DESIGN OF A TRANSPORT PACKAGE TO WITHSTAND ACCIDENT CONDITIONS OF TRANSPORT THROUGH THE PROVISION OF INTERNATIONAL PAINTS CHARTEK 7 INTUMESCENT COATING.

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ABSTRACT

In January 2017, Croft Associates were approached by an existing client with a very challenging project whereby they desired to accelerate the shipment of wasteforms between two UK licensed sites. A particularly challenging aspect of the project was the need for thermal management of the wasteform to prevent adverse degradation of package contents during transport and subsequent on-site storage.

Croft Associates, working with the client and associated stakeholders, initially developed a solution based upon an evolution of the very successful Croft 2816 J B(M)F package, already in service with the client for similar wasteforms. This new solution, the 4085A, was optimised for heat dissipation in order to mitigate against the wasteform degradation mechanisms.

Following further development, including regular briefings held with the regulator to keep them informed of the design progress, it became apparent that the thermal accident case for the developed solution would be challenging, and therefore a means of meeting full thermal accident conditions of transport was highly desirable.

Croft therefore proposed the utilisation of intumescent coating, in particular the International Paints Chartek 7 system, as a means of providing the desired fire protection under accident conditions of transport without compromising the heat dissipation features of the package.

This paper provides an overview of the initial package development, with particular emphasis upon the selection of an appropriate intumescent coating. The paper then describes the substantiation of the package performance, specifically highlighting the intumescent coating performance, by providing an overview of the test, analysis and substantiation works undertaken to support the licensing of this 4085A package.

INTRODUCTION

In January 2017, Croft Associates (Croft) were approached by an existing client with a very challenging project whereby they desired to accelerate the shipment of wasteforms between two UK licensed sites, followed by onsite storage.

The customer was currently utilising the 2816J Safkeg designed by Croft to transport waste with low heat output. However, with regards to suitability of the 2816J for higher heat output waste client issues were raised relating to the higher internal temperatures, and in particular the interaction with Poly Vinyl Chloride (PVC); confirmed as being present in some of the waste. A particular issue raised was that the as designed insulating properties which protect the 2816J from the Accident Conditions of Transport (ACT) fire scenario prescribed by the International Atomic Energy Agency (IAEA) within SSR-6 transport regulations [i] had the potential to cause temperatures within the keg's 2851 Containment Vessel (CV) to be within the temperature range that could contribute towards PVC degradation.

Therefore Croft, working with the client, regulators and further stakeholders, set out to develop a solution based upon an evolution of the 2816J Safkeg, already in service. This new solution, the 4085A, was optimised for heat dissipation by replacing the 2816J's insulting materials with an internal aluminium spacer. The resulting container mitigated against the PVC degradation under Normal Conditions of Transport (NCT), but its conductive properties meant that under the ACT fire scenario the internal 2851 CV could be challenged, as the bulk of the thermal protection had been designed out. Therefore a mechanism was required to provide thermal protection under ACT, but also to retain the 4085A enhanced heat dissipation provided by the internal aluminium spacer.

THE DESIGN PHILOSOPHY OF THE 4085A

The 4085A design philosophy was based upon utilising proven technologies and processes developed upon the previous range of Safkeg designs. A clear requirement for heat dissipation was provided by removing thermal insulation, enabling passive cooling mechanisms to ensure that the inner 2851 CV remains at the lowest possible temperature, whilst remaining within a robust outer container to retain accident performance. Figure 1 shows a section through the 4085A package concept.

OPTIMISED MANUFACTURABILITY

The new design provided scope for manufacturing optimisation, not least as the initial requirement was for 300 units to be delivered within 8 months. Therefore the keg stainless steel casing was formed from a solid shell reducing the number of welded joints, improving manufacturing and impact performance. The handling features were retained from the previous 2816J design to provide consistency in site operations. Further simplification was realised by modifying the top flange and dome to remove the necessity for an additional welded joint. The keg base dome was pressed rather than spun which also simplified the manufacturing process. A single circumferential full penetration butt weld was used to join the top flange and skirt to the keg casing and the base dome and skirt to the keg casing, these weld joints were positioned away from the impact and knock-back zones for enhanced impact performance.

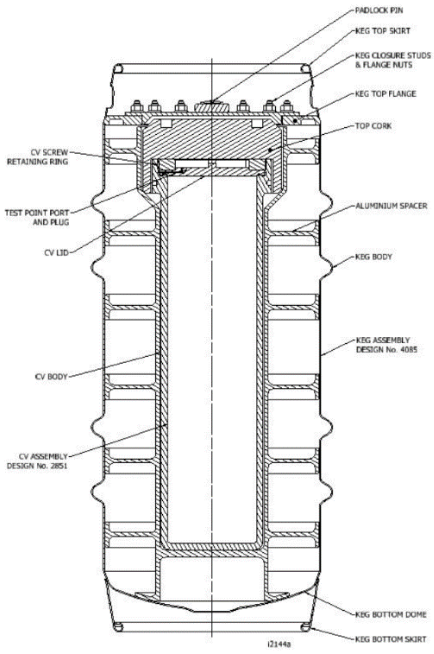

Figure 1- Section through the 4085A

ENHANCED HEAT DISSIPATION

As described within the design philosophy, a clear requirement was for the 4085A to provide a mechanism for heat dissipation to allow for passive cooling of heat generating contents. Following a number of scoping thermal analyses, an aluminium internal structure was selected, referred to as the "aluminium spacer" within the 4085A assembly.

Aluminium was chosen primarily for its excellent thermal conductivity, furthermore its mechanical properties enabled provision of an internal structure able to resist ACT impact loading; retaining the inner CV centrally within the keg. Retaining the CV centrally, with negligible deformation, was considered an essential requirement in order to meet shielding and criticality requirements of the package.

The scoping thermal analyses, allowed the aluminium spacer to be optimised. It was determined that the primary mechanism for heat transfer was via conduction, and so the spacer was constructed with circumferential ribs connected to flanged ends to maximise contact with the outer skin. Figure 2 shows an extract from the scoping thermal model of the aluminium spacer.

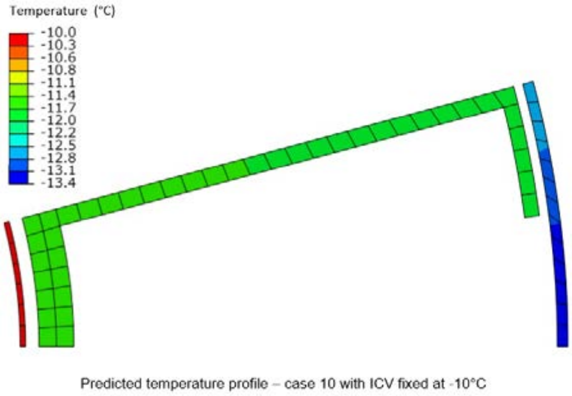

Figure 2 – Image of thermal scoping model utilised to optimise the aluminium spacer heat dissipation

It should be noted that the illustration presented within Figure 2 is for colder conditions, but the thermal behaviour is also typical of hotter temperatures.

A further benefit of the aluminium spacer design was that the fins provided a mechanism for structural rigidity and strain energy absorption under impact, retaining and protecting the CV centrally within the keg.

Advanced manufacturing techniques typically employed within aerospace manufacture were utilised to machine the aluminium spacer completely from one billet. This further enhanced the structural properties and optimised the quality assurance requirements by removing the need for a welded fabrication.

ATTAINMENT OF THERMAL ACT PERFORMANCE

Further thermal Finite Element Analysis (FEA) confirmed that the 4085A design was now optimised to provide excellent heat dissipation, enabling heat generating wasteforms to be transported, and if necessary stored in a safe manner. It was therefore clear, that a system optimised for heat dissipation away from the waste form primarily by conduction would unfortunately then present little resistance to external heat reaching the wasteform under thermal ACT.

Henceforth a mechanism was required to retain the heat dissipation, but prevent excessive heat prejudicing the keg performance in the case of an ACT fire as prescribed in the IAEA transport regulations [i] (800°C for a duration of 30 minutes).

Following a detailed requirements led design process, it was concluded that the most effective mechanism for thermal protection would be utilisation of an intumescent coating. A particular advantage of such a system is that the activation is passive, and so allows a transport safety case to be constructed. Under NCT the intumescent coating remains inactive and has minimal effect upon the heat dissipation. Under ACT the intumescent coating activates, intumesces, and chars to provide the required fire protection.

A special arrangement license application was considered as a viable alternative to a passive thermal protection, but discounted due to the potentially very significant operational difficulties of such an arrangement.

SELECTION OF INTUMESCENT COATING

Having determined that an intumescent coating provided the optimum solution for thermal ACT protection the challenge was to select a system capable of withstanding the ACT test requirements as specified within the transport regulations [i].

A large amount of research was undertaken in order to select the most appropriate coating solution. This was necessarily detailed, not least because the utilisation of such coatings, whilst prevalent in other industries, is not presently routine within the radioactive transport industry.

The key criteria for the coating performance were determined as:-

- A demonstrable withstand to ACT impact conditions for a Type B(M) package, namely:-
    - Consecutive 1.2m Drop test, 1m Penetration test, 9m Drop test and 1m Punch test
- A demonstrable withstand to subsequent ACT thermal accident conditions such that containment is maintained, namely:-
    - 800°C fire for 30 minutes
- Furthermore the withstand to the above criteria was required for both ambient conditions and operations down to circa -25°C to allow for potential transportation and storage in modified refrigerated ISO freight containers

- The coating system was required to resist the likely vibrations witnessed during transportation and as mentioned previously, should not prejudice the heat dissipation under NCT

Following this detailed evaluation, the optimum system was concluded to be from International Paints Chartek intumescent coating range, specifically Chartek 7. Chartek 7 is a high performance, tough, durable and widely certified epoxy intumescent fire protection coating system. Born in the 1970s from NASA space programs, Chartek was the world's first epoxy intumescent passive fire protection material. Chartek quickly became established within the oil industry, since the alternative cement-based materials previously utilised were found to be lacking in the durability required to survive the effects off harsh offshore environments. A major factor in the selection of Chartek was its proven track record of performance in harsh environments over 40 years of operation. Chartek has been utilised to protect installations against explosion, hydrocarbon pool and jet fires in some of the world's harshest environments, from the tropics through to Antarctica. Figure 3 below shows the installation of Chartek 7 upon the Halley VI research facility in Antarctica as an example of utilisation. This was a particularly demanding application as the Chartek 7 was applied to the steel structure in Cape town as part of the facility pre-fabrication, in a humid climate at 25°C. The structure was then shipped in a marine environment to Antarctica, and then installed in an operating environment ranging from -50°C to + 10°C, depending upon the polar season.

Figure 3 - Halley VI facility in operation in Antarctic conditions

A further factor considered in the selection of Chartek 7, was the assurance provided by conformance to very stringent independent test standards, in particular:-

- Test and certification from Lloyds Register (LR), Det Norske Veritas (DNV), American Bureau of Shipping (ABS) and Bureau Veritas (BV)
- ISO 22899-1 [ii] jet fire resistance for up to 3 hours
- Norsok M501 revision 5 [iii] compliant and UL1709 [iv] exterior listed for absolute corrosion protection
    - Norsok M501 standard was developed for challenging offshore environments and adopted ISO20340 for its pre-qualification offshore performance standard
    - ISO 20340 [v] uses three well established laboratory procedures as a 7 day test cycle
    - 72 hours accelerated UV and condensation in accordance with ISO 11507:1997 [vi]
    - 72 hours hot salt spray exposure in accordance with ISO 7253:1996 [vii]
    - 24 hours steady state low temperature testing at -20°C

Having selected the Chartek 7 system, the design and analysis team worked very closely with the International Paints technical experts to develop a practical coating scheme to ensure consistent application and proven performance. The system was applied to the kegs by an International Paints approved applicator, Barrier Fire Protection, Newcastle, UK.

A total of 6 off prototype 4085A kegs were manufactured and coated to support a testing program to substantiate the licence application, and in particular the intumescent coating ACT performance.

TESTING

The 6 off prototypes were subsequently subjected to the tests described below, each package was coated with Chartek 7 (except the initial prototype), and each carried a CV holding 32kg of lead as simulated contents. The regulatory tests were as follows:-

- Impact performance at ambient conditions
- 1.2m Drop, 1m Penetration, 9m Drop, 1m Punch in sequence, undertaken at fully horizontal and lid edge down orientations, which were determined to be the bounding impact conditions. All at ambient temperatures. (See Figure 4)
- As above but repeated for different prototypes at low temperature conditions (-25°C)
- Thermal ACT testing
- 800°C for 30 minutes upon keg previously damaged during ambient impact testing
- 800°C for 30 minutes upon undamaged keg (to provide benchmark case for substantiation of the thermal model)

Further to the regulatory tests, additional tests were carried out in support of the package substantiation, these consisted of:-

- Vibration testing, 4.87 Hz, with a 25.4mm double amplitude vertical displacement, (see Figure 5)
- Discreet plate tests. Coated plates were subject to thermal tests at a range of temperatures, ambient conditions and in both wet and dry conditions. These tests were used to underpin the coating performance, and provide data along with further reassurance to the thermal model benchmarking

Figure 4 –Regulatory impact testing of 4085A

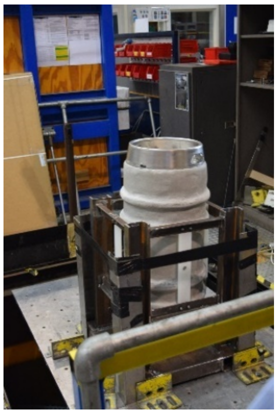

Figure 5 - Vibration testing of 4085A

TEST RESULTS

Regulatory impact tests were carried out to the requirement of a Croft test procedure. These were initially carried out at ambient conditions upon two test specimens at different orientations, before repeating at low temperature (-25°C) for a separate specimen at a worst-case orientation determined from the ambient test damage.

The consecutive ambient tests, (1.2m Drop, 1m Penetration, 9m Drop, 1m Punch in sequence), resulted in negligible damage to the keg, and minimal damage to the intumescent coating. The keg damage was predominantly seen in the top skirt at the top down lid edge orientation. This was entirely as expected and in line with FEA modelling predictions noting that this skirt is designed as a “frangible” feature to convert impact energy into strain under ACT conditions. Figure 6 shows the correlation between impact results and FEA predictions upon this skirt.

Figure 6 – Correlation between impact testing (left image) and Impact FEA (right Image) upon the 4085A Top Skirt.(9m lid edge drop)

The intumescent coating remained predominantly intact, with the worst local damage being caused by the 1m Punch test. The CV remained undamaged and passed a post-test leak test to Type B requirements, (namely 3.73×10^{-6} bar cm^3/s Standardised Leak rate (SLR).

The low temperature impact tests performed in a very similar manner to ambient conditions, with a slightly increased intumescent coating damage area, again caused by the 1m Punch test at worst case orientation. Once more, the CV remained undamaged and successfully passed the post-test leak test.

The worst case damaged keg from impact at ambient conditions was then utilised for a thermal ACT test. The test was performed as a furnace test, nominally at 800°C for 30 minutes as per regulatory requirements. In actuality, the test resulted in peak temperatures significantly higher than anticipated due to the lack of resolution in the furnace control, with peak flame temperatures of 1053.8°C recorded. Therefore this test became a severe “over-test” of the 4085A thermal resistance. Notwithstanding the extreme conditions, the intumescent coating reacted as anticipated, forming a consistent char which remained intact. The char provided the desired passive fire protection, and the containment vessel remained undamaged from the test. Furthermore, although not specifically a test requirement, the CV was shown to be leak tight post-test.

Principally to provide more predictable results for thermal model benchmarking the thermal ACT test was repeated, but upon an undamaged keg, and in a more controlled furnace. This test resulted in a much more controlled environment, with significantly lower peak temperatures. Once more the intumescent coating worked excellently, and the CV remained undamaged, and leak tight as demonstrated by the post-test leak test.

With regards to the further, non-regulatory testing, a total of 16 plate tests were undertaken on samples coated with Chartek 7 using the H-TRIS test rig at Edinburgh University. The samples varied in terms of coating thickness, peak temperature, starting ambient temperature and wet or dry conditions. The data helped to establish the paint thermal properties needed for the thermal modelling, and demonstrated that the coating performance remained largely unaffected by environmental factors such as how wet and cold the coating was prior to testing. This was important data for the program, and helped substantiate the safety cases for transport and storage, within refrigerated ISO containers.

With respect to vibration testing, extreme double amplitude frequencies were utilised to cause significant vibration of a sample keg within its transport stillage. Following these tests, the coating remained almost totally without damage, with only minor cracking witnessed at contact points. This damage was assessed as not having the potential for any discernible effect upon keg thermal ACT performance.

ANALYSIS

As evidenced by Figure 6 previously, a detailed FEA analysis was performed to correlate with the impact testing and allow validation and verification of test results. This analysis was also utilised to confirm worst orientation impact performance. The model was found to correlate very accurately to test results, and no significant deterioration of the CV was predicted, as evidenced by the successful post impact leak testing.

A suite of thermal analyses were undertaken by Wood in order to accurately define a thermal model able to underpin the licence application for any number of contents permeations. Initially scoping studies were performed to determine optimum geometry for heat dissipation, as illustrated previously within Figure 2. Analysis was then performed upon the thermal test of the keg previously damaged under ambient impact conditions. Whilst this provided reasonable correlation to test results, a number of variations pertaining to furnace temperature, intumescent coating thermal conductivity and uncertainty in small air gaps surrounding the Aluminium Liner following impact necessitated a further undamaged test to provide more robust thermal model benchmarking. Therefore the results from the undamaged furnace test were subsequently modelled, and together with the plate tests, provided a very accurate, benchmarked model to substantiate the keg thermal ACT performance.

The benchmarked model was subsequently utilised to predict ACT temperatures, particularly at the CV seal, in order to substantiate the containment case for transport. It is noted that the seal temperature remained well within normal operating limits of the seal material. Furthermore the model, once accurately benchmarked, allowed sensitivity studies to be performed, in particular with regards to damage to the intumescent paint. These studies concluded that damage up to twice that seen under test conditions would be acceptable and would not have a marked effect upon keg thermal performance. Figure 7 shows the transient temperature results v time at the CV seal under thermal ACT conditions (800°C for 30 minutes).

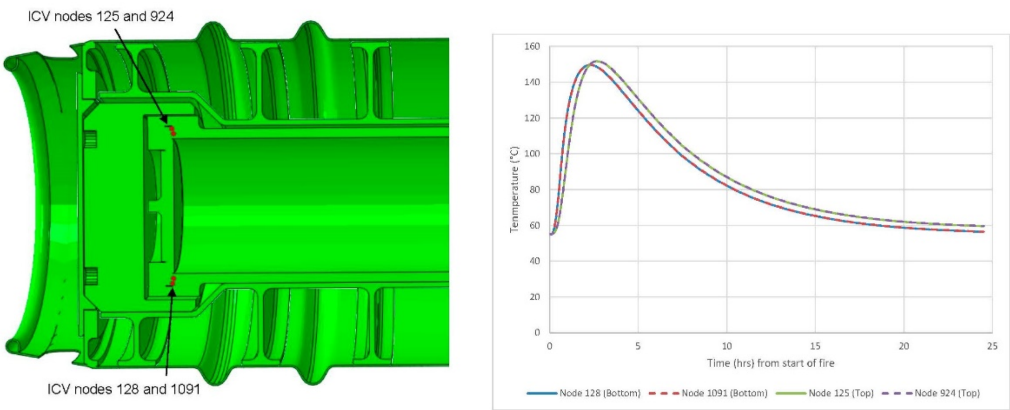

Figure 7 - Transient temperature results v time at the Inner Containment Vessel (ICV)seal under thermal ACT conditions taken from benchmarked thermal model (800°C for 30 minutes)

CONCLUSION

The design, manufacturing, test and analysis data herein demonstrates that Croft Associates successfully met the challenging requirements of developing a transport package optimised for both heat dissipation as well as ACT. Two principal factors in the success of this transport package development were the provision of International Paints Chartek 7 intumescent coating, and the subsequent detailed thermal analysis of this coating to substantiate ACT performance, performed by Wood.

The success of this project has led to a substantial fleet of these transport containers being procured by our client, and these are presently being prepared for transport of radioactive material to meet a challenging, strategically important, waste transfer schedule.

REFERENCES

(i) Regulations for the Safe Transport of Radioactive Material – 2012 Edition (IAEA Safety Standards Series No SSR-6.

(ii) ISO 22899-1:2007 Determination of The Resistance to Jet Fires Of Passive Fire Protection Materials – Part 1: General Requirements.

(iii) NORSOK M501 Surface Preparation and Protective Coating (Edition 6, February 2012).

(iv) UL 1709, 5th Edition, Feb 2017, Standard for Safety Rapid Rise Fire Tests Of Protection Materials for Structural Steel.

(v) ISO 20340:2009, Paints and Varnishes, Performance Requirements for Protective Paint Systems for Offshore and Related Structures.

(vi) ISO 11507:1997, Paints and Varnishes, Exposure of coatings to artificial weathering – Exposure to fluorescent UV and water.

(vii) ISO 7253:1996, Paints and varnishes – Determination of resistance to neutral salt spray (fog)