CONTENTS

2 STRUCTURAL EVALUATION

This section identifies the principal structural members of the Safkeg-LS 3979A package, and the materials and fabrication methods of each are described. The ability of the package to satisfy the regulatory requirements of 10 CFR 71 [2.1], regarding Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC) tests, is demonstrated in Sections 2.6 and 2.7 by Finite Element Analysis (FEA) of the containment vessel and testing of a prototype keg.

2.1 Description of Structural Design

2.1.1 Discussion

The principal structural members of the Safkeg-LS 3979A package are the 3979 keg, inner cork packing and the 3980 containment vessel. The radioactive contents are carried within product containers and inserts placed inside the containment vessel (see Section 1.2.1).

The keg is designed to absorb impacts, provide protection during handling operations and insulate the containment vessel during the HAC thermal test. The inner cork packing is designed to absorb the impact loads preventing damage to the containment vessel under HAC tests. The containment vessel is designed to provide the containment and shielding of the radioactive material and the insert is designed to provide a confinement boundary and additional shielding for the contents. A description of the structural design of each of these members is provided in the following sections.

3979 Keg

The keg comprises of a body, lid, outer cork and liner assembly as shown in drawing 0C-6042 (Section 1.3.2). The body of the keg is constructed from rolled austenitic stainless steel welded to form a cylinder. A base, top flange, skirts and rims are welded to the rolled

cylinder to form the keg body. The outer cork is placed into the keg with the steel assembly liner fitting inside the cork to protect the outer cork during handling operations. The inner liner is formed from 2mm thick austenitic stainless steel.

The keg closure is facilitated by eight closure studs (occasionally referred to as bolts) screwed and glued into position on the top flange and a lock pin which is welded into position. The keg lid is a circular plate with eight holes machined for the closure bolts and one hole for the lock pin. The lid is attached to to the body with eight M12 austenitic stainless steel nuts and washers. A nitrile O-ring is fitted to a groove in the flange ensuring that a weather tight seal is provided on closure of the keg. Two handles are welded to the lid to allow handling of the lid.

A fuse plug is located in the base plate of the keg body. It is present to prevent the over pressurization of the keg during the HAC thermal test. The fuse plug is austenitic stainless steel with a hole drilled through the centre which is filled with a low melting point alloy. This alloy has a melting point of 94 to 98°C which once melted will allow any gases generated within the keg to vent, reducing the pressure in the keg body.

Top and Inner Cork

The inner cork fits inside the keg liner and surrounds the containment vessel. It is designed to reduce impact loads on the keg liner and the containment vessel and provide thermal insulation. The cork surrounds the side walls and the lid of the containment vessel. It varies in width from 58.5 mm to 30.5 mm on the side walls due to the variation in diameter of the containment vessel and is 85 mm thick above the lid. The cork is agglomerated and coated in a water based varnish. The cork components are shown in detail in drawing 0C-6043 (Section 1.3.2).

3980 Containment Vessel

The containment vessel consists of a body and a removable lid assembly bolted together with 8 closure bolts and sealed with an inner and outer O-ring, as shown in drawing 1C-6044 (Section 1.3.2).

The body assembly is formed from a stainless steel shell filled with lead. The stainless steel shell consists of three austenitic stainless steel pieces, the inner cavity wall/flange, outer wall and base. Each piece is machined from solid austenitic stainless steel. The inner cavity wall/flange and outer wall are welded together with a circumferential groove weld which is both visually and liquid penetrant tested. The shielding cavity is filled with lead and the base is welded into position with a circumferential groove weld which is both visually and penetrant tested.

The lead (4% Sb lead alloy) forms the shielding for the walls and base of the containment vessel. The lead used may only contain a maximum of 0.5% impurities and must meet the requirements of BS 3909/2 [2.2].

The inner cavity wall/flange and the bolted flange for the containment vessel closure forms the cavity into which the radioactive contents are placed. The flange is machined with 8 closure holes into which CV closure screws (occasionally referred to as bolts) are fitted.

The containment vessel lid is comprised of two pieces a lid top and a stainless steel clad lead plug. The CV lid top is a circular plate machined from a stock billet of 304L stainless steel. Eight equally spaced counter bored holes are machined to accommodate the closure bolts. Four further holes are machined in the lid, the first accommodates the test port in order to leak test the closure system. The second is in the centre of the lid and is fitted with a threaded insert. This allows a lifting eye to be fitted for the handling of the containment vessel. The last two allow jacking screws to be fitted which assist in the removal of the lid. Two grooves are machined onto the underside of the lid top into which the O-rings are fitted.

The lead is cast into a machined stainless steel casing forming the shielding plug. The plug is welded to the lid top with a circumferential weld which is liquid penetrant and visually tested.

The containment vessel lid is attached to the body with eight L43 alloy steel screws/bolts which are tightened to a torque of 10 ± 5 Nm.

The design pressure for the containment vessel is 10 bar (1,000 kPa) gauge which envelopes the MNOP of 7 bar (700 kPa) gauge. The containment boundary is formed by the inner cavity wall/flange, lid and containment O-ring. This containment boundary is leak tested on manufacture, during annual maintenance and on loading.

Insert

Any one of the three inserts specified in Section 1.3.2 shall be used to provide further shielding and confinement for the contents. Two of the inserts, LS-12x65-Tu Design No 3984 and LS-31x73-Tu Design No 3983, are machined from tungsten with one, LS-50x103-SS Design No 3986, machined from stainless steel. All of the inserts consist of a body and a lid which are machined from a solid. The lid screws onto the body with an O-ring seal. The three types of inserts each have different cavity sizes and provide varying levels of shielding.

2.1.2 Design Criteria

In order to evaluate the containment design, an FEA was performed on the containment vessel under NCT and HAC using the software code Abaqus: as discussed in Vectra Report 925-3272 (Section 2.12.2). The initial load combinations used during the evaluation are discussed in Section 2.1.2.1. The resultant calculated stresses are compared against the allowable stresses presented in Section 2.1.2.2. Further evaluation is carried out to determine buckling, fatigue and brittle fracture as discussed in Sections 2.1.2.3, 2.1.2.4 and 2.1.2.5 respectively.

The effectiveness of the packaging components under all the conditions of the regulatory requirements (both NCT and HAC) have been verified by physical tests. As the structural materials of the package are all austenitic stainless steel, the package is not susceptible to

failure by brittle fracture. The keg, being a composite structure with the outer skin supported by the cork and the inner shell, it is not susceptible to buckling.

2.1.2.1 Load Combinations

The load combinations used in the structural evaluation of the containment vessel were developed in accordance with Regulatory Guide 7.8 [2.3]. The NCT and HAC load combinations used to determine the stresses within the containment vessel are summarized in Table 2-1 and Table 2-2.

Table 2-1 Load Combinations for NCT

Load Case ID	NCT	Initial Conditions								
		Ambient Temperature		Insolation		Decay Heat		Internal Pressure		Fabric-ation Stress
		38°C	-29°C	Max	Zero	Max	Zero	Max	Min	
NCT1	Hot environment (38°C ambient temperature)			X		X		X		X
NCT2	Cold environment (-40°C ambient temperature)				X		X		X	X
NCT3	Reduced external pressure (24.5 kPa)	X		X		X		X		X
NCT4	Increased external pressure (140 kPa)		X		X		X		X	X
NCT5	Vibration (10g vertical)	X		X		X		X		X
NCT6			X		X		X		X	X
NCT7	Free drop on lid (1.2m)	X		X		X		X		X
NCT8			X		X		X		X	X
NCT9	Free drop on side (1.2m)	X		X		X		X		X
NCT10			X		X		X		X	X
NCT11	Free drop on corner (1.2 m)	X		X		X		X		X
NCT12			X		X		X		X	X

Table 2-2 Load Combinations for HAC

Load Case ID	HAC	Initial Conditions								
		Ambient Temperature		Insolation		Decay Heat		Internal Pressure		Fabric-ation Stress
		38°C	-29°C	Max	Zero	Max	Zero	Max	Min	
HAC1	Free drop on lid (9m)	X		X		X		X		X
HAC2			X		X		X		X	X
HAC3	Free drop on side (9m)	X		X		X		X		X
HAC4			X		X		X		X	X
HAC5	Free drop on corner (9m)	X		X		X		X		X
HAC6			X		X		X		X	X

2.1.2.2 Allowable Stress

The allowable stresses used to calculate the design margins within the containment boundary are given in Table 2-3. The allowable stresses were taken from Regulatory Guide 7.6 [2.4]. These are based on the 1977 edition of the ASME Boiler and Pressure Vessel Code [2.5]. This guide only gives allowable stress values for primary membrane stress, primary membrane plus primary bending stress and primary plus secondary stress for both NCT and HAC loading conditions. The allowable values for bearing stress and for the bolts have been taken from ASME Section III Div 3 [2.6] as these are not given in Reg. Guide 7.6 [2.4]. Guidance for classification of stresses was taken from Table WB-3217-1 in ASME Section III Div 3 [2.6].

To demonstrate conformance with the allowable stress limits, it was necessary to determine the stress intensities at critical cross-sections of the containment vessel. Since the critical cross-section locations are load-condition dependent, several "stress evaluation sections" were defined to ensure that all critical locations were evaluated for every load condition. These stress evaluation sections are illustrated in Figure 2-1. For evaluation of conditions producing a stress distribution in the vessel that is not axisymmetric, stress evaluations were performed at multiple circumferential locations.

The section stresses at each stress evaluation location were obtained using the Abaqus "stress linearization" post-processing feature (Vectra Report 925-3272/R1 (Section 2.12.2). The stress linearization provides membrane, bending, membrane plus bending, and peak stress intensities at each section. In Abaqus, the Tresca stress is equal to the stress intensity as defined in Regulatory Guide 7.6 [2.4].

Using the critical sections from each load case, minimum design margins are calculated and reported for all bounding load combinations. The design margin (DM) is defined as follows:

$$DM = \left(\frac{Allowable\_Value}{Calculated\_Value} \right) - 1$$

Therefore a negative design margin indicates that the vessel has failed the assessment.

Table 2-3 Containment System Allowable Design Criteria

Stress Type	Allowable Stress Limits	
	NCT	HAC
Other Than Bolts		
Primary Membrane Stress Intensity (P_m)	S_m	Lesser of 2.4Sm and 0.7Su
Primary Local Membrane Stress Intensity (P_L)	S_m(2)	N/A(3)
Primary + Bending Stress Intensity (P_L or P_m+P_b)	$1.5S_m$	Lesser of 3.6Sm and Su
Primary + Secondary Stress Intensity (P_L or P_m+Q)	$3.0S_m$	N/A
Average Bearing Stress	S_y	N/A
Bolts		
Average Shear Stress	$0.4S_y$	Lesser of $0.42S_u$ and $0.6S_y$
Average Stress(4)	$2S_m$	Lesser of $3S_m$ and $0.7S_u$
Maximum Stress(5)	$3S_m$	N/A(6)

Notes:

1. Stress limits applicable for components and systems evaluated using elastic system analysis.
2. ASME B&PV code [2.6] gives an allowable of 1.5Sm for primary local membrane stress, P_L. However, Reg. Guide 7.6 [2.4] does not specify an allowable for this stress, so a lower allowable value of S_m has been adopted for this assessment.
3. Evaluation of secondary stress is not required for HAC.
4. The axial stress component averaged across the bolt cross-section and neglecting stress concentrations.
5. The stress due to internal pressure and gasket seating loads (e.g. bolt torque) shall not exceed one times S_m.
6. Evaluation of maximum bolt stress not required for HAC

2.1.2.3 Buckling

The containment vessel inner shell is evaluated for buckling in accordance with the requirements of ASME Code Case N-284-2 [2.7]. Capacity reduction factors are calculated in accordance with Section -1511 of ASME Code Case N-284-2 [2.7] to account for possible reductions in the capacity of the shells due to imperfections and nonlinearity in geometry and boundary conditions. Plasticity reduction factors, which account for nonlinear material properties when the product of the classical buckling stresses and capacity reduction factors exceed the proportional limit, are calculated in accordance with Section -1610 of ASME Code Case N-284-2 [2.7]. The theoretical buckling stresses of the vessel inner shell under uniform stress fields are calculated in accordance with Section -1712.1.1 of ASME Code Case N-284-2 [2.7]. The geometric parameters used in the buckling assessment are given in Table 2-4. The capacity reduction factors, plasticity reduction factors, and theoretical buckling stresses for the vessel inner shell are summarized in Table 2-45.

The allowable elastic and inelastic buckling stresses for NCT and HAC are calculated in accordance with the formulas given in Section -1713.1.1 and Section -1713.2.1 of ASME Code Case N-284-2 [2.7]. The allowable buckling stresses include factors of safety of 2.0 for NCT and 1.34 for HAC in accordance with Section -1400 of ASME Code Case N-284-2 [2.7]. Table 2-6 provides a summary of the vessel inner shell elastic and inelastic buckling stresses for NCT and HAC. Buckling interaction ratios are calculated for the containment vessel inner shell for all NCT and HAC tests that load the shells in compression. The interaction ratios for elastic buckling and inelastic buckling are calculated using the highest values of compressive stress and shear stress from the finite element analysis solutions in accordance with the formulas given in Section -1713.1.1 and Section -1713.2.1 of ASME Code Case N-284-2 [2.7].

Table 2-4 Containment vessel shell buckling geometric parameters

Geometric Parameter	Inner Shell
Mean radius, R (mm)	33.75
Shell thickness, t (mm)	3.0
R/t	11.25
Unsupported axial length, l_ϕ (mm)	109
Unsupported circumferential length, l_θ (mm)	212.1

Table 2-5 Buckling reduction factors and theoretical buckling stresses			
Calculation	Parameter	Hot ambient temperature	Cold ambient temperature
Capacity reduction factors (-1511)	$\alpha_{\phi L}$	0.2	0.3
	$\alpha_{\theta L}$	0.8	0.8
	$\alpha_{\phi\theta L}$	0.8	0.8
Plasticity reduction factors (-1610)	η_{ϕ}	0.1	0.1
	η_{θ}	0.1	0.2
	$\eta_{\phi\theta}$	0.0	0.0
Theoretical buckling values (-1712.1.1)	$\sigma_{\phi eL}$	10003 MPa	10702 MPa
	$\sigma_{\theta eL} = \sigma_{reL}$	1574 MPa	1684 MPa
	$\sigma_{\theta eL} = \sigma_{heL}$	1492 MPa	1596 MPa
	$\sigma_{\phi\theta eL}$	3804 MPa	4070 MPa

Table 2-6 Shell allowable buckling stresses					
Buckling Regime	Stress Type	Allowable Buckling Stress (MPa)			
		Hot ambient temp.		Cold ambient temp.	
		NCT	HAC	NCT	HAC
Elastic Buckling	Axial Compression, σ_{xa}	1035	1545	1211	1807
	Hydrostatic Pressure, σ_{ha}	597	891	638	953
	Hoop Compression, σ_{ra}	630	940	674	1006
	In-plane shear, $\sigma_{\tau a}$	1522	2271	1628	2430
Inelastic Buckling	Axial Compression, σ_{xc}	66.0	98.5	86.0	128.4
	Radial external pressure, σ_{rc}	66.0	98.5	86.0	128.4
	In-plane shear, $\sigma_{\tau c}$	39.6	59.1	51.6	77.0

2.1.2.4 Fatigue

The fatigue analysis was carried out in accordance with section C3 in NRC Regulatory Guide 7.6 [2.4]. The fatigue analysis was performed as follows:

1. The alternating stress, S_{alt}, was calculated as one-half the maximum absolute value of S'_{12}, S'_{23}, S'_{31} for all possible stress states i and j where σ_1, σ_2, σ_3 are principal stresses and

   $$S'_{12} = (\sigma_{1i} - \sigma_{1j}) - (\sigma_{2i} - \sigma_{2j})$$
   $$S'_{23} = (\sigma_{2i} - \sigma_{2j}) - (\sigma_{3i} - \sigma_{3j})$$
   $$S'_{31} = (\sigma_{3i} - \sigma_{3j}) - (\sigma_{1i} - \sigma_{1j})$$

   State i is after the bolt pre-load has been applied and state j is after all the other loads have been applied. This calculation of S_{alt} is carried out in the post processor.

2. S_{alt} is multiplied by the ratio of the modulus of elasticity given on the design fatigue curve to the modulus of elasticity used in the analysis to obtain a value of stress to be used with the design fatigue curves.

3. The highest value of S_{alt} determined in step 2 is then compared with the design fatigue curves (Figure I-9.2.2) in appendix I of ASME B&PV Section III [2.6].

The number of cycles that the Safkeg LS CV will undergo is approximately 50 cycles/year for 20 years = 1000 cycles. The number of cycles was multiplied by 10 to give 10000 cycles, to give a safety margin.

2.1.2.5 Brittle Fracture

All the structural components of the package are fabricated from austenitic stainless steel which is ductile at low temperatures. According to Regulatory Guide 7.11 [2.8] austenitic stainless steel is not susceptible to brittle facture at temperatures encountered in transport.

The HAC drop tests have been conducted at -40°C to determine if brittle fracture has any effect on the package, with compliance demonstrated if the containment vessel is undamaged and leak tight on completion of testing.

2.1.3 Weights and Centers of Gravity [71.33]

The nominal weight of the package plus the individual components and the maximum content weights are shown in Table 2-7. The maximum package gross weight is 68 kg. The center of gravity of the assembled package is approximately in the center of the 3979A keg.

The weights of the components in Table 2-7 are calculated maximum weights at extreme tolerance to give maximum material condition with rounding.

Table 2-7 Weights of SAFKEG 3979A

Components	Approximate Weight	
	Kg	lbs
Keg Body, Lid, Liner, Outer Cork, Nuts & Washers	35.5	78
Cork Packing	2.9	7
Keg plus inner and top corks	38.4	85
Containment vessel	23.7	52
LS SAFKEG 3979A excluding contents	62.1	137
Insert Plus Contents (max)	5.9	13
LS SAFKEG 3979A including contents	68	150

2.1.4 Identification of Codes and Standards for Package Design

The package has been designed to transport normal and special form material in quantities of greater than 3000A_2, therefore it is classified as a Category I package, as defined in Regulatory Guide 7.11 [2.8]. The standards to which the package has been designed, fabricated, tested and maintained have been selected based on the guidance provided in Regulatory Guide 7.6 [2.4] and NUREG/CR-3854 [2.9].

The package containment system was designed in accordance with the requirements of Regulatory Guide 7.6. The load combinations used for the package structural evaluation have been taken from Regulatory Guide 7.8 as discussed in section 2.1.2.1. The buckling evaluation of the containment vessel inner shell is evaluated in accordance with the requirements of ASME code case N-284-2 as discussed in section 2.1.2.3.

The package containment system is fabricated in accordance with the applicable requirements of ASME Section III, Division 1, subsection NB [2.10]. All welds are qualified in accordance with ASME section IX [2.11] and subjected to non destructive visual and liquid penetrant examination in accordance with ASME section V [2.15]. The applicable acceptance criteria for these tests are given in Section III sub section NB 5350 of the ASME code.

The containment system is subjected to further tests during manufacture. Prior to manufacture, the stock material used to form the lid and flange/cavity wall is liquid penetrant tested to ASME III subsection NB 2546 [2.10] and ultrasonically examined using the straight beam UT method in accordance with ASME III subsection NB 2532.1 [2.10]. The containment vessel lid and flange/cavity body once machined are helium leak tested in accordance with ANSI N14.5 [2.12]. The closure seal is also tested to this standard once the

containment vessel is assembled. The containment vessel is also pressure tested on manufacture in accordance with 10 CFR 71.85(b).

A full chemical analysis of the batch used for the lead shielding will be required prior to casting to ensure it satisfies the shielding requirements. The cork is fabricated and tested to the vendor's standard procedures and provided with a CoC.

The containment vessel is required to be leak tested throughout its service life. The containment vessel is also required to be leak tested to ANSI N14.5 [2.12] during loading of the containment vessel in accordance with Section 7.1 and on maintenance in accordance with Section 8.2.

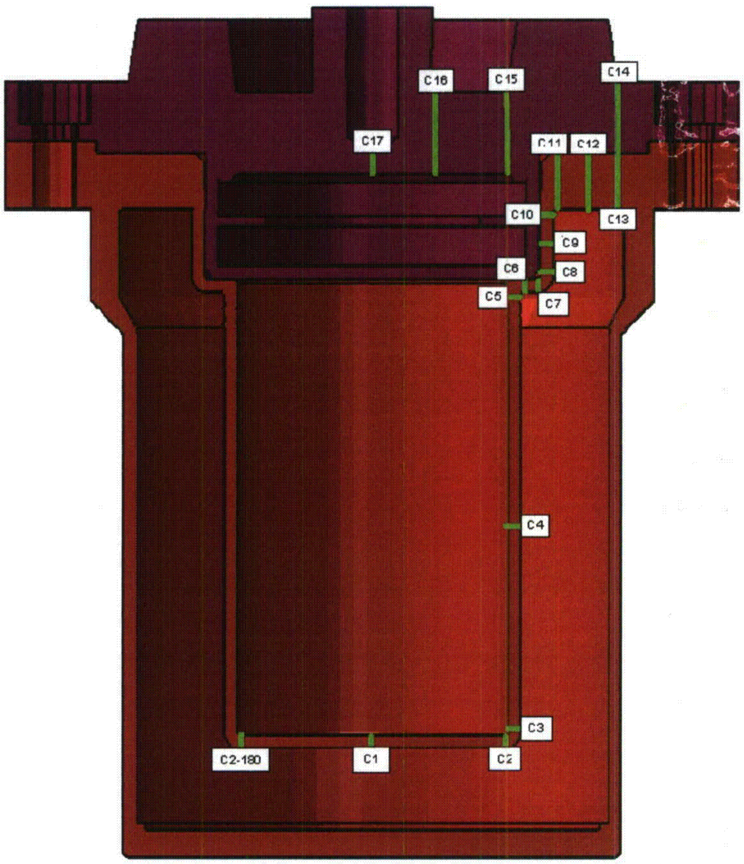

Figure 2-1 Stress Evaluation Locations

2.2 Materials

2.2.1 Material Properties and Specifications

The materials used in the construction of the package are listed in Table 2-8. The mechanical properties of the materials used in the structural evaluation of the containment vessel are presented in Sections 2.2.1.1 to 2.2.1.3.

Table 2-8 Packaging Material Specifications

Packaging Component	Material Specification
Keg 3979	
Top and bottom rim	Stainless Steel AISI 304
Top and bottom skirt	Stainless steel A240/A240M 304L
Keg outer shell	Stainless steel A240/A240M 304L
Top flange	Stainless Steel A240/A240M 304L
Base plate	Stainless Steel A240/A240M 304L
Outer cork	Amorim CA 8113 Aglomerated Cork
Keg liner	Stainless Steel A240/A240M 304L
Keg liner disc	Stainless Steel A240/A240M 304L
Keg lid	Stainless Steel A240/A240M 304L
Keg lid handle	Stainless Steel A240/A240M 304L
Keg lid seal	Nitrile 70 ± 5 IRHD
Keg closure stud	Stainless Steel A249/A249M 304L
Keg closure nut	ASME/ANSI Stainless Steel A2-70
Keg closure washers	ASME/ANSI Stainless Steel A2
Lock pin	Stainless Steel A249/A249M 304L
Fuse plug	Stainless steel A2
Fuse plug alloy	Bismuth/Tin/Lead alloy ASTM B774
Inner Cork Packing	
Cork body and lid	Amorim CA 8113 Aglomerated Cork
Cork sealant	Water based satin varnish Traffic Red RAL 3020
Containment Vessel 3980	
Flange/cavity wall	Stainless Steel A249/A249M 304L
Outer wall	Stainless steel ASTM A511/A511M Type MT304L
Body shielding	Lead 4% antimony

Table 2-8 Packaging Material Specifications	
Packaging Component	**Material Specification**
Base	Stainless Steel ASTM A240/A240M Type 304L or A249/A249M 304L
Lid shielding casing	Stainless Steel A249/A249M 304L
Lid shielding	Lead 4% antimony
Lid Top	Stainless Steel A249/A249M 304L
Test point plug	Stainless Steel
Containment seal	EPM ASTM D2000 M3 BA 710 F17 Z1
Test seal	EPM ASTM D2000 M3 BA 710 F17 Z1
Test point seal	EPM BS 4518 0036-24
Closure screws/bolts	Alloy steel ASTM A320/A320M L43
Jacking screw	Steel
12x65 Tu Insert	Tungsten
31x73 Tu Insert	Tungsten
50x103 SS Insert	Stainless Steel

2.2.1.1 Structural Materials

The containment vessel is fabricated entirely from stainless steel. The structural members in the main are fabricated from Type 304L stainless steel in either plate or bar form. The only exception is the containment vessel bolts which are fabricated from a high strength grade L43 alloy bolting steel material. All the insulating and shock absorbing material is fabricated from resin bonded cork.

The structural evaluation of the containment vessel was assessed under NCT using a temperature range of – 40°C to 110°C. In order to carry out the stress analysis a Poisson ratio of 0.3 and a density of 8030 kg/m^3 were used for the stainless steel 304L components. A Poisson ratio of 0.3 and a density of 7860 kg/m^3 were taken for Grade L43 bolting steel.

The mechanical properties used in the structural analysis are taken from the ASME Section II Part D [2.14]. Table 2-9 provides the mechanical properties of stainless steel 304L, which makes up the majority of the structural component materials, over a range of temperatures. Table 2-10 summarizes the mechanical information for SA-320/A320 Grade L43 Bolting Steel which is used for the bolts in the containment vessel.

2.2.1.2 Shielding Material

The shielding is formed from lead cast within the stainless steel cladding. The lead is alloyed with 4% antimony to provide greater hardness and strength. The mechanical properties of lead used in the structural evaluation are presented in Table 2-11.

2.2.1.3 Cork Packing

The inner and outer cork is machined from resin bonded cork. The cork may be formed from one piece or from several pieces glued with a contact adhesive.

The mechanical properties of the cork have been determined by testing. Loads were applied by a piston at a rate of 4.5 mm/minute to 45 mm thick racially constrained cork samples. The displacement of the cork was then recorded continuously at a rate of 20 readings/second. In order to cover the full range of service temperatures tests were carried out with corks at -29°C, 20°C and 100°C. The test details and results are discussed in the Serco Report SERCO/TAS/002762/01 [Section 2.12.2].

Table 2.12 presents the mechanical properties of the cork determined from testing. The test results show that cork is harder at low temperatures and softer at high temperatures. At an applied stress of 8 MPa, the cork at 100°C showed most deformation: which would indicate the containment vessel will travel a further distance into the cork before it is resisted by the same forces it would be resisted with at room temperature.

2.2.2 Chemical, Galvanic or Other Reactions [71.43(d)]

The package has been evaluated to determine all the material interactions of chemically or galvanic dissimilar materials. These interactions are identified in Table 2-13.

There is no potential for chemical, galvanic or other reactions between the components of the package which are stainless steel and cork in dry conditions, and stainless steel and encapsulated lead which is sealed and therefore dry. The only contents which could cause reactions or generate gases are liquids carried in product containers within the tungsten or steel inserts which are fitted with an EPM O-ring seal. Under NCT, the liquids are contained within the product containers and inserts and therefore no liquid comes into contact with the containment system. Under HAC, the liquids are assumed to leak from the product containers and inserts and therefore the liquid may come into contact with the containment system but this would be only for a short time. The containment system is stainless steel and EPM which would be only slightly affected by even acidic contents (limited to HCL and, HNO_3 of maximum concentration 0.1N) during the short period that the package would be in the public domain following an accident (HAC).

2.2.3 Effects of Radiation on Materials

The contents of the package emit one or all of alpha, beta, gamma and neutron radiation. Austenitic stainless steel, lead and cork were chosen for the construction of the package

because they are durable materials that are able to withstand the damaging effects from the radiation.

The EPM O-ring seals fitted to the containment system are the only material on which the radiation may have an effect; however it has been shown in Section 4.1 that for the radioactive contents limited according to Section 1.2.2, the maximum dose to the containment seal is << 10^4 Gy (10^6 rad) whereas no change of physical properties of the EPM containment seal is expected at radiation levels up to 10^4 Gy (10^6 rad). These seals are required to be replaced annually at maintenance (Section 8.2).

Table 2-9 Material Properties for Grade 304L Stainless Steel									
Stainless Steel ASTM A240/A240m and ASTM A479/A479m Grade 304L Material Properties				Values at Different Temperatures					
				-40°C	20°C	149°C	204°C	232°C	260°C
				-40°F	68°F	300°F	400°F	450°F	500°F
				a	b	c	d	e	d
Design Stress Intensity	S_m	MN/m²	f	115.1	115.1	115.1	108.9	105.4	102.0
		ksi	g	16.7	16.7	16.7	15.8	15.3	14.8
Yield Strength	S_y	MN/m²	f	172.3	172.3	132.4	120.7	116.5	113.1
		ksi	h	25.0	25.0	19.2	17.5	16.9	16.4
Tensile Strength	S_u	MN/m²	f	483	483	422	405	401	396
		ksi	i	70	70	61.2	58.7	58.1	57.5
Coefficient of Thermal Expansion (Mean)	a_m	10^{-6} m/m °C	f	14.7	15.3	16.6	17.1	17.3	17.5
		10^{-6} in/in °F	j	8.2	8.5	9.2	9.5	9.6	9.7
Thermal Conductivity	k	W/m K	f	13.9	14.9	17.0	18.0	18.5	18.9
		BTU/h ft °F	k	8.0	8.6	9.8	10.4	10.7	10.9
Modulus of Elasticity	E	GN/m²	f	198.4	195.0	186.0	182.6	180.2	177.8
		Mpsi	l	28.8	28.3	27	26.5	26.2	25.8
Fatigue Strength @ 10^6 and 10^4 cycles	S_a	MN/m²	f	195.1 and 441					
		ksi	m	28.3 and 64					

Some values are extrapolated or interpolated

a -40°F is the lowest temperature to be considered for packaging. Data at 40°F is extrapolated where not given specifically in the ASME code. Note that the packaging is required to remain leak tight at 40°F under no loading; however, the specified structural loadings need not be considered below -20°F.

b These data are used for calculations at normal ambient temperature

c The temperature for this data is close to the maximum NCT temperature

d These data are used to calculate the data at the maximum HAC

e This data is interpolated from 400°F and 500°F

f Calculated from the data in imperial units

g ASME Section II (2001), Part D, Subpart 2 [2.14], Table 2A (pages 312-315)

h ASME Section II (2001), Part D, Subpart 2 [2.14], Table Y-1 (pages 552-555)

i ASME Section II (2001), Part D, Subpart 2 [2.14], Table U (pages 450-451)j

k ASME Section II (2001), Part D, Subpart 2 [2.14], Table TE-1 18 Cr-8 Ni (page 651 Group 3)

l ASME Section II (2001), Part D, Subpart 2 [2.14], Table TM-1 Material Group G - Austenitic steels (page 671)

m ASME Section III (2001), Appendix I [2.10], Table I-9.1 Line I-9.2.1 (page 4)

Table 2-10 Mechanical Properties of SA-320/A320 Grade L43 Bolting Steel											
Properties				Values at Different Temperatures							
				-40°C	-30 °C	25 °C	40 °C	65 °C	100 °C	120 °C	150 °C
				-40°F	-22	77	104	149	212	248	302
				a							
Design Stress Intensity	S_m	MN/m²	1	241	241	241	241	235	226	224	220
		ksi		34.95	34.95	34.95	34.95	34.1	32.8	32.5	31.9
Yield Strength	S_y	MN/m²	2	723	723	723	723	704	678	671	660
		ksi		104.9	104.9	104.9	104.9	102.1	98.3	97.3	95.7
Tensile Strength	S_u	MN/m²	3	860	860	860	860	860	860	860	860
		ksi		124.7	124.7	124.7	124.7	124.7	124.7	124.7	124.7
Coefficient of Thermal Expansion (Mean)	a_m	10^{-6} m/m °C	4	10.9	11.0	11.6	11.7	11.9	12.1	12.2	12.2
		10^{-6} in/in °F		6.06	6.1	6.4	6.5	6.6	6.7	6.8	6.8
Modulus of Elasticity	E	GN/m²	5	195	194	191	190	189	187	186	184
		Mpsi		28.3	28.1	27.7	27.6	27.4	27.1	27.0	26.7

1 ASME Code, Section II, Part D, Table 4 [2.14]
2 In accordance with ASME code, Section II, Part D, Table 4 [2.14] general note (A), the yield strength is equal to 3 times the allowable stress value S_m
3 Minimum tensile strength from ASME code, Section II part D, table 4 [2.14]
4 ASME Code Section II, Part D, Table TM-1, Material Group G [2.14]
5 ASME Code Section II, Part D, Table TE-1, Group 1, Coefficient B (mean from 70°F) [2.14]
6 Values in italics are calculated using linear interpolation or linear extrapolation.

Table 2-11 Mechanical Properties of Lead Shielding			
Density (kg/m³)	Modulus of Elasticity (GPa)	Poisson's Ratio	Mean Coef. of Thermal Expansion (m/m/°C x 10^{-6})
11680	16.1	0.44	29

Table 2.12 Average compressive Modulus of Elasticity and Compressive Strength at 10% Relative Deformation for Cork at each Test Temperature		
Test Temperature (^{o}C)	Compressive Modulus of Elasticity E (MPa)	Compressive Strength at 10% relative deformation (MPa)
- 29	23.4	1.60
20	15.0	0.57
100	4.6	0.34

Table 2-13 Summary of Material Interactions

	Contents	Stainless Steel Insert	Tungsten shielding insert	Stainless steel	EPM O-rings	O-ring lubricant	Lead	Cork	Cork sealant	Fuse plug alloy	Nitrile lid seal	Thread lubricant
Contents		NH	NH	H	H	H						
Stainless steel Insert				NH								
Tungsten shielding insert				NH								
Stainless steel					NH	NH	NH	H	NH	NH	NH	NH
EPM O-rings						NH						
O-ring lubricant												
Lead												
Cork									NH	H		
Cork sealant										NH		NH
Fuse plug alloy												NH
Nitrile lid seal												

N = NCT, H = HAC

2.3 Fabrication and Examination

2.3.1 Fabrication

All work performed in the fabrication of the 3979A is required to be carried out under an NRC approved quality assurance program. The containment system shall be fabricated in accordance with ASME Section III, Division 1 sub section NB [2.10]. All materials used for fabrication will meet the permitted requirements of this code.

All welding shall be carried out in accordance with the requirement of ASME IX [2.11] using the GTAW (TIG) process. All the consumables used in the process meet the requirements of

ASME III Division 1, subsection NB-2400 [2.10]. All welds shall be carried out under a Weld Specification Procedure (WPS). The status of each weld as either a qualified or non qualified weld has been defined on the licensing drawings. All qualified welds shall be carried out by welders holding a valid qualification in accordance with the appropriate parts of ASME section IX [2.11].

The lead used shall be 4% Sb lead as specified in the drawings (by specification BS 3909/2 [2.2]). It shall be cast using standard industry practices. The outer cork shall be supplied with a certificate of conformity to demonstrate it meets the required specifications. The machined cork shall be supplied with a certificate of conformity and marked with a unique identification number which will match it to the corresponding keg.

Any consumables used during manufacture such as thread inserts and O-rings shall be procured from commercial suppliers that are approved to a level commensurate with the safety functions of the consumable purchased.

2.3.2 Examination

All examinations shall be carried out under the scope of an NRC approved quality assurance program. Examinations shall be carried out on materials, components and finished assemblies throughout the manufacturing process. These tests will assure that the manufactured article meets the critical characteristics to allow the safe transport of radioactive material. All tests shall be carried out to approved procedures, with calibrated equipment. The records of the tests will be maintained with the manufacturing records for each package.

The examinations required during manufacture are described below:

Material Tests

Material examinations, from a sample of the stock material, used to fabricate the containment vessel lid top and the flange/cavity are required. These integrity tests will be an Ultrasonic straight beam test to ASME III Division 1 NB 2532.1 [2.10] and a liquid penetrant test to ASME III Division 1 NB 2546 [2.10].

Integrity tests of the stock material used to manufacture the CV lid top and flange/cavity wall are required, using a helium leak test. The test shall have a maximum permissible leakage rate of 1×10^{-7} ref-cm^3/s.

A specimen of the lead used as the shield is required to be tested by the manufacturer to assure that it meets the required chemical composition as defined in BS 3909/2 [2.2].

For the cork the supplier is required to provide a Certificate of Conformance to confirm that the composition and specified properties listed in 0C-6043.

Fabrication Tests and Examinations

Once the lid and flange are machined a helium leak test is required to be carried out in accordance with ANSI N14.5 [2.12]. This leak test is required to demonstrate that the leak rate of the machined items is less than or equal to 1 x 10^{-7} ref-cm^3/s. No additional examinations are required for items which are not primary containment items.

All welds are required to be subjected to non-destructive visual and liquid penetrant examinations in accordance with ASME Section V [2.15].

All components and assemblies are required to be visually inspected and the dimensions measured using calibrated equipment to assure compliance with the dimensions shown on the general arrangement drawings. The weight of the finished containment vessel and fully assembled package are required to be measured to ensure the weight requirements are met.

Acceptance Tests

On completion of manufacture the containment vessel closures are required to be leak tested in accordance with ANSI 14.5 [2.12] to demonstrate the leak rate is less than or equal to 1 x 10^{-7} ref-cm^3/s.

The completed containment vessels are required to be pressure tested to a maximum pressure of 13.5 barg which meets both the requirement of 10 CFR 71.85 (b) and ASME Section III sub section NB 6000 [2.10].

2.4 General Requirements for All Packages [71.43]

2.4.1 Minimum Package Size [71.43 (a)]

10 CFR 71.43(a) states: "The smallest overall dimension of a package may not be less than 10 cm (4 in)." The Keg 3979 has an outer diameter of 424 mm (16.69 in.) and a length of 483 mm (19.02 in.). Therefore, the smallest overall dimension of the package is not less than 10 cm (4 in), as required in 10 CFR 71.

2.4.2 Tamper Indicating Feature [71.43 (b)]

10 CFR 71.43(b) states: "The outside of a package must incorporate a feature, such as a seal, that is not readily breakable and that, while intact, would be evidence that the package has not been opened by unauthorized persons."

The tamper-proof feature of Keg 3979 is the hole provided in each closure stud which enables a wire security seal to be fitted through the studs. In addition, the keg closure is provided with a lock pin that may be fitted with a padlock. Therefore, the package can be fitted with a tamper indicating seal to provide indication that the package has not been opened.

2.4.3 Positive Closure [71.43 (c)]

10 CFR 71.43(c) states: "Each package must include a containment system securely closed by a positive fastening device that cannot be opened unintentionally or by a pressure that may arise within the package." The lid of the containment vessel is held in place using 8 screws/bolts which are screwed into the CV flange. The CV closure screws are tightened or released using appropriate tools to the torque prescribed in the operating requirements (Section 7.1). The keg lid is attached by permanently fitted studs and secured by nuts (see Figure 1-1a). Therefore, the package cannot be inadvertently opened.

The package cannot be opened unintentionally by any pressure that may arise within the package. The information presented in Section 2.6.3 shows that the containment vessels remain closed under the design pressure (which bounds the maximum internal pressure that can be generated). The keg lid will remain in place under any pressure that may arise within the package. This has been demonstrated by the thermal test reported in Section 2.7.4.

2.5 Lifting and Tie-Down Standards for All Packages

2.5.1 Lifting Devices [71.45 (a)]

The package itself has no structural devices designed for lifting the package therefore it is anticipated that the package will be man handled into position and lifted on a truck tail lift or lifted using a fork lift truck with drum clamps fitted. These methods of handling do not stress the structure of the package.

2.5.2 Tie-Down Devices [71.45 (b)]

The SAFKEG has no specifically designed tie-down devices. The normal method of securing the package during transport is expected to be by the use of dunnage, cargo nets or an equivalent system that envelope the package without being attached to it: such a system cannot stress the structure of the package. The package may be secured in either the horizontal or vertical position. Testing of both package positions during the steady state thermal test as described in CTR 2009/1 has demonstrated that either position is safe.

2.6 Normal Conditions of Transport

2.6.1 Heat [71.71 (c)(1)]

According to 10CFR 71.71 (c) (1), the package must be evaluated in an ambient temperature of 38°C, in still air and insolation. Under these conditions the maximum temperature and pressure generated have been calculated and discussed in Section 2.6.1.1. These temperatures and pressures have then been used to determine the differential thermal expansion in Section 2.6.1.2 and therefore the stresses present in the containment vessel. The calculated stresses are then used to determine if the containment vessel meets the structural design criteria.

2.6.1.1 Summary of Pressures and Temperatures

The calculated maximum temperatures in the containment vessel and keg with maximum heat load of 10W under NCT are shown in Section 3, Table 3-2. The maximum temperature for the containment vessel is 116°C. The stress calculations were carried out assuming a temperature of 110°C which is very close to the calculated maximum temperature.

The upper pressure experienced by the containment vessel is 700 kPa gauge pressure. This value has been used in the structural evaluation.

The heat load for liquid contents is limited to 5W for which the calculated maximum temperature of the CV under NCT is 91°C (Section 3.1.3, Table 3-1). There is therefore no pressure increase due to the vapour pressure of the liquid contents (the liquid contents are aqueous with a boiling point of 100°C).

2.6.1.2 Differential Thermal Expansion

The finite element analysis model investigated the deformations caused within the containment vessel as a result of the differing expansion rates of the lead shielding and the stainless steel cladding. The results of the analysis included the effect of differential thermal expansion in both the radial and longitudinal directions. The results of analysis indicate that the base of the body was distorted due to the thermal expansion of the lead being greater than that of steel. The expansion of the lead also caused the internal web of the lid to bend upwards.

The 3979 keg is designed to have a 3 mm clearance between the cork and containment vessel and another 9 mm clearance between the cork and the keg lid. As the cork is free standing within the keg liner this allows movement of the top cork of up to 9 mm and hence expansion of the containment vessel of 12 mm. The radial expansion of 0.067 mm (0,003") calculated for the containment vessel is adequately covered by this gap.

The model has assumed no gap is present between the lead and the stainless steel and determined the stresses within the containment vessel boundary caused as a result of the differing thermal expansion rates. The results of the stress calculations are discussed in section 2.6.1.3.

2.6.1.3 Stress Calculations

In order to determine the effect of heat on the containment vessel a finite element analysis was carried out as documented in the Vectra Report No. 925-3272/R1 (Section 2.12.2). The model was applied with a uniform temperature of 110°C across the containment vessel and an internal gauge pressure of 700 kPa.

Stresses within the containment vessel boundary were calculated at the points shown in Figure 2-1. From these calculations the maximum stress intensities were determined and

presented in Table 2-14. The maximum stress of 166 MPa occurred in the top corner of the flange and was due to the differential thermal expansion of the lead and steel. The stresses in the bolts were calculated and are presented in Table 2-15.

A buckling evaluation was also carried out using the FEA model, as described in the Vectra report No 925-3272/R1. The results of the calculation are presented in Table 2-16. The stresses used for the calculations were taken from point C4 in Figure 2-1, which is mid-way along the length of the inner shell of the containment vessel. Where one of the components was tensile in the finite element analysis it should be given a value of 0 Pa however in order to avoid zero errors it was given a very small positive value in the buckling calculation.

In order to determine the effect of repeated cycles of thermal loading on the containment vessel, fatigue calculations have been carried out in accordance with Section 2.1.2.4 and are detailed in the Vectra Report 925-3272/R1 (Section 2.12.2). The values calculated are given in Table 2-17.

2.6.1.4 Comparison with Allowable Stress

The maximum stresses calculated were compared against the allowable stresses and the design margin calculated as detailed in Section 2.1.2.2. All the design margins are greater than the design criteria of 0 as shown in Table 2-14, therefore, the containment vessel satisfies the requirements of Regulatory Guide 7.6 [2.4]. The lowest design margin calculated is 0.32 which is due to the bearing stress under the bolts.

The stresses calculated in the bolts have been compared against the allowable stresses and the design margin has been calculated as described in Section 2.1.2.2. All the design margins are greater than 0 as shown in Table 2-15. Therefore the containment vessel bolts satisfy the requirements of Regulatory Guide 7.6 [2.4].

The buckling stresses were compared against the allowable stresses as detailed in Section 2.1.2.3. As all of the stress components were tensile in this case, the design margin is effectively infinite, hence the containment vessel satisfies the requirements of Regulatory Guide 7.6 [2.4] for buckling as shown in Table 2-16.

The fatigue evaluation is given in Table 2-17. As the value of the maximum alternating stress in the containment vessel was below the fatigue threshold, the design margin is effectively infinite. Hence the containment vessel satisfies the requirements of Regulatory Guide 7.6 [2.4] for fatigue.

Table 2-14 Containment Vessel Stress Summary under Heat Conditions

NCT Case ID	Description	Stress Type	Maximum Stress Intensity (MPa)	Stress Location	Allowable stress intensity (MPa)	Minimum Design Margin
1	Heat	P_m	71.5	C10	115	0.61
		P_m+P_b	109	C13	173	0.59
		P_m+P_b+Q	166	C11	345	1.08
		Bearing	100	Under bolts	132	0.32

Table 2-15 Containment Vessel Bolts Stress Analysis under Heat Conditions

NCT Case ID	Description	Stress Type	Maximum stress (MPa)	Allowable stress intensity (MPa)	Minimum design margin
1	Heat	Average Shear	3.32	268	79
		Average Stress	135	448	2.31
		Max Stress	149	672	3.51

Table 2-16 Containment Vessel Buckling Calculations Under Heat Conditions

NCT Case ID	Description	Stress (MPa)			Design Margin
		Axial Compression	Hoop Compression	In-plane shear	
1	Heat	0	0	0.07	4.3×10^5

Table 2-17 Containment Vessel Fatigue Evaluation under Heat Conditions

Maximum alternating stress	Required No of cycles	Cycles to failure	Design Margin
128	10000	$> 10^{11}$	n/a

2.6.2 Cold [71.71 (c) (2)]

10CFR 71.71 (c) (2) requires that the package performance is evaluated at an ambient temperature of -40°C in still air and with no insolation. This should be considered along with no internal heat load and the minimum internal pressure.

As discussed in Section 3, at -40°C ambient temperature the package has a minimum internal pressure of 0 kPa and it is assumed the entire package temperature is -40°C. The stresses were calculated in the containment vessel using the FEA analysis described in the Vectra Report 925-3272/R1 (Section 2.12.2). It was assumed that the external pressure was 100 kPa and the internal pressure was 0 kPa absolute, so the internal gauge pressure applied to the model was -100 kPa.

The effect of temperature on the components of the containment vessel was determined with the model, as described in the Vectra Report 925-3272/R1 (Section 2.12.2]. Stresses within the containment vessel boundary were calculated at the points shown in Figure 2-1. From these calculations the maximum stress intensities were determined and presented in Table 2-18. The maximum stresses calculated were compared with the allowable stresses and the design margin calculated as detailed in Section 2.1.2.2. All the design margins are greater than 0 as shown in Table 2-18 therefore the containment vessel satisfies the requirements of Regulatory Guide 7.6 [2.4].

The stresses in the bolts were calculated and are presented in Table 2-19. These stresses have been compared against the allowable stresses and the design margin has been calculated as described in Section 2.1.2.2. All the design margins are greater than 0 as shown in Table 2-19. Therefore the containment vessel bolts satisfy the requirements of Regulatory Guide 7.6 [2.4].

A buckling evaluation was also carried out using the FEA model, as described in the Vectra report No 925-3272/R1. The results of the calculation are presented in Table 2-20. The stresses used for the calculations were taken from point C4 in Figure 2-1, which is mid-way along the length of the inner shell of the containment vessel. Where one of the components was tensile in the finite element analysis it should be given a value of 0 Pa however in order to avoid zero errors it was given a very small positive value in the buckling calculation.

The buckling stresses were compared against the allowable stresses as detailed in Section 2.1.2.3. The design margin is greater than 0 hence the containment vessel satisfies the requirements of Regulatory Guide 7.6 [2.4] for buckling as shown in Table 2-20.

In order to determine the effect of repeated cycles of thermal loading on the containment vessel, fatigue calculations have been carried out in accordance with Section 2.1.2.4 and are detailed in the Vectra Report 925-3272/R1 (Section 2.12.2). The values calculated are given in Table 2-21. As the value of the maximum alternating stress in the containment vessel was below the fatigue threshold, the design margin is effectively infinite. Hence the containment vessel satisfies the requirements of Regulatory Guide 7.6 [2.4] for fatigue.

Brittle fracture has not been considered because the containment vessel and keg are fabricated from austenitic stainless steel which is ductile even and low temperatures and therefore not susceptible to brittle fracture [2.4].

Table 2-18 Containment Vessel Stress Summary under Cold Conditions						
NCT Case ID	Description	Stress Type	Maximum Stress Intensity (MPa)	Stress Location	Allowable stress intensity (MPa)	Minimum Design Margin
2	Cold	P_m	50.3	C2	115	1.29
		P_m+P_b	96.1	C2	173	0.80
		P_m+P_b+Q	92.5	C4	345	2.73
		Bearing	61.9	Under bolts	172	1.78

Table 2-19 Containment Vessel Bolts Stress Analysis under Cold Conditions					
NCT Case ID	Description	Stress Type	Maximum stress (MPa)	Allowable stress intensity (MPa)	Minimum design margin
2	Cold	Average Shear	1.32	289	218
		Average Stress	83.4	482	4.77
		Max Stress	149	723	3.85

Table 2-20 Containment Vessel Buckling Calculations Under Cold Conditions					
NCT Case ID	Description	Stress (MPa)			Design Margin
		Axial Compression	Hoop Compression	In-plane shear	
2	Cold	20.9	37.9	0.46	1.27

Table 2-21 Containment Vessel Fatigue Evaluation under Cold Conditions			
Maximum alternating stress	Required No of cycles	Cycles to failure	Design Margin
66.4	10000	$> 10^{11}$	n/a

2.6.3 Reduced External Pressure [71.71 (c) (3)]

Section 71.71 (c) (3) requires that the package is subjected to a reduced external pressure of 25 kPa absolute. According to Regulatory Guide 7.8 [2.3] the reduced external pressure should be combined with the worst case initial conditions shown in Table 2-1.

To determine the effect of the reduced external pressure with the worst case initial conditions a finite element analysis was carried out on the containment vessel as detailed in the Vectra Report 925-3272/R1 (Section 2.12.2). The analysis was carried out with an ambient temperature of 38°C in still air, with insolation and the maximum decay heat. It was assumed that under these conditions the containment vessel was at a uniform temperature of 110°C. The external pressure was 24.5 kPa with the internal pressure at 800 kPa absolute, so the internal gauge pressure applied to the model was 775.5 kPa.

The stresses were calculated at the points shown in Figure 2-1. From these calculations the maximum stress intensities were determined and presented in Table 2-22. As shown all of the design margins are greater than zero therefore satisfying the requirements of Regulatory Guide 7.6 [2.4].

A stress analysis of the containment vessel closure bolts under reduced external pressure was performed. The axial force from the finite element analysis model was extracted and divided by the bearing area of the bolt heads, to give the average bearing stress and divided by the cross sectional area of the bolts to give the average stress.

The calculated values for average shear, average stress and maximum stress of the closure bolts for the vibration load conditions are summarized in Table 2-23. The design margins are all greater than 0 therefore the bolts satisfy the requirements of Regulatory Guide 7.6 [2.4].

Buckling evaluations of the inner containment shell were carried out in accordance with the requirements of ASME Code Case N-284-2 [2.7] as detailed in Section 2.1.2.3. The stresses used for the calculations were taken from point C4 in Figure 2-1, which is mid-way along the length of the inner shell of the containment vessel. Where one of the components was tensile in the finite element analysis it should be given a value of 0 Pa however in order to avoid zero errors it was given a very small positive value in the buckling calculation.

The calculated stress from the FEA is tensile for the reduced external pressure condition. Therefore the stress is 0 MPa for axial and hoop compression, In-plane shear does have a maximum stress of 0.07. The design margin for the buckling stress was 3.1×10^5 which is greater than 0, therefore satisfying the requirements of Regulatory Guide 7.6 [2.4].

In accordance with Regulatory Guide 7.8 [2.3] regular pressurization loads should be evaluated to determine how they contribute to mechanical fatigue. The fatigue analysis was carried out in accordance with section C.3 in Regulatory Guide 7.6 [2.4]. It was assumed that the containment vessel would undergo approximately 50 cycles/year, for 20 years, which equates to 1000 cycles in its lifetime. This number was multiplied by 10 to give 10000 cycles, providing a safety margin. The maximum alternating stress was calculated as 128 MPa, this figure is below the fatigue threshold meaning that the design margin is effectively infinite with the number of cycles to failure of $>10^{11}$ far in excess of the actual number of cycles.

The results of the calculations resulting from the reduced external pressure have shown that the containment vessel satisfies the allowable design criteria. Reduced external pressure will not cause the permanent deformation of the containment vessel. It will not cause the failure of

the containment vessel boundary or deformation of the bolts therefore it shall not result in any loss or dispersal of the radioactive contents.

Table 2-22 Containment Vessel Stress Summary for Changes to External Pressure

NCT Case ID	Description	Stress Type	Maximum Stress Intensity (MPa)	Stress Location	Allowable stress intensity (MPa)	Minimum Design Margin
3	Reduced External Pressure	P_m	71.7	C10	115	0.60
		P_m+P_b	108	C13	173	0.59
		P_m+P_b+Q	167	C11	345	1.07
		Bearing	100	Under bolts	132	0.32
4	Increased External Pressure	P_m	42.0	C2	115	1.74
		P_m+P_b	81.1	C2	173	1.13
		P_m+P_b+Q	76.7	C4	345	3.50
		Bearing	64.2	Under bolts	172	1.67

Table 2-23 Containment Vessel Bolts Stress Analysis for Changes to External Pressure

NCT Case ID	Description	Stress Type	Maximum stress (MPa)	Allowable stress intensity (MPa)	Minimum design margin
3	Reduced External Pressure	Average Shear	3.29	268	80.5
		Average Stress	135	448	2.31
		Max Stress	116	672	4.75
4	Increased External Pressure	Average Shear	1.2	289	247
		Average Stress	86.9	482	4.54
		Max Stress	119	723	5.08

2.6.4 Increased External Pressure [71.71 (c) (4)]

10 CFR 71.71 (c) (4) requires that the package is subjected to an increased external pressure of 140 kPa absolute. According to Regulatory Guide 7.8 [2.3] the increase in external pressure should be combined with the worst case initial conditions shown in Table 2-1.

To determine the effect of the increased external pressure with the worst case initial conditions a finite element analysis was carried out on the containment vessel as detailed in the Vectra Report 925-3272/R1 (Section 2.12.2). The analysis was carried out with an ambient temperature of -29°C in still air, with zero insolation and zero decay heat. The

external pressure was 140 kPa with the internal pressure at 800 kPa absolute, so the internal gauge pressure applied to the model was -140 kPa. A bolt pre load of 8.12 kN was applied to the bolts at the start of the analysis prior to any other load being applied.

The stresses were calculated at the points shown in Figure 2-1. From these calculations the maximum stress intensities were calculated and are presented in Table 2-22. As shown all of the design margins are greater than zero, therefore satisfying the requirements of Regulatory Guide 7.6 [2.4].

A stress analysis of the containment vessel closure bolts under increased external pressure was performed. The axial force from the finite element analysis model was extracted and divided by the bearing area of the bolt heads, to give the average bearing stress and divided by the cross sectional area of the bolts to give the average stress.

The calculated values for average shear, average stress and maximum stress of the closure bolts for the increased external pressure conditions are summarized in Table 2-23. The design margins are all greater than 0 therefore the bolts satisfy the requirements of Regulatory Guide 7.6 [2.4].

Buckling evaluations of the inner containment shell were carried out in accordance with the requirements of ASME Code Case N-284-2 [2.7] as detailed in Section 2.1.2.3. The stresses used for the calculations were taken from point C4 in Figure 2-1, which is mid-way along the length of the inner shell of the containment vessel. Where one of the components was tensile in the finite element analysis it should be given a value of 0 Pa however in order to avoid zero errors it was given a very small positive value in the buckling calculation.

The calculated stress from the FEA is tensile for the reduced external pressure condition. Therefore the stress is 0 MPa for axial and hoop compression, In-plane shear does have a maximum stress of 0.07. The design margin for the buckling stress was 3.1×10^5 which is greater than 0, therefore satisfying the requirements of Regulatory Guide 7.6 [2.4].

In accordance with Regulatory Guide 7.8 [2.3] regular pressurization loads should be evaluated to determine they contribute to mechanical fatigue. The fatigue analysis was carried out in accordance with Section 2.1.2.4. It was assumed that the containment vessel would undergo approximately 50 cycles/year, for 20 years, which equates to 1000 cycles in its lifetime. This number was multiplied by 10 to give 10000 cycles, providing a safely margin. The maximum alternating stress was calculated as 128 MPa, this figure is below the fatigue threshold meaning that the design margin is effectively infinite with the number of cycles to failure of $>10^{11}$ far in excess of the actual number of cycles.

The results of the calculations for increased external pressure have shown that the containment vessel satisfies the allowable design criteria as defined in Regulatory Guide 7.6 [2.4]. Increased external pressure will not cause the permanent deformation of the containment vessel. It will not cause the failure of the containment vessel boundary or deformation of the bolts therefore it shall not result in any loss or dispersal of the radioactive contents.

2.6.5 Vibration [71.71 (c) (5)]

10 CFR 71.71 (c) (5) requires that the package is subjected to vibration normally incident during transport. The package will be transported by all modes of transport and tied down using cargo nets or a similar system that envelope the package.

Vibration analysis has been carried out using a bounding vertical downward acceleration of 10g. Vibration loading has been applied to the containment vessel in combination with temperature and pressure loadings in accordance with Table 2-1. The stresses in the containment vessel were determined using the finite element model discussed in the appended Vectra Report 925-3272/R1 (Section 2.12.2].

Under the hot vibration conditions, a uniform temperature of 110°C and an internal gauge pressure of 700 kPa have been applied to the containment vessel. Under the cold vibration conditions an ambient temperature of -29°C is applied, along with an internal gauge pressure of -100 kPa to the containment vessel. For both tests a body force was applied to the model which was equivalent to a downward vertical acceleration of 10g. A pre load of 8.12 kN was applied to the bolts at the start of the analysis prior to any other loads being imposed. This corresponds to an applied torque of 10 Nm.

Under these vibration loading conditions the primary membrane (Pm), primary plus bending (Pm+Pb), primary plus secondary (Pm+Pb+Q) and bearing stresses have been evaluated at the locations shown on Figure 2-1. The stress distribution is given in the Vectra Report 925-3272/R1 (Section 2.12.2). The stress distribution is similar to the hot conditions stress calculation, which indicates the stresses are dominated by the thermal stress.

The maximum stress intensities calculated, along with the location of the maximum stress is summarized for each vibration load combination in Table 2-24. Each maximum stress is compared to the allowable stress intensity and a design margin given. All the design margins are greater than 0 therefore the containment vessel satisfies the requirements of Regulatory Guide 7.6 [2.4]. The lowest design margin calculated is 0.59 which is due to primary plus bending stresses on the corner of the lead shielding under hot vibration conditions.

A stress analysis of the containment vessel closure bolts under vibration load conditions was performed. The axial force from the finite element analysis model was extracted and divided by the bearing area of the bolt heads, to give the average bearing stress and divided by the cross sectional area of the bolts to give the average stress.

The calculated values for average shear, average stress and maximum stress of the closure bolts for the vibration load conditions are summarized in Table 2-25. The design margins are all greater than 0 therefore the bolts satisfy the requirements of Regulatory Guide 7.6 [2.4]. The maximum stress is 156 MPa, the maximum average stress is 135 MPa and the maximum average shear is 3.28 MPa: these values occur under the hot vibration conditions.

Buckling evaluations of the inner containment shell were carried out in accordance with the requirements of ASME Code Case N-284-2 [2.7] as detailed in Section 2.1.2.3. The stresses

used for the calculations were taken from point C4 in Figure 2-1, which is mid-way along the length of the inner shell of the containment vessel. Where one of the components was tensile in the finite element analysis it should be given a value of 0, however, in order to avoid zero errors it was given a very small positive value in the buckling calculation.

The maximum calculated buckling stresses are shown in Table 2-26 along with the design margin. The maximum buckling stress of 16.3 MPa was encountered during the cold vibration condition. Table 2-26 shows that all the design margins are greater than 0 therefore the containment vessel will not buckle under an NCT free drop test and satisfies the requirements of Regulatory Guide 7.6 [2.4].

The results of the NCT Vibration structural evaluation show that the containment vessel meets all the applicable stress design criteria. The vibration loads will not result in any permanent deformation of the containment vessel or failure within the containment boundary.

Table 2-24 Containment Vessel Stress Summary for Vibration Loads

NCT Case ID	Description	Stress Type	Maximum Stress Intensity (MPa)	Stress Location	Allowable stress intensity (MPa)	Minimum Design Margin
5	Vibration (hot)	P_m	72	C10	115	0.60
		P_m+P_b	109	C13	173	0.59
		P_m+P_b+Q	168	C11	345	1.06
		Bearing	100	Under bolts	132	0.32
6	Vibration (cold)	P_m	45.8	C7	115	1.51
		P_m+P_b	79.3	C2	173	1.17
		P_m+P_b+Q	77.3	C4	345	3.46
		Bearing	64.2	Under bolts	172	1.67

Table 2-25 Containment Vessel Bolts Stress Analysis under Vibration Load Conditions

NCT Case ID	Description	Stress Type	Maximum stress (MPa)	Allowable stress intensity (MPa)	Minimum design margin
5	Vibration (hot)	Average Shear	3.28	268	80.7
		Average Stress	135	448	2.31
		Max Stress	156	672	3.51
6	Vibration (cold)	Average Shear	1.08	289	268
		Average Stress	86.9	482	4.55

Table 2-25 Containment Vessel Bolts Stress Analysis under Vibration Load Conditions					
NCT Case ID	Description	Stress Type	Maximum stress (MPa)	Allowable stress intensity (MPa)	Minimum design margin
		Max Stress	119	723	5.08

Table 2-26 Containment Vessel Buckling Calculations under Vibration Load Conditions					
NCT Case ID	Description	Stress (MPa)			Design Margin
		Axial Compression	Hoop Compression	In-plane shear	
5	Vibration (hot)	0	0	0.06	4.3×10^5
6	Vibration (cold)	15.0	16.3	0.42	4.26

2.6.6 Water Spray [71.71 (c) (6)]

10 CFR 71.71 (c) (6) requires that a package must be subjected to a water spray test that simulates exposure to rainfall of approximately 5 cm/hour for at least 1 hour. However the package was not subjected to a water spray test. This is because all materials both inside and out are made from materials that are water resistant. The lid of the keg is fitted with an O-ring seal for weather protection which would aid in the prevention of water entry due to water spray (rain). Therefore the water spray test would have no effect on the structural design of the package or its components and has not been performed during the regulatory tests.

2.6.7 Free Drop [71.71 (c) (7)]

10 CFR 71.71 (c) (7) requires that a package of less than 5,000 kg is subjected to a free drop test from a distance of 1.2 m onto an essentially unyielding, horizontal surface, striking in a position for which the maximum damage is expected.

The package was evaluated in three different drop orientations as shown in Figure 2-2, in all cases the centre of gravity was over the point of impact. These orientations were considered worst case because previous experience has shown that a drop on the side leads to the highest stresses in the package. A drop on the lid or the top rim of the package may distort the lid and open the seals which would be more likely to cause a loss of containment.

The effect of a free drop test on the package was determined with a series of physical drop tests on a prototype package and a finite element analysis of the containment vessel.

The NCT free drop tests were carried out on a prototype package within the series of NCT and HAC tests, as described in the Croft Report CTR 2009/21, appended in Section 2.12.2. The test package of 61.8 kg mass was dropped 1.2 meters onto a steel target with a mass of 500 kg,

which was located on a thick concrete base. The NCT free drop tests were all carried out at an ambient temperature of 14°C.

In order to determine the effect of testing on the package several modifications were made to the containment vessel, cork and keg. To accommodate the wiring for the test equipment small holes of up to 25 mm were drilled though the center of the containment vessel lid, top cork and keg lid. A drain hole on the side of the keg was enlarged to allow the test equipment wiring to pass through it. Finally two cavities and threaded holes were machined into the containment vessel lid to allow the attachment of the accelerometers. The changes are discussed in more detail in the Croft Report CTR 2009/21 (Section 2.12.2). These changes are would not affect the structural integrity of the package or the test results: if anything they would slightly weaken the integrity causing the tests to have a greater effect on the test package than the actual package.

Aside from minor weight differences and the modifications discussed for testing, the prototype package was identical to the manufactured package.

The drop tests caused minor denting to the bottom and top rim of the 3979 keg. No visible damage or deformation was present on the body of the keg after each of the drop tests. This indicates there would be no significant change in the radiation level. Helium leakage testing was carried out prior to and after the entire test series. The leakage testing demonstrated the containment vessel remained leak tight throughout the test series. The containment vessel bolts did not loosen during the test series.

A detailed analysis of the stress present in the containment vessel during the free drop test was carried out using a finite element model of the containment vessel as described in Vectra Report 925-3272/R1 appended in Section 2.12.2.

The three drop orientations illustrated in Figure 2-2 were modeled under 'hot' and 'cold' conditions as required by Regulatory Guide 7.8 [2.3]. The hot conditions assumed the package experienced the maximum ambient temperature of 38°C, in still air with maximum insolation and decay heat. With these conditions it was assumed that the containment vessel was at a uniform temperature of 110°C. Along with the hot temperature it was assumed that the containment vessel had an internal pressure of 800 kPa. The external pressure was taken as 100 kPa, so the internal gauge pressure was 700 kPa

The cold conditions assumed an ambient temperature of -29°C, in still air with no insolation or decay heat. It has been assumed that the internal pressure is 0 kPa with an external pressure of 100 kPa, so the internal gauge pressure is -100 kPa. The load combinations modeled for the NCT drop tests are outlined in Table 2-1.

A body force was applied to the model which was equivalent to an upward vertical acceleration of 120 g plus an additional factor of 50% to ensure conservatism. This g value exceeds the maximum accelerations measured during the 1.2 meter free drop tests. The measured g values are shown in Table 2-27. A dynamic load factor (DLF) has not been applied to the model because the measured impact pulse duration, as shown in Table 2-27,

lasts between 8.5 and 23 milliseconds. This time is long in comparison to the natural frequency therefore, the DLF is close to unity. Because the accelerations applied to the model exceed those in reality this should include sufficient allowance for the DLF.

For the entire NCT free drop analysis a pre load of 8.12kN was applied to the bolts at the start of the analysis, prior to any other loads being imposed. The bolts were tied to the CV body along the threaded length with the bolt heads free to slide.

Stress calculations were carried out for each free drop load combination. Stress distributions presented in Vectra Report 925-3272/R1 (Section 2.12.2] indicated that the highest stresses were in the outer part of the body resisting thermal expansion. However the drop on the lid caused distortion of the lid due to the tungsten insert impacting the bottom of the lid. The drop on the side was found to cause the body of the containment vessel and tungsten insert to rotate clockwise.

The primary membrane (Pm), primary plus bending (Pm+Pb), primary plus secondary (Pm+Pb+Q) and bearing stresses were evaluated at the locations shown on Figure 2-1, for each of the free drop load combination identified in Table 2-1 (NCT load ids 7 – 12). The maximum stress intensities calculated along with the location of the maximum stress is given for each free drop load combination in Table 2-28. Each maximum stress is compared to the allowable stress intensity and the design margin given. All the design margins are greater than 0 therefore the containment vessel satisfies the requirements of Regulatory Guide 7.6. The lowest design margin calculated is 0.25 which is due to primary plus bending stresses on the bottom corner of the containment boundary when a cold containment vessel undergoes the free drop test on the side. The lowest design margins under the primary membrane stress, primary plus secondary and bearing stresses occur during the free drop onto the side when the containment vessel is under hot conditions.

The calculated values for average shear, average stress and maximum stress of the closure bolts for each free drop condition are summarized in Table 2-29. The design margins for drop conditions are all greater than 0 therefore the bolts satisfy the requirements of Regulatory Guide 7.6 [2.4]. The maximum stress is 150 MPa and the maximum average stress is 137 MPa, both these values occur under hot conditions when the package is dropped onto the side and top corner. The maximum average shear of 6.65 MPa occurs when the package is dropped under hot conditions onto the lid.

Buckling evaluations of the inner containment shell were carried out in accordance with the requirements of ASME Code Case N-284-2 [2.7] as detailed in Section 2.1.2.3, for all the NCT free drop load combinations. The stresses used for the calculations were taken from point C4 in Figure 2-1, which is mid-way along the length of the inner shell of the containment vessel. Where one of the components was tensile in the finite element analysis it should be given a value of 0 Pa however in order to avoid zero errors it was given a very small positive value in the buckling calculation.

The maximum calculated buckling stresses are shown in Table 2-30 along with the design margin. The maximum buckling stress of 33 MPa was encountered during the drop on the

side under cold conditions. Table 2-30 shows that all the design margins are greater than 0 therefore the containment vessel will not buckle under an NCT free drop test and satisfies the requirements of Regulatory Guide 7.6 [2.4].

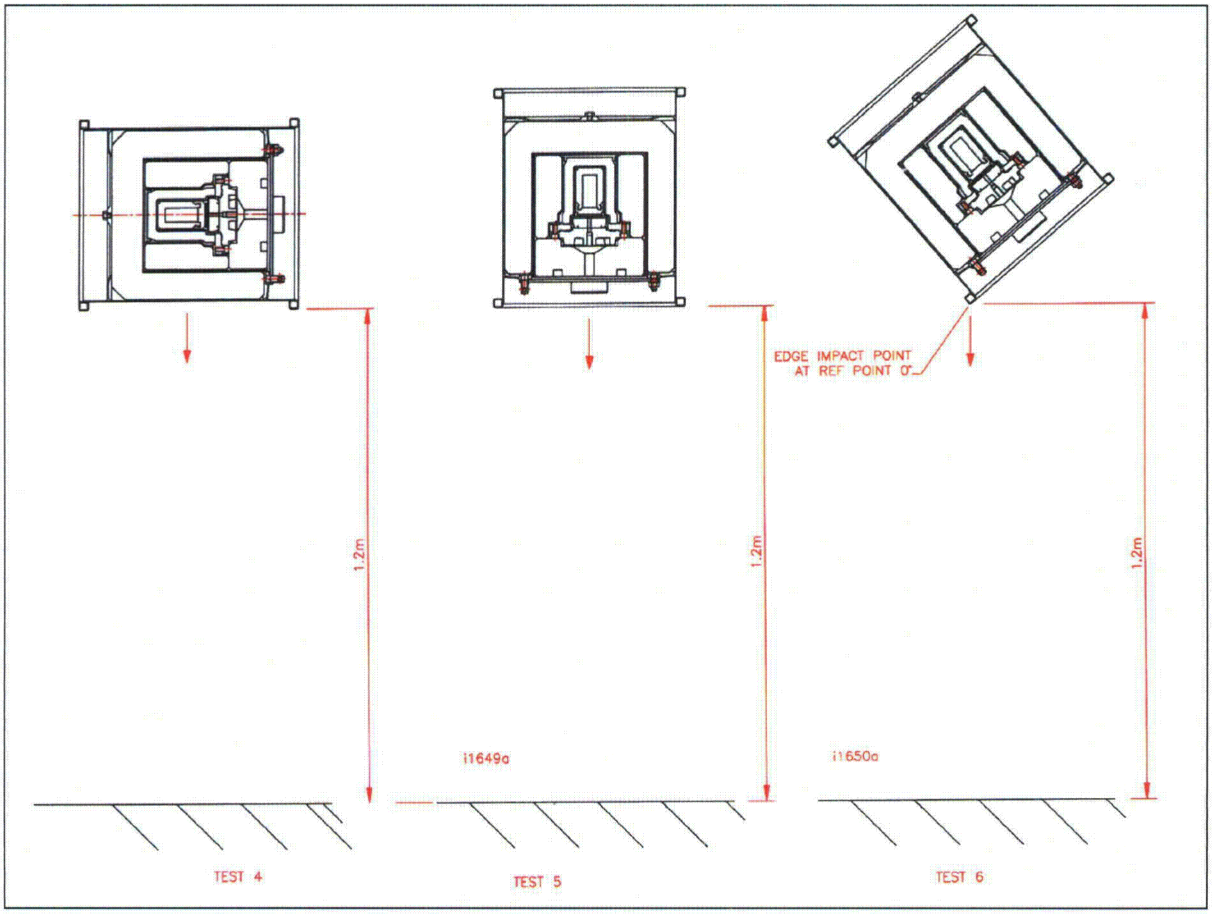

Figure 2-2 NCT Free Drop Impact Orientations

Table 2-27 Acceleration Data Recorded during Drop Tests

Test			Drop on side	Drop on top end	Drop on top rim	Drop on side	Drop on top rim	Drop on top end
Drop Height (m)			1.2	1.2	1.2	10.2	10.2	10.2
Velocity on impact (m/s)			4.85	4.85	4.85	14.15	14.15	14.15
Acceleration response pulse duration (millisecond)			23	20	8.5	21	40	23
Peak Acceleration	Axial (g)	Accelerometer 1	136	56	132	149	156	224
		Accelerometer 2	134	40	103	127	194	170
	Radial (g)	Accelerometer 1	28	66	124	212	84	93
		Accelerometer 2	35	72	139	215	89	96

Table 2-28 NCT Free Drop Stress Summary

NCT Case ID[1]	Description[2]	Stress Type	Maximum Stress Intensity (MPa)	Stress Location[3]	Allowable stress intensity (MPa)	Minimum Design Margin[4]
7	Drop on lid from 1.2m (hot)	P_m	69.8	C10	115	0.65
		P_m+P_b	116	C13	173	0.48
		P_m+P_b+Q	153	C11	345	1.25
		Bearing	101	Under bolts	132	0.32
8	Drop on lid from 1.2m (cold)	P_m	49.7	C2	115	1.31
		P_m+P_b	71.9	C2	173	1.40
		P_m+P_b+Q	116	C7	345	1.97
		Bearing	65.0	Under bolts	172	1.64
9	Drop on side (hot)	P_m	77.9	C10-180	115	0.48
		P_m+P_b	107	C13	173	0.63
		P_m+P_b+Q	186	C11-180	345	0.85
		Bearing	100	Under bolts	132	0.32
10	Drop on side (cold)	P_m	58.7	C2-180	115	0.73
		P_m+P_b	119	C2-180	173	0.25
		P_m+P_b+Q	99.2	C7-180	345	2.48
		Bearing	66.4	Under bolts	172	1.59
11	Drop on	P_m	73.9	C10-180	115	0.56

Table 2-28 NCT Free Drop Stress Summary

NCT Case ID[1]	Description[2]	Stress Type	Maximum Stress Intensity (MPa)	Stress Location[3]	Allowable stress intensity (MPa)	Minimum Design Margin[4]
	corner (hot)	P_m+P_b	112	C13-180	173	0.53
		P_m+P_b+Q	167	C11	345	1.06
		Bearing	102	Under bolts	132	0.30
12	Drop on corner (cold)	P_m	61.5	C7-180	115	0.87
		P_m+P_b	125	C2-180	173	0.38
		P_m+P_b+Q	133	C7-180	345	1.59
		Bearing	66.1	Under bolts	172	1.60

Notes:

1. NCT case IDs are obtained from Table 2-1
2. The orientation of the drop is given in Figure 2-2
3. Stress locations are shown in Figure 2-1. Locations ending -180 are on the opposite side of the vessel to those shown in Figure 2-1, i.e. they are on the side of the vessel closest to the impact with the cork impact limiter.

Table 2-29 Containment Vessel Closure Bolts NCT Free Drop Stress Summary

NCT Case ID[1]	Description[2]	Stress Type	Maximum stress (MPa)	Allowable stress intensity (MPa)	Minimum design margin
7	Drop on lid from 1.2m (hot)	Average Shear	8.29	268	31.4
		Average Stress	136	448	2.30
		Max Stress	151	672	3.46
8	Drop on lid from 1.2m (cold)	Average Shear	5.74	289	49.4
		Average Stress	87.8	482	4.49
		Max Stress	122	723	4.92
9	Drop on side (hot)	Average Shear	5.92	268	44.3
		Average Stress	135	448	2.31
		Max Stress	150	672	3.48
10	Drop on side (cold)	Average Shear	2.61	289	110
		Average Stress	89.7	482	4.38
		Max Stress	121	723	4.96
11	Drop on corner	Average Shear	7.82	268	33.3

	(hot)	Average Stress	138	448	2.26
		Max Stress	150	672	3.48
12	Drop on corner (cold)	Average Shear	9.53	289	29.3
		Average Stress	89.2	482	4.40
		Max Stress	120	723	5.00

Notes:

1. NCT case IDs are obtained from Table 2-1
2. The orientation of the drop is given in Figure 2-2

Table 2-30: NCT Free Drop Buckling Evaluation Summary

NCT Case ID	Description	Stress (MPa)			Design Margin
		Axial Compression	Hoop Compression	In-plane shear	
7	Drop on lid from 1.2m (hot)	0	0	0.05	6.2×10^5
8	Drop on lid from 1.2m (cold)	30.0	24.0	0.21	1.87
9	Drop on side (hot)	5.20	0	0.57	11.7
10	Drop on side (cold)	20.7	34.4	0.30	1.61
11	Drop on corner (hot)	4.14	0	0.11	14.9
12	Drop on corner (cold)	28.8	34.3	0.16	1.51

Notes:

1. NCT case IDs are obtained from Table 2-1
2. The orientation of the drop is given in Figure 2-2

2.6.8 Corner Drop [71.71 (c) (8)]

The requirement of 10 CFR 71.71(c) is that a fiberboard, wood or fissile material rectangular package not exceeding 50 kg (110 lbs) and fiberboard, wood, or fissile material cylindrical packages not exceeding 100 kg (220 lbs) must be subjected to a free drop onto each corner of the rectangular package or onto each quarter of each rim of the cylindrical package. The package must be dropped from a height of 0.3 m onto a flat, essentially unyielding surface.

The Safkeg-LS 3979A package is a robust steel shell package which only suffered minor deformation under both 1.2 m and 10.2 m drop tests: these tests demonstrated that a 0.3m drop would have no significant effect on the package.

2.6.9 Compression [71.71 (c) (9)]

According to 71.71(c) (9), the package must be subjected to a compressive load for a period of 24 hours. This load must be applied uniformly to the top and bottom of the package in the

position in which the package is normally transported. The load applied must be the greater of 5 times the weight of the package or the equivalent of 13 kPa multiplied by the vertically projected area of the package.

The maximum mass of the package is 68 kg therefore 5 times the mass is 340 kg. The vertically projected area of the package is 0.116 m^2 multiplied by 13 kPa this results in a force of 1504 N which is equivalent to a stacking weight of 154 kg. Five times the mass of the package (340 kg) is the greater of the two and was used as the appropriate test weight.

The compression test was carried out on a prototype keg. The test procedure and results are documented in the Croft Report CTR 2009/21 appended in Section 2.12.2.

An empty keg body was subjected to a compressive load of 500 kg which is well in excess of the 340 kg required. The keg was weighed and dimensions taken before and after testing. On completion of the test no part of the keg showed any visually observed evidence of plastic deformation and no changes in dimensions or weight was found. These results show that the package satisfies the compression test criteria.

2.6.10 Penetration [71.71 (c) (10)]

In accordance with section 71.71 (c) (10) a 6 kg steel bar with a diameter of 3.2 cm was dropped from a height of 1m onto the side of a prototype package. The side was considered the most vulnerable area to puncture. The penetration test was carried out during the NCT test series and is described in CTR 2009/21 appended in Section 2.12.2. The test caused a dent of 8.9 mm in depth and 105 mm width in the keg skin but the skin was not punctured or torn.

A dent of 8.9 mm was the largest dent encountered during NCT test conditions, therefore this dent shall provide the basis for the allowable dents during the maintenance and package loading checks described in sections 7 and 8.

2.7 Hypothetical Accident Conditions [71.73]

Section 71.51 requires that when subjected to the HAC tests, the damage caused to the package does not lead to the loss of radioactive material exceeding a total amount of A_2 in one week, or an increase in the external radiation dose above 10 mSv/hr at 1m from the external surface of the package. In order to demonstrate compliance a prototype package was subjected to a series of HAC tests and the stresses in the containment vessel were modeled under the HAC test conditions.

The HAC tests were performed on the prototype keg after the NCT penetration and drop tests. The HAC tests were carried out sequentially in the order of puncture tests, drop tests, additional puncture test and thermal test. Therefore the keg was tested for the cumulative effects of both the NCT and HAC tests. The drop and final puncture tests were carried out with the package at -40°C to take into account any brittle failure. The containment vessel was analyzed under the most unfavorable initial conditions for each individual HAC test condition.

The results of the tests and analysis show that the package and the containment vessel satisfy the design criteria of Regulatory Guide 7.6 [2.4] when subjected to the affects of the HAC tests.

2.7.1 Free Drop [71.73 (c)(1)]

10 CFR 71.73 (c) (1) requires that a specimen undergoes a free drop through a distance of 9 m onto a flat and essentially unyielding, horizontal surface striking in a position for which the maximum damage is expected. In order to fulfill this requirement a prototype package was dropped 10.2 meters in several orientations.

The procedure, sequence of testing and results are documented in the Croft Report CTR 2009/21 appended in Section 2.12.2. A series of 10.2 m drop tests were performed at the Croft Associates, Didcot Test Facility, as part of the NCT and HAC test series. This facility has a test target consisting of a 50 mm thick non alloy structural steel plate. This plate sits at ground level on a one piece, continuously poured, cast in situ concrete block. The mass of the target is 50 tonnes.

The drop height was increased from 9 m to 10.2 m to provide a margin of safety within the test results and to allow the combination of both the NCT and HAC free drop heights. Regulatory Guide 7.8 suggests that the following orientations are considered, top end, top corner, side, bottom end and bottom corner. Previous tests on other Safkeg packages have shown that the highest shock is produced by the side impact, based on the assumption that the minimum measured deformation of the package produces the highest deceleration. On the basis of this evidence, and consideration of the damage mechanisms that could lead to loss of containment or failure to meet other regulatory criteria, the first orientation of the 10.2 m drop test was chosen to be a side impact (with axis horizontal). It was considered that a drop on the bottom or bottom rim of the package would cause less damage than a drop on the lid or the rim of the package. A drop on the lid or rim may distort the lid and open the seals however this would not occur with a drop on the bottom or the bottom corner. Therefore the 10.2 m drop tests were carried out in the order and orientations illustrated in Figure 2-3.

The drop tests were performed with the test package cooled to -40°C. This temperature was considered the most challenging because brittle fracture is more likely at lower temperatures and the cork is also harder at lower temperatures thus providing less impact protection.

The package for the 10.2 m drop consisted of the fully assembled package with some modifications made to allow for test equipment to be fitted and data to be recorded. Several modifications were made to the containment vessel, cork and keg. To accommodate the wiring of the test equipment small holes of up to 25 mm were drilled though the center of the containment vessel lid, top cork and keg lid. A drain hole on the side of the keg was enlarged to allow the test equipment wiring to pass through it. Finally two cavities and threaded holes were machined into the containment vessel lid to allow the attachment of the accelerometers. The changes are discussed in more detail in the Croft Report CTR 2009/21 (Section 2.12.2). These changes would not affect the structural integrity of the package or the test results.

Aside from minor weight differences and modifications discussed for testing, the prototype package will be identical to the manufactured package. The test package was loaded with the 12 x 65 tungsten insert filled with 42 g (0.09 lb) of lead shot, to simulate the maximum permissible mass of contents.

Prior to the NCT and HAC test series the package and its components were measured and weighed. The containment vessel was also helium leak tested to ensure it was leak tight. On completion of the test series these tests were repeated to determine the damage sustained to the package and if the containment vessel remained leak tight.

Along with the physical tests a stress analysis of the containment vessel under HAC test conditions, was carried out, using a finite element analysis detailed in the Vectra Report 925-3272/R1 (Section 2.12.2). In accordance with Regulatory Guide 7.8 [2.3] each drop orientation was evaluated in combination with the worst case initial conditions. The load conditions used along with each drop test orientation is given in Table 2-2.

Once the load conditions had been applied a body force of 300g was applied to the vessel which was equivalent to the deceleration on impact. This value bounds that measured during the drop tests, with 224 g being the highest measured, as shown in Table 2-27.

The maximum stresses in the containment vessel are calculated and shown to satisfy the requirements of ASME Section III Div 3 [2.6] for bearing stress and bolt stress and satisfying Regulatory Guide 7.6 for all other stresses. In addition the containment vessel inner shell was evaluated for buckling in accordance with the requirements of ASME Code Case N-284-2 [2.7].

The results of each drop test and stress analysis are given in the following sections.

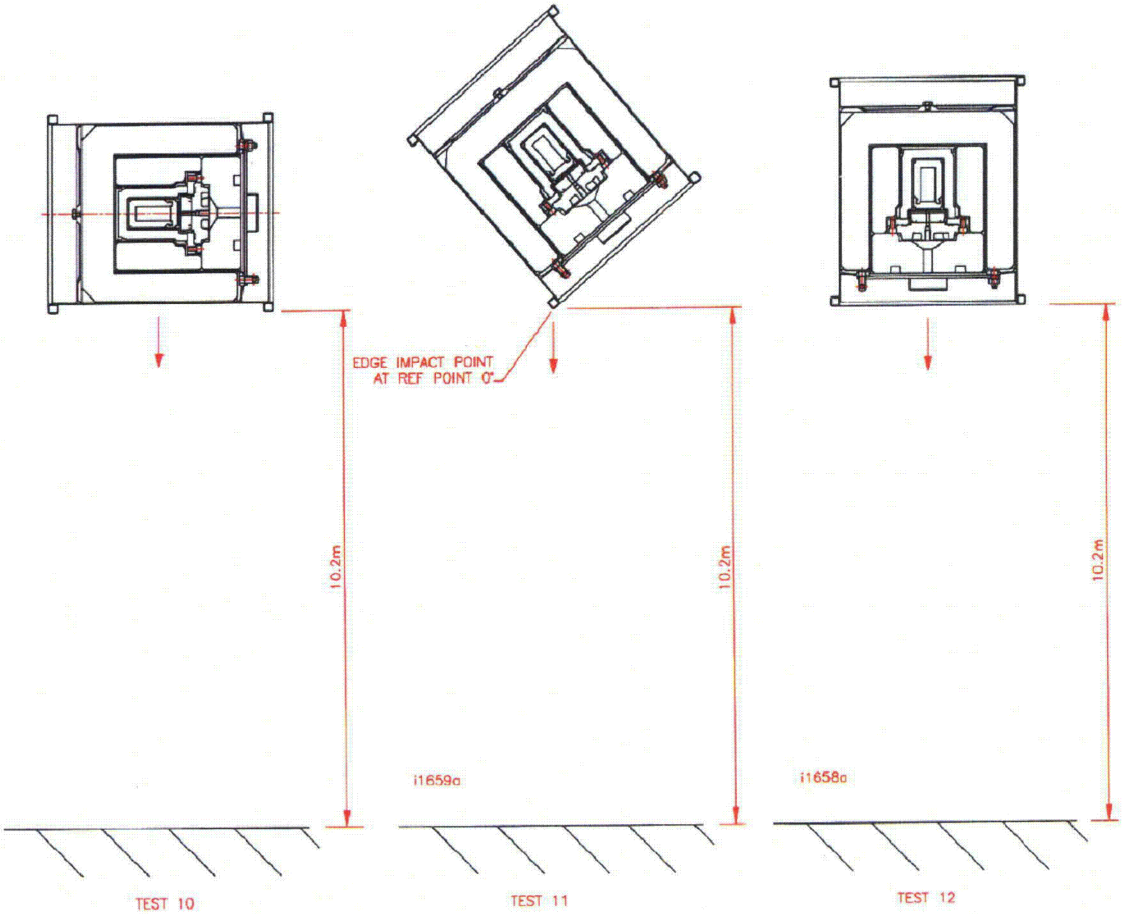

Figure 2-3 HAC Free Drop Impact Orientations

2.7.1.1 End Drop

The package was evaluated for a 10.2 m end drop occurring on the top of the package. This orientation is the worst case end drop because a drop on the lid may distort the lid and open the seals however this would not occur with a drop on the bottom. Testing of a prototype established the effect on the package along with a structural analysis determining the effect on the containment vessel.

Package Test

As described in Section 2.7.1. the prototype test package was cooled to -40°C and dropped onto its side, top corner and then the top end with damage from each drop accumulating for the next test. The end drop is described in the appended report CTR 2009/21. The package was slung in the correct orientation and dropped onto the test target. The package impacted the target on the top rim bounced and landed on its side.

The maximum g values recorded during the end drop are given in Table 2-27. The accelerations were measured by accelerometers attached to the lid of the containment vessel. The accelerometers logged at 100,000 samples per second. The raw data was filtered using a low pass digital 4th order Butterworth filter with a cut off frequency of 500 Hz. The maximum axial acceleration is 224g and the maximum radial acceleration is 96 g. The acceleration response pulse duration was 23 milliseconds and this was the time taken between the package impacting the target and the kinetic energy equaling the potential energy.

The keg received some minor denting which is discussed in Section 2.7.1.5.

Containment Vessel Evaluation

A detailed analysis of the stress present in the containment vessel during the free drop test was carried out using a finite element model of the containment vessel as described in the Vectra Group report 925-3272/R1(Section 2.12.2).

The end drop was modeled under 'hot' and 'cold' conditions as required by Regulatory Guide 7.8. The hot conditions assumed the package experienced the maximum ambient temperature of 38°C, in still air with maximum insolation and decay heat. With these conditions it was assumed that the containment vessel was at a uniform temperature of 150°C. Along with the hot temperature it was assumed that the containment vessel had an internal pressure of 800 kPa. The external pressure was taken as 100 kPa, so the internal gauge pressure was 700 kPa

The cold conditions assumed an ambient temperature of -29°C, in still air with no insolation or decay heat. It has been assumed that the internal pressure is 0 kPa with an external pressure of 100 kPa, so the internal gauge pressure is -100 kPa. The load combinations modeled for the NCT drop tests are outlined in Table 2-1.

A body force was applied to the model which was equivalent to an upward vertical acceleration of 300 g plus an additional factor of 50% to ensure conservatism. This g value exceeds the maximum accelerations measured during the 10.2 meter free drop tests. The measured g values are shown in Table 2-27. A dynamic load factor (DLF) has not been applied to the model because the measured impact pulse duration, as shown in Table 2-27, lasts between 21 and 40 milliseconds. This time is long in comparison to the natural frequency therefore, the DLF is close to unity. Because the accelerations applied to the model exceed those in reality this should include sufficient allowance for the DLF.

For the entire HAC free drop analysis a pre load of 8.12kN was applied to the bolts at the start of the analysis, prior to any other loads being imposed. The bolts were tied to the CV body along the threaded length with the bolt heads free to slide.

Stress calculations were carried out for both the hot and cold end drop load combinations. Stress distributions presented in VECTRA report 925-3272/R1 (Section 2.12.2] indicated that under the hot and cold conditions the drop on the side causes the inner part of the body to rotate causing the lead shielding to compress. The cold conditions were also found to cause the tungsten insert to rotate.

The primary membrane (Pm), primary plus bending (Pm+Pb) stresses were evaluated at the locations shown on Figure 2-1, for each of the free drop load combination identified in Table 2-2. The maximum stress intensities calculated along with the location of the maximum stress is given for each free drop load combination. Each maximum stress is compared to the allowable stress intensity and the design margin given. All the design margins are greater than 0 therefore the containment vessel satisfies the requirements of Regulatory Guide 7.6. The lowest design margin calculated is 1.36 which is due to primary plus bending stresses on the flange which is located over the corner of the lead shielding.

The calculated values for average shear, average stress and maximum stress of the closure bolts for each free drop condition are summarized in Table 2-32. The design margins for drop condition are all greater than 0 therefore the bolts satisfy the requirements of Regulatory Guide 7.6 [2.4].

Buckling evaluations of the inner containment shell were carried out in accordance with the requirements of ASME Code Case N-284-2 [2.7]. The stresses used for the calculations were taken from point C4 in Figure 2-1, which is mid-way along the length of the inner shell of the containment vessel. Where one of the components was tensile in the finite element analysis it should be given a value of 0 Pa however in order to avoid zero errors it was given a very small positive value in the buckling calculation.

The maximum calculated buckling stresses are shown in along with the design margin. The maximum buckling stress of 45.3 MPa was calculated. Table 2-33 shows that all the design margins are greater than 0 therefore the containment vessel will not buckle under an end drop and satisfies the requirements of Regulatory Guide 7.6 [2.4].

Table 2-31 End Drop Containment Vessel Stress Summary

HAC Case ID	Description	Stress Type	Maximum Stress Intensity (MPa)	Stress Location	Allowable stress intensity (MPa)	Minimum Design Margin
1	Drop on lid from 10.2m (hot)	P_m	103	C9	276	1.68
		P_m+P_b	175	C13	414	1.36
2	Drop on lid from 10.2m (cold)	P_m	78.3	C7	276	2.52
		P_m+P_b	162	C8	414	1.56

Table 2-32 End Drop Containment Vessel Bolt Stress Summary

HAC Case ID	Description	Stress Type	Maximum stress (MPa)	Allowable stress intensity (MPa)	Minimum design margin
1	Drop on lid from 10.2m (hot)	Average Shear	14.1	361	24.6
		Average Stress	152	602	2.95
2	Drop on lid from 10.2m (cold)	Average Shear	8.68	361	40.6
		Average Stress	88.5	602	5.81

Table 2-33 End Drop Containment Vessel Buckling Evaluation

NCT Case ID	Description	Stress (MPa)			Design Margin
		Axial Compression	Hoop Compression	In-plane shear	
7	Drop on lid from 1.2m (hot)	0	0	0.06	9.6×10^5
8	Drop on lid from 1.2m (cold)	45.3	25.6	0.07	1.83

2.7.1.2 Side Drop

The package was evaluated for a 10.2 m side drop. Testing of a prototype established the effect on the package along with a structural analysis determining the effect on the containment vessel.

Package Test

As described in Section 2.7.1, the prototype test package was cooled to -40°C and dropped onto its side, top corner and then the top end with damage from each drop accumulating for the next test. The side drop is described in the appended report CTR 2009/21 (Section 2.12.2). The package was slung in the correct orientation and dropped onto the test target. The package impacted the target with the bottom rim first and then rocked over for the secondary impact to occur on the top rim and came to rest on the side.

The maximum g values recorded during the end drop are given in Table 2-27. The accelerations were measured by accelerometers attached to the lid of the containment vessel. The accelerometers logged at 100,000 samples per second. The raw data was filtered using a low pass digital 4th order Butterworth filter [2.16] with a cut off frequency of 500 Hz. The maximum axial acceleration is 149 g and the maximum radial acceleration is 215 g. The acceleration response pulse duration was 21 milliseconds and this was the time taken between the package impacting the target and the kinetic energy equalling the potential energy.

The keg received some minor denting which is discussed in Section 2.7.1.5.

Containment Vessel Evaluation

A detailed analysis of the stress present in the containment vessel during the free drop test was carried out using a finite element model of the containment vessel as described in the Vectra Group report 925-3272/R1 (Section 2.12]. The commercial finite element code Abaqus/Standard v 6.8 was used for the analysis. A half symmetry model was generated because the geometry and load cases were all symmetric about a vertical plane through the centre of the vessel. The model is described in detail in the Vectra report.

The side drop was modelled under 'hot' and 'cold' conditions as required by Regulatory Guide 7.8. The hot conditions assumed the package experienced the maximum ambient temperature of 38°C, in still air with maximum insolation and decay heat. With these conditions it was assumed that the containment vessel was at a uniform temperature of 150°C. Along with the hot temperature it was assumed that the containment vessel had an internal pressure of 800 kPa. The external pressure was taken as 100 kPa, so the internal gauge pressure was 700 kPa

The cold conditions assumed an ambient temperature of -29°C, in still air with no insolation or decay heat. It has been assumed that the internal pressure is 0 kPa with an external pressure of 100 kPa, so the internal gauge pressure is -100 kPa. The load combinations modelled for the NCT drop tests are outlined in Table 2-1.

A body force was applied to the model which was equivalent to an upward vertical acceleration of 300 g plus an additional factor of 50% to ensure conservatism. This g value exceeds the maximum accelerations measured during the 10.2 meter free drop tests. The measured g values are shown in Table 2-27. A dynamic load factor (DLF) has not

been applied to the model because the measured impact pulse duration, as shown in Table 2-27, lasts between 21 and 40 milliseconds. This time is long in comparison to the natural frequency therefore, the DLF is close to unity. Because the accelerations applied to the model exceed those in reality this should include sufficient allowance for the DLF.

For the entire HAC free drop analysis a pre load of 8.12kN was applied to the bolts at the start of the analysis, prior to any other loads being imposed. The bolts were tied to the CV body along the threaded length with the bolt heads free to slide.

Stress calculations were carried out for both the hot and cold end drop load combinations. Stress distributions presented in VECTRA report 925-3272/R1 (Section 2.12.2] indicated that under the hot and cold conditions the drop on the side causes the inner part of the body to rotate causing the lead shielding to compress. The cold conditions also were found to cause the tungsten insert to rotate.

The primary membrane (Pm), primary plus bending (Pm+Pb) stresses were evaluated at the locations shown on Figure 2-1, for each of the free drop load combination identified in Table 2-2. The maximum stress intensities calculated along with the location of the maximum stress is given for each free drop load combination in. Each maximum stress is compared to the allowable stress intensity and the design margin given. All the design margins are greater than 0 therefore the containment vessel satisfies the requirements of Regulatory Guide 7.6 [2.4]. The lowest design margin calculated is 1.20 which is due to primary plus bending stresses on the flange which is located by the corner of the lead shielding.

The calculated values for average shear, average stress and maximum stress of the closure bolts for each free drop condition are summarized in Table 2-35. The design margins for drop condition are all greater than 0 therefore the bolts satisfy the requirements of Regulatory Guide 7.6 [2.4].

Buckling evaluations of the inner containment shell were carried out in accordance with the requirements of ASME Code Case N-284-2 [2.7]. The stresses used for the calculations were taken from point C4 in Figure 2-1, which is mid-way along the length of the inner shell of the containment vessel. Where one of the components was tensile in the finite element analysis it should be given a value of 0 Pa however in order to avoid zero errors it was given a very small positive value in the buckling calculation.

The maximum calculated buckling stresses are shown in along with the design margin. A maximum buckling stress of 37.6 MPa was calculated. Table 2-36 shows that all the design margins are greater than 0 therefore the containment vessel will not buckle under an end drop and satisfies the requirements of Regulatory Guide 7.6 [2.4].

Table 2-34 Side Drop Containment Vessel Stress Summary

HAC Case ID	Description	Stress Type	Maximum Stress Intensity (MPa)	Stress Location	Allowable stress intensity (MPa)	Minimum Design Margin
3	Drop on side from 9m (hot)	P_m	109	C10-180	276	1.53
		P_m+P_b	188	C10-180	414	1.20
4	Drop on side from 9m (cold)	P_m	79.5	C2-180	276	2.47
		P_m+P_b	167	C2-180	414	1.48

Table 2-35 Side Drop Containment Vessel Bolt Stress Summary

HAC Case ID	Description	Stress Type	Maximum stress (MPa)	Allowable stress intensity (MPa)	Minimum design margin
3	Drop on side from 9m (hot)	Average Shear	8.83	361	39.9
		Average Stress	156	602	2.87
4	Drop on side from 9m (cold)	Average Shear	3.79	361	94.2
		Average Stress	91.0	602	5.62

Table 2-36 Side Drop Containment Vessel Buckling Evaluation

HAC Case ID	Description	Stress (MPa)			Design Margin
		Axial Compression	Hoop Compression	In-plane shear	
3	Drop on side from 9m (hot)	11.9	0	0.81	7.30
4	Drop on side from 9m (cold)	25.0	37.6	0.27	2.421

2.7.1.3 Corner Drop

The package was evaluated for a 10.2 m corner drop occurring on the top of the package. This orientation is considered the worst case corner drop because a drop on the top rim may distort the package lid and open the keg, this however would not occur with a drop on the bottom corner. Testing of a prototype established the effect on the package, with a structural analysis determining the effect on the containment vessel.

Package Test

As described in Section 2.7.1, a prototype test package was cooled to -40°C and dropped onto its side, top corner and then the top end with damage from each drop accumulating for the next test.

The package was slung in the correct orientation, raised to 10.2 m and dropped onto the test target. The package impacted the target on the top rim bounced, spun and landed on its side.

The maximum g values recorded during the corner drop are given in Table 2-27. The accelerations were measured by accelerometers attached to the lid of the containment vessel. The accelerometers logged at 100,000 samples per second. The raw data was filtered using a low pass digital 4th order Butterworth filter [2.16] with a cut off frequency of 500 Hz. The maximum axial acceleration is 194 g and the maximum radial acceleration is 89 g. The acceleration response pulse duration was 40 milliseconds and this was the time taken between the package impacting the target and the kinetic energy equaling the potential energy.

The keg received some minor denting which is discussed in Section 2.7.1.5.

Containment Vessel Evaluation

A detailed analysis of the stress present in the containment vessel during the free drop test was carried out using a finite element model of the containment vessel as described in the Vectra Group report 925-3272/R1 (Section 2.12). The commercial finite element code Abaques/Standard v 6.8 was used for the analysis. A half symmetry model was generated because the geometry and load cases were all symmetric about a vertical plane through the centre of the vessel. The model is described in detail in the Vectra report.

The corner drop was modeled under 'hot' and 'cold' conditions as required by Regulatory Guide 7.8 [2.3]. The hot conditions assumed the package experienced the maximum ambient temperature of 38°C, in still air with maximum insolation and decay heat. With these conditions it was assumed that the containment vessel was at a uniform temperature of 150°C. Along with the hot temperature it was assumed that the containment vessel had an internal pressure of 800 kPa. The external pressure was taken as 100 kPa, so the internal gauge pressure was 700 kPa

The cold conditions assumed an ambient temperature of -29°C, in still air with no insolation or decay heat. It has been assumed that the internal pressure is 0 kPa with an external pressure of 100 kPa, so the internal gauge pressure is -100 kPa. The load combinations modeled for the HAC drop tests are outlined in Table 2-2.

A body force was applied to the model which was equivalent to an upward vertical acceleration of 300 g plus an additional factor of 50% to ensure conservatism. This g value exceeds the maximum accelerations measured during the 10.2 meter free drop tests.

The measured g values are shown in Table 2-27. A dynamic load factor (DLF) has not been applied to the model because the measured impact pulse duration, as shown in Table 2-27, lasts between 8.5 and 40 milliseconds. This time is long in comparison to the natural frequency therefore, the DLF is close to unity. Because the accelerations applied to the model exceed those in reality this should include sufficient allowance for the DLF.

For the entire HAC free drop analysis a pre load of 8.12kN was applied to the bolts at the start of the analysis, prior to any other loads being imposed. The bolts were tied to the CV body along the threaded length with the bolt heads free to slide.

Stress calculations were carried out for both the hot and cold end drop load combinations. Stress distributions presented in VECTRA report 925-3272/R1 (Section 2.12) indicated that under the hot and cold conditions the drop on the side causes the inner part of the body to rotate causing the lead shielding to compress. The cold conditions also were found to cause the tungsten insert to rotate.

The primary membrane (Pm), primary plus bending (Pm+Pb) stresses were evaluated at the locations shown on Figure 2-1, for each of the free drop load combination identified in Table 2-2. The maximum stress intensities calculated along with the location of the maximum stress is given for each corner drop load combination in Table 2-37. Each maximum stress is compared to the allowable stress intensity and the design margin given. All the design margins are greater than 0 therefore the containment vessel satisfies the requirements of Regulatory Guide 7.6. The lowest design margin calculated is 1.40 which is due to primary plus bending stresses on the flange which is located over the corner of the lead shielding.

The calculated values for average shear, average stress and maximum stress of the closure bolts for each free drop condition are summarized in Table 2-38. The design margins for drop condition are all greater than 0 therefore the bolts satisfy the requirements of Regulatory Guide 7.6 [2.4].

Buckling evaluations of the inner containment shell were carried out in accordance with the requirements of ASME Code Case N-284-2 [2.7]. The stresses used for the calculations were taken from point C4 in Figure 2-1, which is mid-way along the length of the inner shell of the containment vessel. Where one of the components was tensile in the finite element analysis it should be given a value of 0 Pa however in order to avoid zero errors it was given a very small positive value in the buckling calculation.

The maximum calculated buckling stresses are shown in Table 2-39 along with the design margin. Table 2-39 shows that all the design margins are greater than 0 therefore the containment vessel will not buckle under a corner drop, satisfying the requirements of Regulatory Guide 7.6 [2.4].

Table 2-37 Corner Drop Containment Vessel Stress Summary						
HAC Case ID	Description	Stress Type	Maximum Stress Intensity (MPa)	Stress Location	Allowable stress intensity (MPa)	Minimum Design Margin
5	Drop on corner from 9m (hot)	P_m	105	C9-180	276	1.63
		P_m+P_b	172	C13-180	414	1.40
6	Drop on corner from 9m (cold)	P_m	79.5	C6-180	276	2.47
		P_m+P_b	156	C7-180	414	1.66

Table 2-38 Corner Drop Containment Vessel Bolt Stress Summary					
HAC Case ID	Description	Stress Type	Maximum stress (MPa)	Allowable stress intensity (MPa)	Minimum design margin
5	Drop on corner from 9m (hot)	Average Shear	14.1	361	24.6
		Average Stress	154	602	2.90
6	Drop on corner from 9m (cold)	Average Shear	8.32	361	42.4
		Average Stress	88.3	602	5.82

Table 2-39 Corner Drop Containment Vessel Buckling Evaluation					
HAC Case ID	Description	Stress (MPa)			Design Margin
		Axial Compression	Hoop Compression	In-plane shear	
5	Drop on corner from 9m (hot)	8.11	0	0.90	11.1
6	Drop on corner from 9m (cold)	43.2	37.0	0.09	2.52

2.7.1.4 Oblique Drops

An oblique drop is considered to produce lower "g"s and less damage to the package as less of the energy of the drop is absorbed in the initial impact. As the package does not have a large length to diameter ratio, increase of impact forces due to slap down cannot occur.

2.7.1.5 Summary of Results

The stress evaluation carried out on the containment vessel indicated that it satisfied all the applicable design criteria, therefore no significant deformation of the containment

vessel or the closure bolts will occur. Testing of a prototype package confirmed that on completion of the NCT and HAC test series the containment vessel remained leak tight and undamaged as described in the Croft Associates report CTR 2009/21. The only damage suffered during the HAC drop tests was to the keg body which is discussed below.

HAC End Drop

The end drop was the final drop in the HAC test series so all the damage from the side drop and drop with the C of G over the top rim was present on the keg prior to the test. The end drop caused minimal damage to the top of the keg however the body of the keg was bellowed beneath the top rim.

HAC Side Drop

As discussed in the report CTR 2009/21 (Section 2.12.2), two HAC side drops were conducted with the first invalidated due to failure of test equipment. This meant that the keg had sustained a dent to the bottom of the keg. On carrying out the second 10.2 m drop test minimal additional damage was caused to the already dented bottom rim. Secondary impact caused minimal denting to the top rim. No damage was caused to the body of the keg.

HAC Corner Drop

The corner drop occurred on completion of the side drop, therefore the bottom rim was dented and the top rim had some very minor dents prior to the corner drop. The primary impact of the top rim with the target caused 12 mm of deformation to the top rim which caused the top skirt to deform. No other damage was caused to the keg.

2.7.2 Crush [71.73 (c)(2)]

The crush test is not required as the package has a density of 1,540 kg/m^3. The calculation of the density of the package is described in CS 2010/11 [Section 2.12.2].

2.7.3 Puncture [71.73 (c)(3)]

10 CFR 71.73 (c) (3) requires that a package is dropped from 1m onto the upper end of a solid, vertical, cylindrical mild steel bar mounted on an essentially unyielding, horizontal surface. The package must be dropped onto the bar in the orientation in which the maximum damage is expected.

In order to fulfill this requirement a prototype package was dropped in the orientations illustrated in Figure 2-4, onto a steel punch with a diameter of 150 mm and 150 mm in length. The test procedure and results of the puncture tests are reported in the report CTR 2009/21 (Section 2.12.2) and summarized in this section.

The first three puncture tests were carried out at ambient temperature prior to the 10.2m drop tests. This is because the HAC drop tests can result in the cork crushing which increases the density. This increase in density causes the increase in the cork crush strength, therefore a puncture test on a damaged package would have less impact than a test on an undamaged package.

The package orientations chosen are illustrated in Figure 2-4. These orientations are those expected to cause the maximum damage to the package. The final puncture test (test 12a) illustrated in Figure 2-4 was carried out with the package at -40°C after the 10.2m drop test series. This test allowed the effects of brittle fracture during the punch test to be assessed. It also ensured that the maximum damage had been caused to the seal area of the containment vessel prior to the thermal test.

The penetration drops on the bottom end and the top rim resulted in minimal damage to the keg. The side penetration drop resulted in a dent of 14.6 mm in depth in the side of the keg. The penetration test carried out at -40°C on the top of the keg bent one of the keg handles. No tearing or penetration of the keg skin was observed.

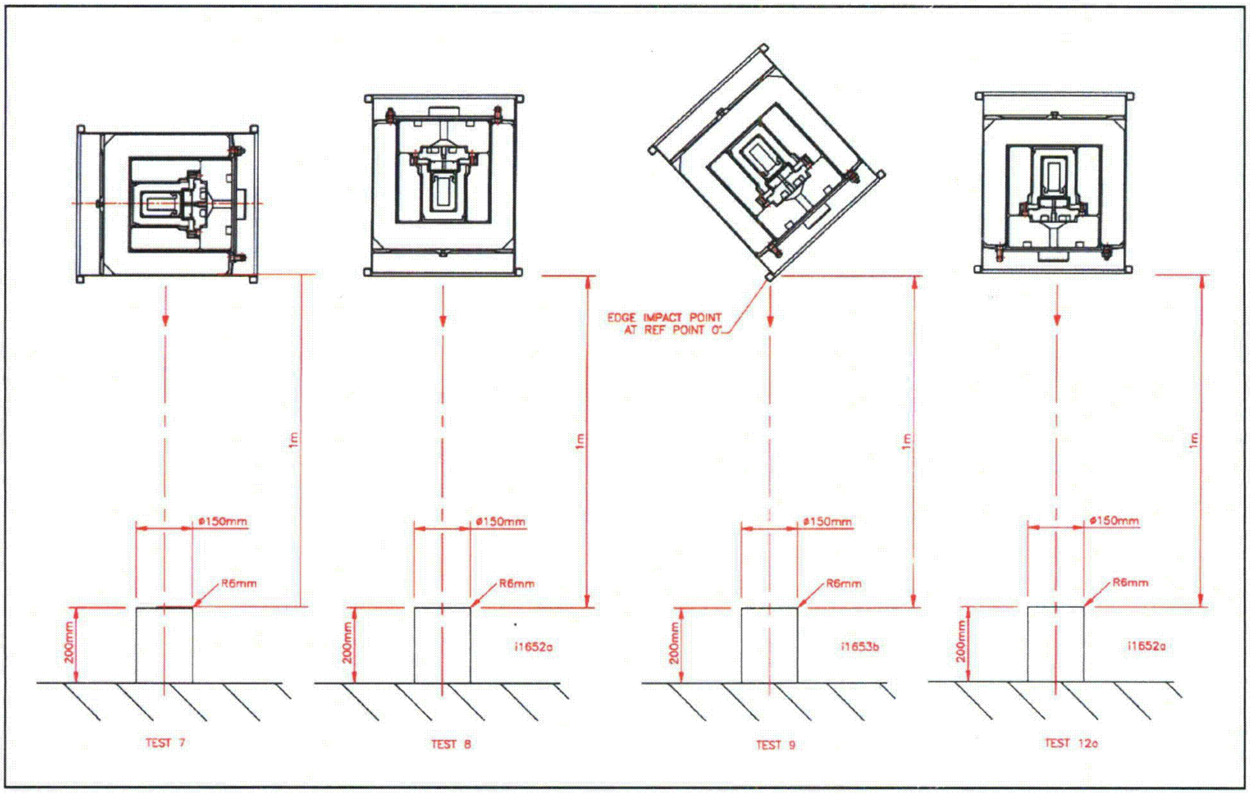

Figure 2-4 Puncture Tests Impact Orientations

2.7.4 Thermal [71.73 (c)(4)]

10 CFR 71.73 (c) (4) requires that the package can withstand a 30 minute fire with an average flame temperature of 800°C. The requirement was demonstrated by carrying out a thermal test on a prototype package after it had undergone a NCT penetration test, NCT drop tests, HAC puncture tests and HAC drop tests. The thermal test has been reported in Section 3.10.2. The analyses of the structural design during the thermal test are presented within this section.

2.7.4.1 Summary of Pressures and Temperatures

During the thermal test the keg skin reaches a maximum temperature similar to that of the fire (800°C). The containment vessel insulated from the full effect of the fire by the cork reaches a maximum temperature of 184°C with a heat load of 10W from the contents. The temperature each component reaches during the HAC thermal test is within it maximum allowable service temperature. The containment vessel maximum internal pressure during the HAC fire is 10 bar or 1000 kPa gauge.

HAC Operating Condition	CV
Assumed Max. Temperature	200°C
Max. Pressure	10 bar (1,000kPa) gauge 11 bar (1,100kPa) abs
Min. Temperature	-40°C
Min. Pressure	-1 bar (-100 kPa) gauge 0 bar (0 kPa) abs

2.7.4.2 Differential Thermal Expansion

The HAC thermal evaluation shows that on initiation and on completion of the fire there is no significant temperature gradient over the lead shielding and the stainless steel cladding. Therefore it is expected that the differential thermal expansion is bounded by the results for the NCT heat test discussed in section 2.6.1.2.

2.7.4.3 Stress Calculations

In accordance with the ASME code the stresses in the package resulting from temperature loading are classified as secondary and need not be evaluated under HAC. The HAC thermal evaluation shows that the thermal gradient of the containment vessel under HAC will be negligible and therefore bounded by the NCT heat test discussed in section 2.6.1.3.

2.7.4.4 Comparison with Allowable Stress

The HAC thermal test stresses are bounded by the stresses in the NCT thermal test. As detailed in Section 2.6.1.4 all the maximum stresses are less than the allowable stresses. Therefore the package meets the requirements under HAC conditions.

2.7.5 Immersion – Fissile Material [71.73 (c)(5)]

The quantity of fissile material to be carried does not depend on water exclusion for criticality safety and therefore this water immersion test is not required,

2.7.6 Immersion – All Packages [71.73 (c)(6)]

71.73(c)(6) requires that a package be subjected to a maximum external pressure due to immersion under 15 m (50 ft) of water (equivalent pressure is 150 kPa gauge).

The maximum pressure differential that could occur under the water immersion condition arises from external pressure of 150 kPa combined with a reduced internal pressure of 0 kPa absolute giving a maximum pressure differential of 150 kPa.

As described in section 2.6.4, the effect of an increased external pressure of 140 kPa with the worst case initial conditions has been determined: the maximum stresses encountered and the minimum design margins are presented in Table 2-22. In order to determine the effect of an external pressure of 150 kPa, the stresses calculated for an external pressure. of 140 kPa have been scaled by 150/140 = 1.07: the results are given in Table 2-40. Scaling of the stresses indicates that the design margins are all greater than zero. This demonstrates the containment vessel will be acceptable under an immersion test.

Table 2-40 Containment Vessel Stress Summary for Immersion

NCT Case ID	Description	Stress Type	Maximum Stress Intensity (MPa)	Stress Location	Allowable stress intensity (MPa)	Minimum Design Margin
4	Increased External Pressure	P_m	44.9	C2	115	1.56
		P_m+P_b	86.8	C2	173	0.99
		P_m+P_b+Q	82.1	C4	345	3.2
		Bearing	68.7	Under bolts	172	1.50

2.7.7 Deep Water Immersion Test (for Type B Packages Containing More than 10^5 A2) [71.61]

Not applicable as the contents are < 10^5A2.

2.7.8 Summary of Damage

The mechanical damage sustained by the package during the NCT and HAC test series is reported in CTR 2009/21 [Section 2.12.2]. The testing was carried out in series with the NCT drop testing, followed by the HAC puncture tests, HAC drop tests and the HAC thermal test.

The NCT drop tests caused minimal denting to the rim of the keg at the points of impact. The puncture tests also caused minimal damage to the keg rim however the side puncture test did cause an indent of 14.6 mm on the side of the keg. The 10.2 meter drop tests caused more severe denting to the top and bottom rims with the drop test over the top rim causing a 12 mm dent and the side drop causing a dent to the bottom rim.

The thermal test was carried out on completion of the HAC drop and puncture tests, to determine if the damaged package was able to withstand the rigors of this test. During the test the package skin reached 800°C however the containment vessel was insulated by the design and to some extent by the damage and only reached a temperature of 110°C which is within the operational range of the containment seal. On completion of the test series the keg and the components were inspected and revealed that the outer cork was charred with the inner and top cork partially charred.

On completion of the test series, examination of the containment vessel found no damage and no change in the measured dimensions. Leak tests carried out prior to and on completion of testing detected no signs of leaks, indicating that the containment vessel remained leak tight throughout the NCT and HAC tests. The examination of the containment vessel (as detailed in report CTR 2009/21, Table 9, page 46, under the table section headed Containment Vessel in rows 12 -15), showed the outside diameter of the CV body at lower and mid height of the body at reference and 90° to reference – all are seen to be close to the nominal diameter of 118.5 mm and there are no significant changes following the drop test program. This demonstrates that there was no distortion of the CV shell due to lead slumping.

2.8 Accident Conditions for Air Transport of Plutonium [71.74]

Not applicable – air shipment of > A2 plutonium is not required.

2.9 Accident Conditions for Fissile Material Packages for Air Transport [1.55(f)]

Not applicable – air shipment of fissile materials is not required.

2.10 Special Form [71.75]

Special form is not claimed for the contents or for any part of the package.

2.11 Fuel Rods

Irradiated fuel rods are not to be carried in this package.

2.12 Appendix

2.12.1 References

[2.1] Title 10, Code of Federal Regulations, Part 71, Office of the Federal Register, Washington D.C.

[2.2] British Standards Institution, *Specification for Ingot Lead for Radiation Shielding* BS 3909/2, 1965

[2.3] Regulatory Guide 7.8, *Load Combinations for the Structural Analysis of Shipping Casks for Radioactive Material*, Revision 1, U.S. Nuclear Regulatory Commission, Office of Standards Development, March 1989.

[2.4] Regulatory Guide 7.6, *Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels*, Revision 1, March 1978.

[2.5] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 3, *Containment Systems for Storage and Transport Packagings of Spent Nuclear Fuel and High Level Radioactive Material and Waste*, 1977 Edition.

[2.6] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 3, *Containment Systems for Storage and Transport Packagings of Spent Nuclear Fuel and High Level Radioactive Material and Waste*, 2001 Edition with Addenda through July 1, 2003.

[2.7] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 1, Code Cases: Nuclear Components, Case N-284-1, *Metal Containment Shell Buckling Design Methods, Class MC*, 2001 Edition with Addenda through July 1, 2003.

[2.8] Regulatory Guide 7.11, *Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of 4 Inch (0.1 m)*, U.S. Nuclear Regulatory Commission, Office of Standards Development, June 1991.

[2.9] NUREG/CR-3854, *Fabrication Criteria for Shipping Containers,* U.S. Nuclear Regulatory Commission, Washington D.C., April 1984.

[2.10] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NB, *Supports*, 2001 Edition with Addenda through July 1, 2003.

[2.11] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI, *Ferrous Material Specification, 2001 Edition with Addenda through July 1, 2003*

[2.12] American National Standards Institute, for Radioactive Material*, Leakage Tests on Packages for Shipment*, ANSI N14.5-1997

[2.13] Parker Hannifin Corporation, *Parker O-ring Handbook*, ORD 5700/USA, 2001.

[2.14] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section II, Part D, *Materials*, 2001 Edition with Addenda through July 1, 2003.

[2.15] American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section V, *Non Destructive Examination*, 2001 Edition, with Addenda through July 1, 2001

[2.16] Vibration, Measurement and Analysis, JD Smith, Butterworth-Heinemann

2.12.2 Supporting Documents

Document Reference	Title
SERCO/TAS/002762/01	Compression Testing of Cork
Vectra, 925-3272/R1	Stress Analysis of Safkeg LS 3979A Containment Vessel
CTR 2009/21	Prototype SAFKEG LS 3979A/0002 NCT and HAC Regulatory Test Report
CS 2010/10	Calculation of the Density of the 3977A Package

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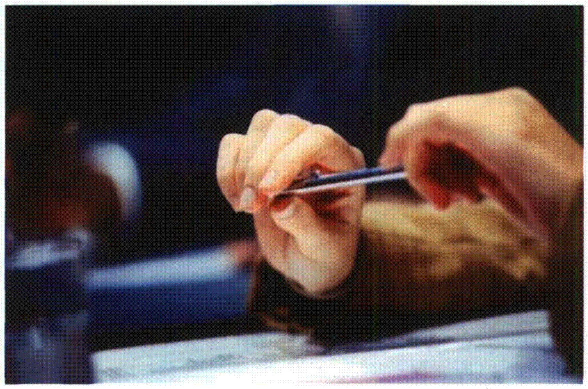

Compression Testing of Cork

Report to Croft Associates Ltd

Your Reference: PO5607TC

Our Reference: SERCO/TAS/002762/01 Issue 1

Date: October 2008

serco

Title Compression Testing of Cork

Customer Croft Associates Ltd

Customer reference PO5607TC

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	Name	Signature	Date
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Executive Summary

This report details the results of a series of compression tests on cork, which have been conducted by Serco Technical and Assurance Services (TAS) on behalf of Croft Associates Ltd. The experimental programme was carried out as specified in Croft document CTN 2008/02 Issue A(1) and in accordance with the procedures described in test standard BS ISO 844:2001(2).

The tests were performed at temperatures of 20, 100, and -29°C using samples of material provided by Croft Associates. These samples were manufactured from a material conforming to specification Amorim 8113i, as per inspection report Croft GRC 1550(3).

The work was carried out within the Serco Materials and Component Research Laboratory during August 2008 under contract number PO5607TC.

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1 Introduction

Croft Associates Ltd. has a requirement to determine the behaviour of rigid cellular material (cork) when it is subjected to a compressive force. In order to provide the necessary data, Serco TAS conducted a series of compression tests on specimens prepared from a material conforming to specification Amorim 8113i, as per inspection report Croft GRC 1550. The experimental programme was carried out as specified in Croft Associates document CTN 2008/02 Issue A and generally in accordance with the procedures described in Test Standard BS ISO 844:2001. Five samples were tested at each of the specified temperatures; 20, 100, and -29°C.

Croft Associates Ltd provided the samples. These comprised cylindrical coupons of material, nominally 76mm in diameter and 45mm in length. The samples were conditioned at the required temperature prior to testing. They were then placed in a cylindrical pot, to provide radial constraint, and crushed axially at a controlled rate up to a load of 50kN. Measurements of applied force and deformation were recorded continuously during the test.

The data were analysed to provide values of applied stress and relative deformation (strain) and the compressive modulus of elasticity was evaluated. The results are presented in the form of test certificates, and are included in the Appendices of this report.

2 Quality Assurance and Control

Serco TAS Quality Management arrangements have been assessed by Lloyds Register Quality Assurance (LRQA) against the requirements BS EN ISO 9001:2000 and certificate number LRQ 0964988 has been issued.

The overall scope of testing is defined in Croft Associates Test Specification CTN 2008/02 Issue A. The tests were conducted generally in accordance with British Standard BS ISO 844:2001 with the following permitted deviations:

i) The test specimens were radially constrained.
ii) The humidity of the environment during conditioning and testing of the samples was not controlled or measured.
iii) Testing was terminated at a maximum load of 50kN.
iv) Tests were conducted at temperatures other than 20°C.

Tests were performed in accordance with a Serco TAS Local Working Instruction[(4)] prepared specifically for compression testing of rigid plastic materials and cork. This was prepared for a previous experimental programme conducted on behalf of Croft Associates[(5)]. This has been entered in the Serco TAS Quality Assurance register and has been approved by Croft Associates Ltd.

3 Test Details.

Details of the specimens, the equipment used and testing procedure are described below.

3.1 Test Specimens

A total of 20 cork specimens were prepared by Croft Associates Ltd. and were identified as samples GRC 1550/1 to GRC 1550/20. These were delivered to Serco TAS in July 2008 and registered within the laboratory QA system. The specimens were cylindrical and were nominally 76 mm in diameter and 45mm in length.

Prior to testing, the specimens were conditioned by storing them for a minimum period of 6 hours at the required test temperature. The dimensions of individual samples were recorded both at 20°C and at temperature immediately prior to installation into the testing machine.

3.2 Test Machine

The tests were carried out using a conventional servo-electric testing machine with a maximum load capacity of 250kN although the tests were terminated at a load of 50kN for consistency with data generated during a previous programme[5]. The machine was equipped with a fan-assisted environmental enclosure allowing tests to be conducted at temperatures from -170°C to 350°C to an accuracy of ± 2°C.

Radial constraint was a requirement of the test specification. This was achieved by placing the specimens into a cylindrical pot and applying the compressive force through a piston inserted into the top. The design of the pot included a removable base to simplify the extraction of the specimen on completion of the test. A detailed drawing of the containment is shown in Figure 1.

In order to ensure good axial alignment of the specimen during the test, the pot was supported on a platen incorporating a self-aligning spherical bearing.

A photograph illustrating the key elements of the complete testing arrangement is shown in Figure 2.

3.3 Instrumentation

The applied force was measured using the integral test machine load cell, which had been calibrated by a UKAS accredited authority to ISO 7500-1:1999 and ascribed a grade 1.0 classification.

The displacement of the test machine crosshead, and hence the deformation of the sample, was measured using a linear encoder, the calibration of which was checked using a traceable reference and found to be accurate to within +/- 0.15% over the range used during the test (40mm).

Data from the load and displacement instrumentation were recorded using a high-resolution PC based data acquisition system.

The temperature of the samples during conditioning and testing was checked using a hand-held digital thermometer with either two type 'T' thermocouples (20° and -29°C) or two type 'K' thermocouples (100°C). One thermocouple was attached to the outer surface of the containment pot, the other located in a hole drilled into the centre of one of the 'spare' specimens, placed inside the environmental enclosure.

3.4 Test Procedure

The specimens were conditioned in batches of five at the required temperature for a minimum period of 6 hours prior to testing. Meanwhile, the pot was placed into the environmental enclosure and allowed to stabilise at the same temperature as the specimens. After conditioning, the specimen to be tested was measured, placed into the pot, and the complete assembly was then installed into the test machine. The temperature was again allowed to stabilise for a minimum period of 1 hour before testing was carried out.

The crushing force was applied by displacing the piston at a controlled rate of approximately 4.5 mm/minute. This continued until a load of 50kN was attained. The load and displacement data were recorded continuously during the test at a rate of 20 readings/second. On completion

the test specimen was removed and the recorded data were analysed as described in Section 4.

4 Data Analysis

The computer records were analysed to provide the required data using the procedure described below. At all test temperatures values of displacement were calculated from the "zero-deformation point" as specified in BS ISO 844.

The terms used in the calculation of these results are illustrated in Figure 3.

4.1 Applied Stress and Compressive strength

The applied stress (**σ**) in MPa was calculated as follows:

$$\sigma = \frac{F}{A_0}$$

where:

F = Applied force (N)
A_0 =Initial cross-sectional area of the test specimen (mm^2)

Note that a value for compressive strength was not applicable as crushing did not occur hence no peak load was determined.

4.2 Relative Deformation

The relative deformation (**ε**) was calculated from:

$$\varepsilon = 100 \times \frac{x}{h_0}$$

where:

x = displacement (mm) from the "zero-deformation point"
h_0 = initial thickness of the specimen (mm)

The compressive stress has been calculated at a range of relative deformations from 1% to 65%. These results are tabulated in the test certificates provided in the Appendices.

4.3 Compressive Modulus of Elasticity

The Compressive Modulus of Elasticity (***E***) was calculated for the linear portion of the force-displacement curve (elastic zone) from:

$$E = \frac{\sigma_e}{\varepsilon_e} \qquad \text{(MPa)}$$

where:

$$\sigma_e = \frac{F_e}{A_0}$$

σ_e = Stress at end of elastic region (MPa)
F_e = force at the end of the elastic region (N).
A_0 = Initial cross-sectional area of the test specimen (mm^2).

and

$$\varepsilon_e = \frac{x_e}{h_0}$$

where:

ε_e = strain at force F_e
X_e = displacement (mm) at force F_e measured from the "zero-deformation point"
h_0 = initial thickness of the specimen (mm)

Plots of the relative deformation as a function of applied stress have been produced for each test.

5 Results and Discussion

Test certificates were compiled containing details of each specimen tested, the results of the analyses described in Section 4, and plots of stress vs. relative deformation. These are presented in Appendices 1 to 3 for temperatures of 20, 100 and -29°C respectively.

5.1 Test Temperature of 20°C

At a test temperature of 20°C, the curve generally showed a reduction in slope at approximately 1% relative deformation. There was then a gradual increase in stress as the material was compacted, with the slope of the curve becoming increasingly steep after 40% relative deformation. The final load of 50kN was reached at a relative deformation of approximately 70%.

5.2 Test Temperature of 100°C

The results from the tests at 100°C showed a gradual increase in stress with the slope of the curve increasing significantly at about 45% relative deformation. The final load of 50kN was reached at a relative deformation of approximately 74%.

5.3 Test Temperature of -29°C

At a test temperature of -29°C the curve showed a reduction in slope at approximately 5% relative deformation. The stress then increased gradually, with the increase in slope occurring at approximately 35% relative deformation. The final load of 50kN was reached at approximately 60-65% relative deformation.

The tests at -29°C exhibited significantly more experimental scatter than the tests at 20°C and 100°C.

At -29°C all test traces exhibited a very steep gradient up to an applied load of approximately 1000N. Beyond 1000N the gradient of each curve became much shallower. It is this second part of the curve that was used in the calculation of the compressive modulus of elasticity. This is illustrated graphically in Figure 4.

The average results are summarised in the table below and the stress versus relative deformation data from all the specimens tested at each temperature are plotted for comparison in Figures 5-7.

Test Temperature (°C)	Compressive Modulus of Elasticity E, calculated from Initial Deformation (MPa)	Compressive Stress at 10% relative deformation (MPa)
20	15.0	0.57
100	4.6	0.34
-29	23.4	1.60

Table 1 – Average Compressive Modulus of Elasticity and Compressive Strength at 10% Relative Deformation for each Test Temperature

6 Conclusions

Compressive tests have been conducted at temperatures of 20, 100 and -29°C on samples manufactured from cork. Plots of applied stress versus strain have been produced and the relative moduli calculated.

7 References

1 Low Strain Rate Test Specification for Amorim Cork. - Croft Report CTN 2008/02 Issue A. June 2008.

2 BS ISO 844:2001. Cellular plastics - Compression Test for Rigid Materials - Specification

3 Specification for Manufacture of Cork Blocks - Croft Report GRC 1550 for Cork Amorim 8113i

4 SA/QA/LWI/SUS/212. Compression Testing of Rigid Plastic Materials and Cork.

5 SA/RJCB/RD04970/R002 Issue 1: Compression testing of Cork: July 2002

8 Distribution

Name	Organisation	Copies
Dr. R. Vaughan	Croft Associates Ltd	1
Mr. P. Hutchinson	Serco TAS	1
Mr. G. Melvin	Serco TAS	1

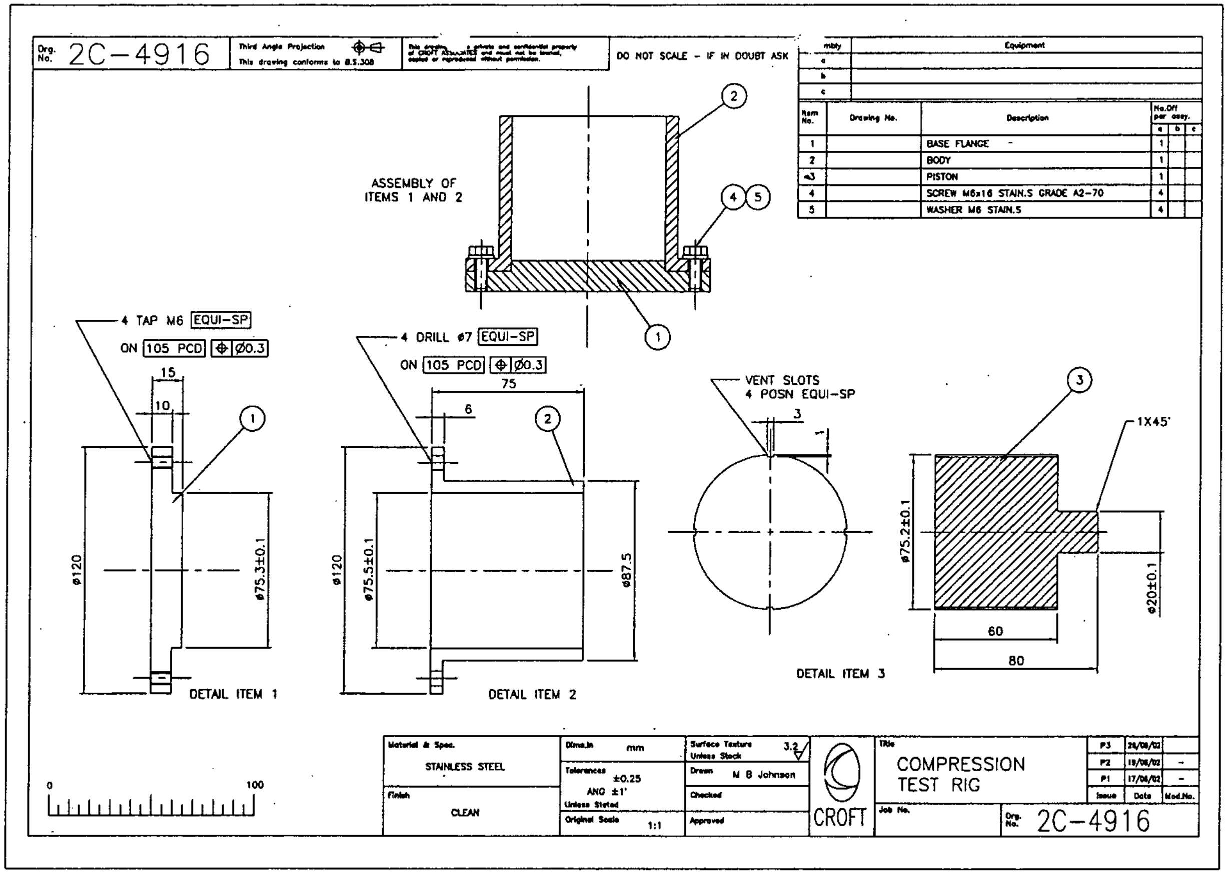

Figure 1 – Design of Pot used to Provide Radial Constraint during Compression Tests

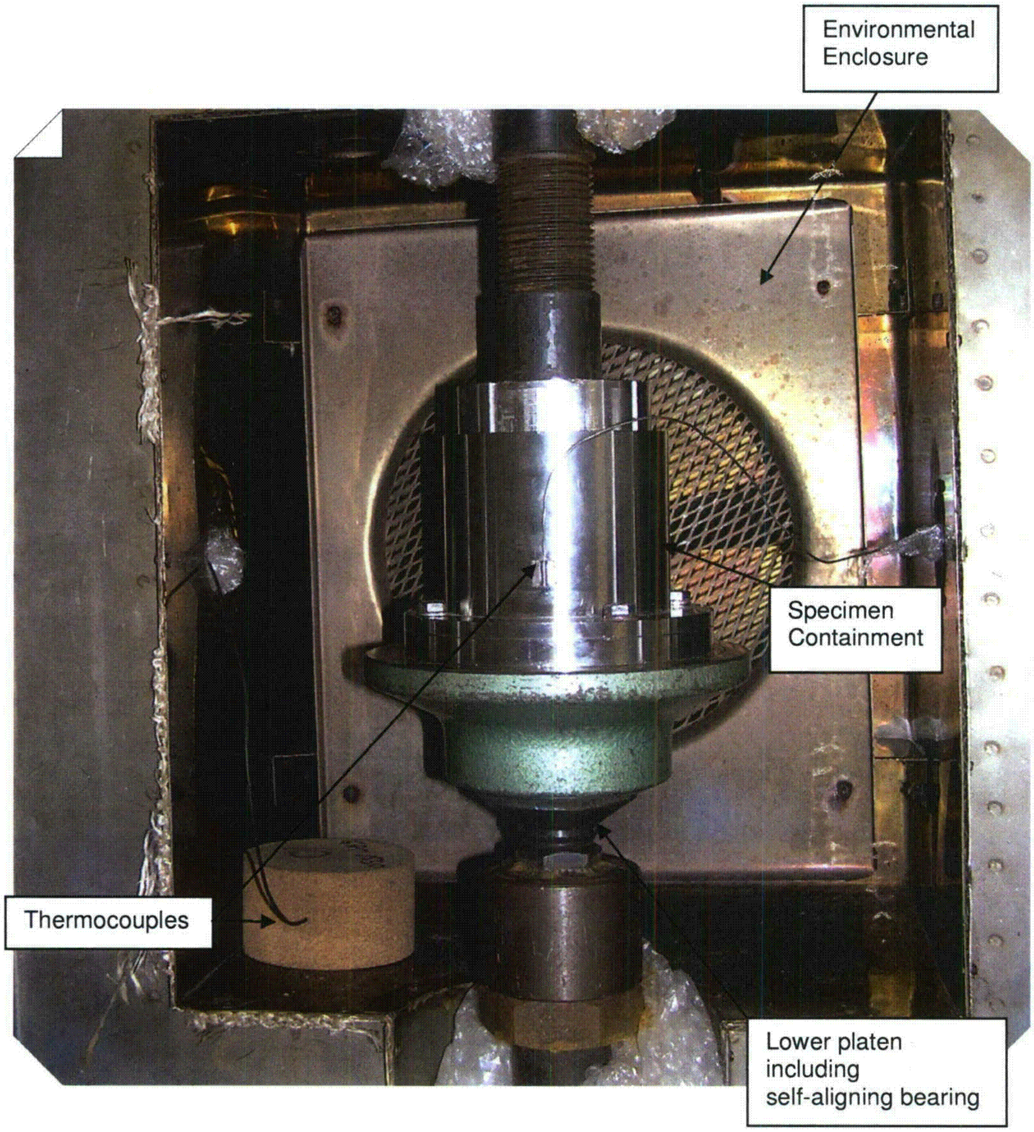

Figure 2 - Photograph of Test Assembly in Test Machine

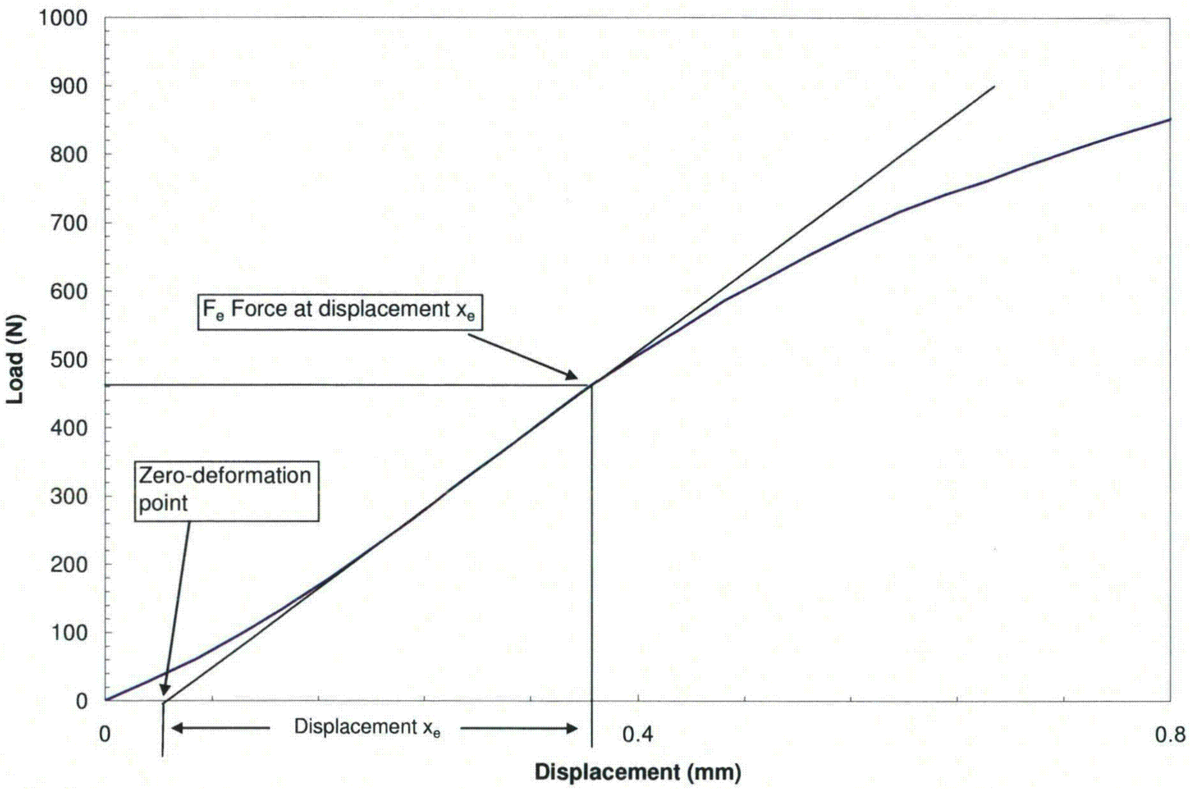

Figure 3 – Force-Displacement Curve: Illustration of terms used for analysis of data in accordance with BS ISO 844:2001

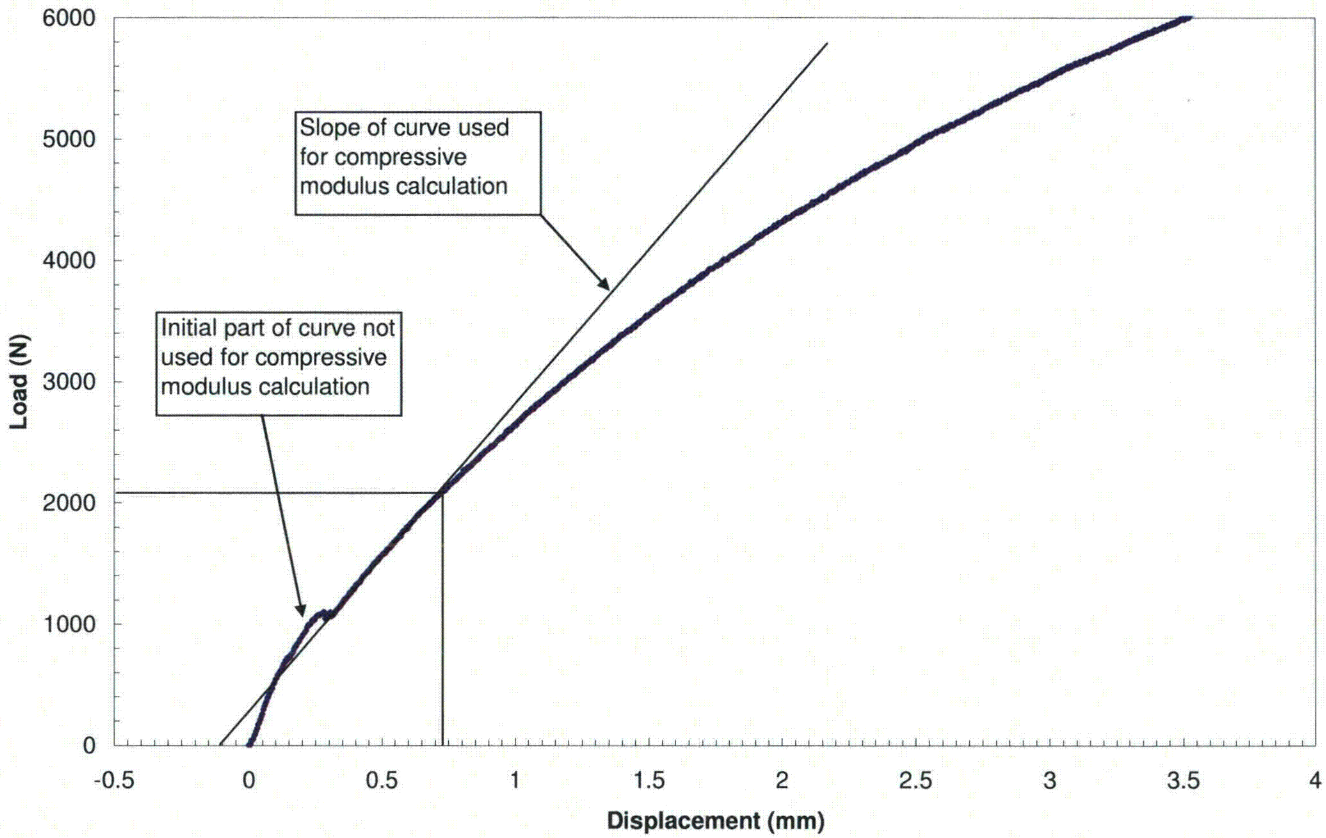

Figure 4 – Illustration of Slope of Curve used for Modulus Calculation at -29°C (Specimen GRC 1550-1)

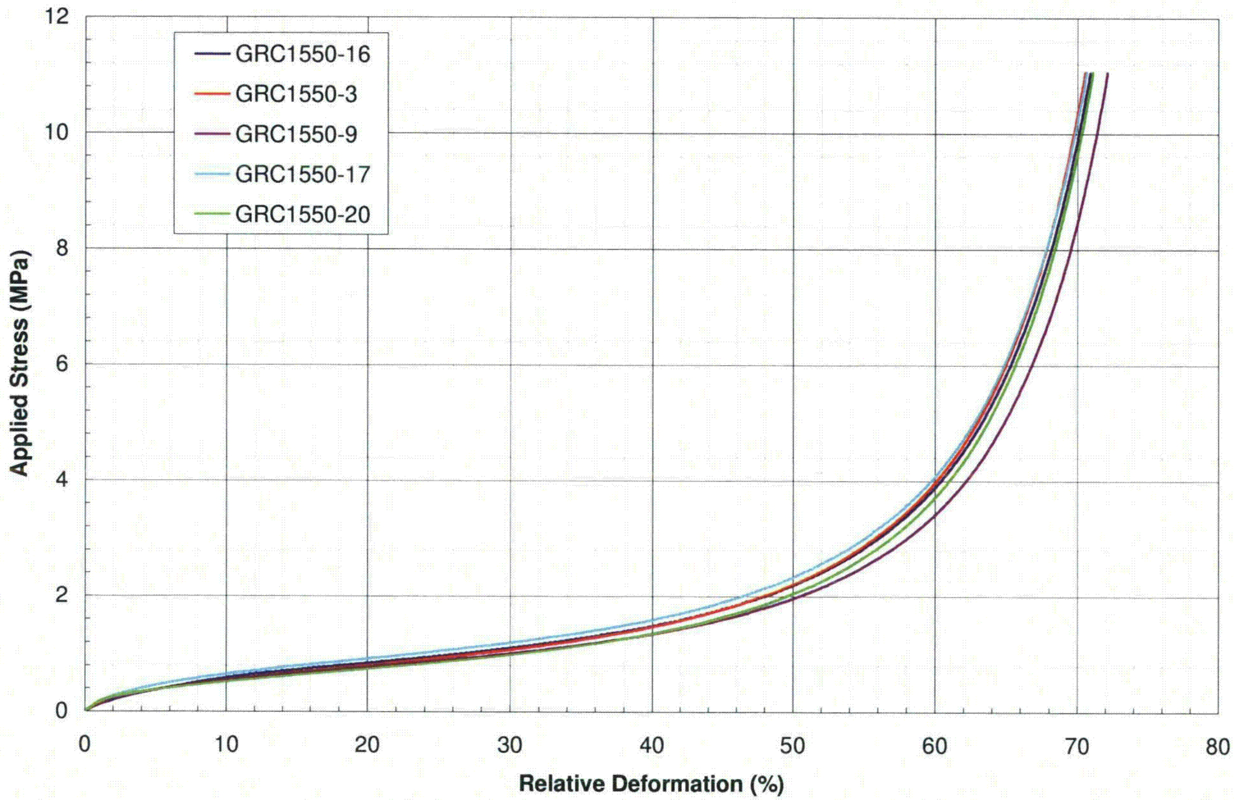

Figure 5 – Stress vs. Relative Deformation plot for Cork Samples Tested at 20°C

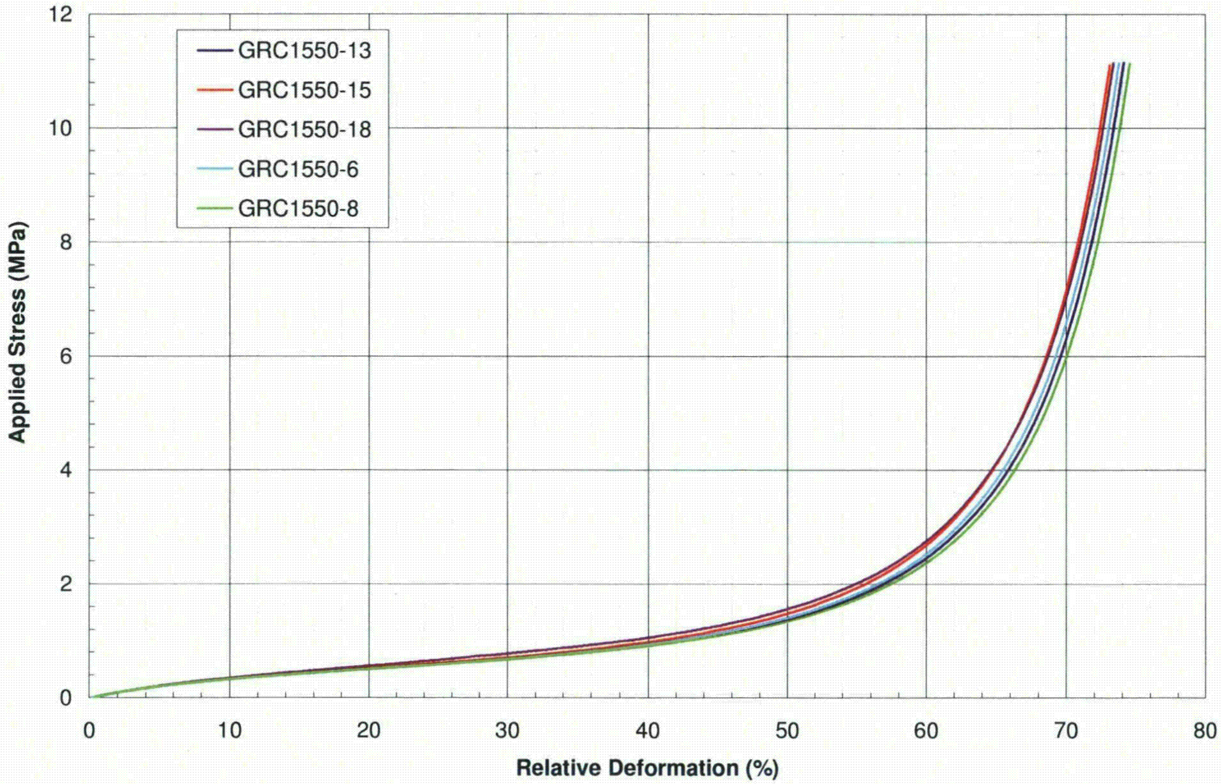

Figure 6 – Stress vs. Relative Deformation plot for Cork Samples Tested at 100°C

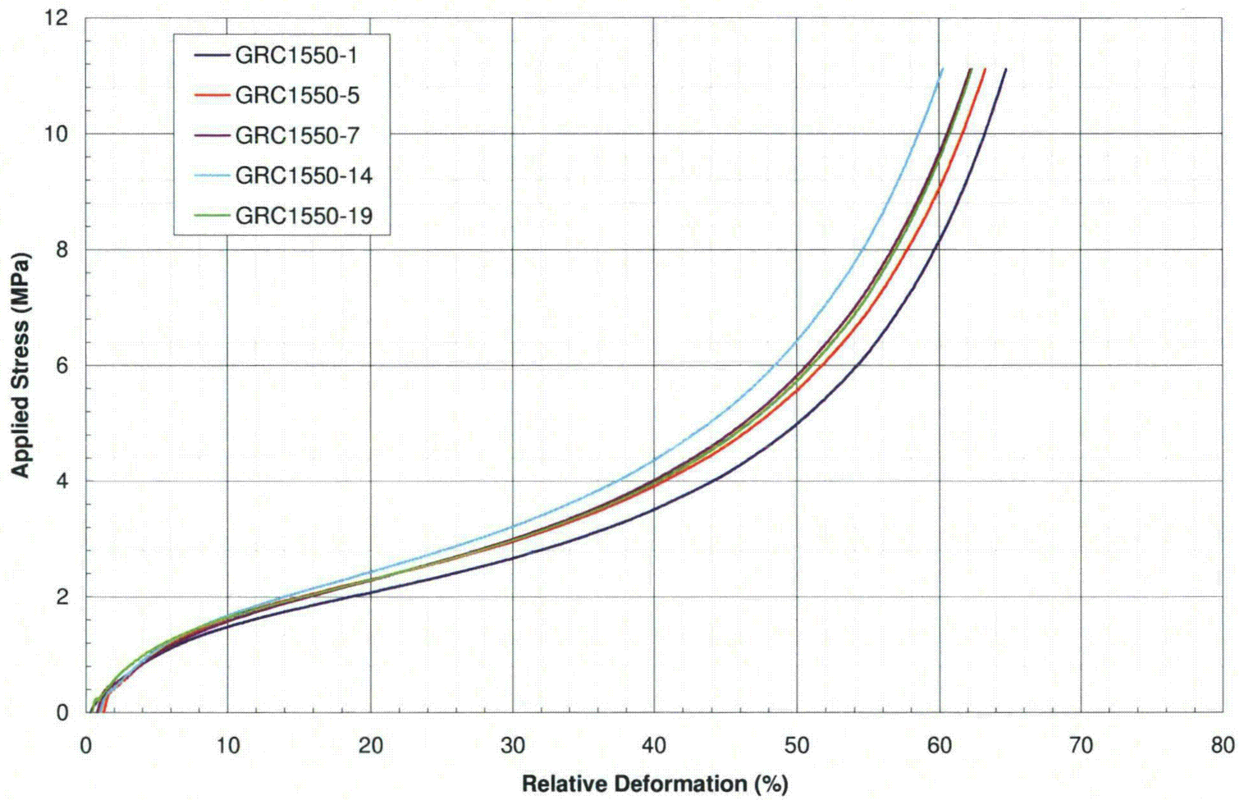

Figure 7 – Stress vs. Relative Deformation plot for Cork Samples Tested at -29°C

Appendices

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Compression Testing of Cork at 20°C

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