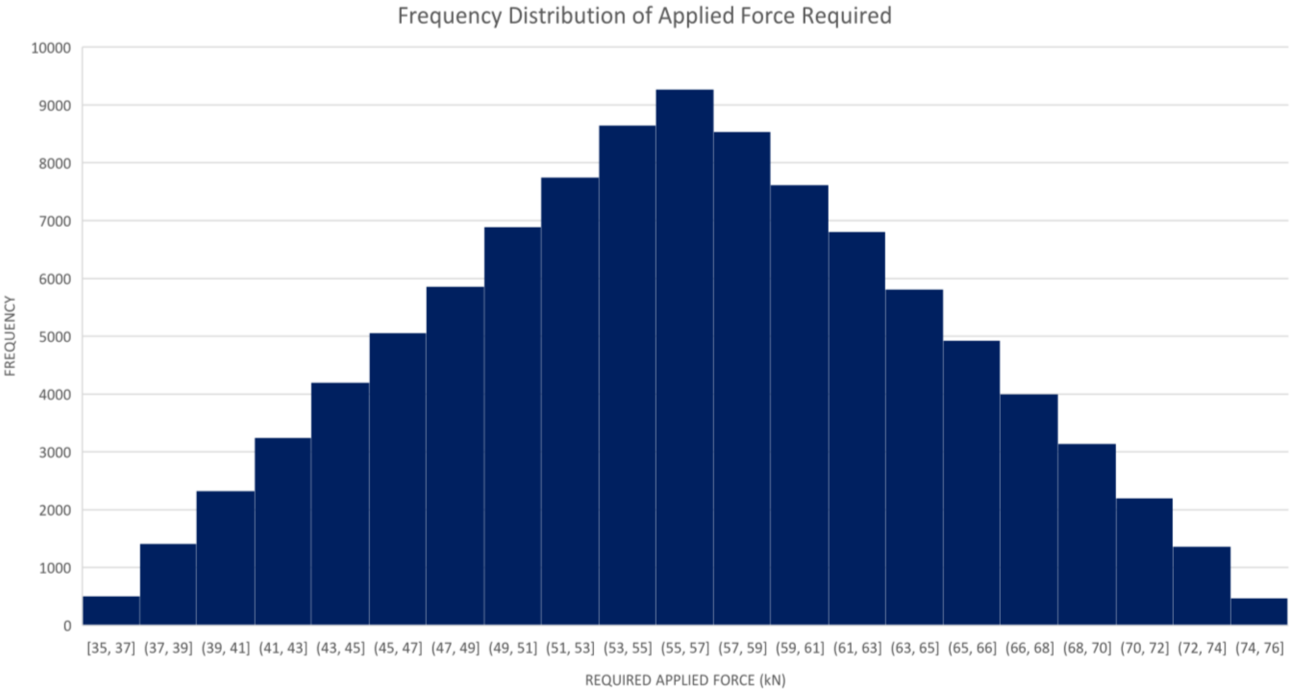

Figure 8. Distribution of Required Applied Load

A comparison between the calculated applied force dataset and required applied force dataset was used to calculate the probability that metal-to-metal contact was achieved. The result was that in 98.5% of the 100,000 randomly generated scenarios, full compression of the seals was achieved, thus providing confidence in the accuracy and reproducibility of the system.

To provide further insurance that full seal compression is achieved in practice, physical match marks were added to the CV body and screw retaining ring to indicate when metal-to-metal contact has been achieved. This fail-safe feature eliminated the possibility of the CV being transported without sufficient O-ring compression. The intent being that this marking alignment will be checked prior to each shipment and subsequently followed by a pre-shipment leakage test using a CALT (Croft Associates Leakage Tester).

CONCLUSIONS

Croft Associates has over 40 years' experience within the design and substantiation of radioactive transport packages. This paper has outlined the processes adopted by Croft Associates when developing a new Type B(U)F packaging, in this case utilising an optimised process based upon the existing SAFKEG® range. Focus has been placed on the development and substantiation of the novel screw-ring design, including the challenges faced with the application of the large torque required. Insight has been given into the level of analysis used to provide confidence in the system and verify the containment performance of the package, this includes prototype manufacture, testing, physical trials, and statistical analysis.

ACKNOWLEDGMENTS

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