HYDROGEN INNOVATION

IMPACT OF HYDROGEN ON BALL VALVE MATERIALS AND MAINTENANCE STRATEGY

Prepared by: [redacted]

Originator: Score (Europe) Limited

Score Job No: 715297 EDC

0	26/03/26	Final for Comment	JC / PB	KD	MB	NGT
0D	10/02/26	Draft	JC / KD	MB	MB	NGT
Rev	**Date**	**Description**	**Author**	**Checked**	**Approved**	**Client**

Manager Approval:	**Document Number:**
[redacted]	ENG-SC01-ZF-4353 Rev 0

IMPACT OF HYDROGEN ON BALL VALVE MATERIALS AND MAINTENANCE STRATEGY

CONTENTS

LIST OF FIGURES

LIST OF APPENDICES

LIST OF TABLES

LIST OF ABBREVIATIONS

AGI – Above Ground Installation
AISI – American Iron and Steel Institute
ASME – American Society of Mechanical Engineers
ASTM – American Society for Testing and Materials
BPVC – Boiler and Pressure Vessel Code
CAD – Computer Aided Design
EDC – Engineering Design & Consultancy
EIGA – European Industrial Gases Association
ENP – Electroless Nickel Plating
FAD – Failure Assessment Diagram
FAT – Factory Acceptance Test
FEA – Finite Element Analysis
GIS - Gas Industry Standard
GNCC – Gas National Control Centre
H_2 – Hydrogen
H_2S – Hydrogen Sulphide
HE – Hydrogen Embrittlement
HIC – Hydrogen Induced Cracking
HTHA – High Temperature Hydrogen Attack
K_{IH} – Fracture Toughness after Hydrogen Exposure
LR – Load Ratio
LC – Load Case
N_2 – Nitrogen
NACE – National Association of Corrosion Engineers
NDE – Non-Destructive Examination
NGT – National Gas Transmission
NTS – National Transmission System
OEM – Original Equipment Manufacturer
PMI – Positive Material Identification
QVD – Qualified Vendor Database
RFI – Request for Information
SLH – Specification Level for Hydrogen
SMYS – Specified Minimum Yield Strength
UTS - Ultimate Tensile Strength
WP – Work Pack

LIST OF UNITS

in – inch
MPa – Megapascals
$MPa\sqrt{m}$ - Fracture toughness
mm – millimetre
m.barL/s – millibar litres per second
ppm – parts per million

psi	– pounds per square inch
psig	– pounds per square inch (gauge)
rpm	– revolutions per minute
thou	– 1 thousandth of an inch

1.0 INTRODUCTION

This technical report documents the work carried out as part of the innovation project: Impact of Hydrogen on Ball Valve Materials and Maintenance Strategy, commissioned by National Gas Transmission (NGT). NGT have been investigating the potential of introducing gaseous Hydrogen into the National Transmission System (NTS), either as a blend with Natural Gas or 100% Hydrogen, and this innovation project falls within the overall objective of re-purposing the NTS for Hydrogen.

This project has the specific aims of analysing the materials and pressure boundary stress distribution of a typical ball valve currently installed in the NTS, assessing the valve leak detection effectiveness and evaluating associated maintenance regimes, for when the NTS is exposed to pressurised Hydrogen.

The project has been broken down into four different Work Packages (WPs):

- WP1 – Literature review, looking at the fracture toughness of current valve materials and assessment strategies
- WP2 – Design Analysis, looking at an existing valve design and assessing for Hydrogen readiness
- WP3 – Review of current operations, diagnostics / monitoring and OEM Maintenance Recommendations
- WP4 – In-Service Assessment, testing of a valve to investigate impact of operations on valve leakage

2.0 BACKGROUND

National Gas Transmission (NGT) are committed to reducing emissions from the operation of the National Transmission System (NTS) and eliminating emissions by 2050. A key route to achieving this involves transitioning the network from natural gas to hydrogen. To do this, ~2000km of transmission pipeline is being considered for repurposing for Project Union, including all assets in and around the pipeline.

Valves are an essential part of a functioning NTS and are installed throughout the system to enable effective isolation of sections of the network, limit gas loss in an emergency, manage flow direction, facilitate maintenance, repair, modification, testing and commissioning, and to enable safe and effective start-up and shutdown.

Score have been engaged to review the approach to ball valves materials and maintenance for use with Hydrogen / Methane blends and how this may differ from the current 100% Natural Gas.

3.0 SUMMARY AND CONCLUSIONS

3.1 The literature review undertaken within WP1 demonstrates that while a significant body of research exists relating to hydrogen effects on metallic materials, particularly for pipeline steels and laboratory-scale specimens, there remains a lack of publicly available data relating to full-scale hydrogen-specific fracture toughness data for common valve materials, particularly welds and heat affected zones. As a result, while existing literature provides a strong theoretical foundation, it is insufficient on its own to fully characterise valve integrity and performance in hydrogen service. This gap highlights the need for targeted experimental validation, component-level testing, and application-specific assessment methodologies, as addressed in subsequent work packages (See Section 5).

3.2 The majority of NTS valves assessed are manufactured from materials falling within the carbon steel and low-alloy steel material groupings defined in ASME B16.34, typically including [redacted] Within the context of ASME B16.34, these materials are classified as Group 1 and Group 2 materials, representing carbon steels and carbon–manganese / low-alloy steels commonly used for pressure-containing components. These material groups are well established in natural gas transmission service and provide a favourable combination of strength, ductility and manufacturability. The measured low hardness values associated with these materials indicate a relatively ductile condition, which is beneficial from a hydrogen embrittlement screening perspective. However, these material groupings and compliance with hardness limits alone are not sufficient to demonstrate hydrogen suitability, as hydrogen-induced degradation of fracture toughness must also be considered (See Section 5.1.8). Hydrogen service introduces fracture-controlled failure mechanisms, whereby resistance to crack initiation and propagation governs structural integrity rather than conventional strength-based criteria (See Section 5.3).

3.3 Published literature confirms that hydrogen exposure results in a significant reduction in fracture toughness, typically in the range of 30–50% or greater. Hydrogen-affected fracture toughness (K_{IH}) for pipeline-equivalent steels is commonly within the range of approximately 40–80 MPa√m, with lower values observed in weld and heat-affected zones (See Section 5.5).

3.4 A conservative lower-bound fracture toughness value of approximately 30 MPa√m is therefore appropriate for engineering assessment of carbon steel valve materials in hydrogen service where material-specific data is not available (See Section 5.5.4).

3.5 Valve geometries inherently contain stress concentrators, welds, and regions of elevated triaxiality, including bonnet interfaces, seat pockets, and welded connections. These features represent fracture-critical locations where hydrogen-assisted cracking is most likely to initiate and propagate (See Section 5.4).

3.6 ASME BPVC Section VIII Division 2 assessment confirms that the valve satisfies conventional pressure containment requirements under all assessed load cases. However, this standard does not account for hydrogen-induced degradation mechanisms and therefore cannot be used in isolation to demonstrate hydrogen service suitability (See Section 6.3.1 and Section 6.4.2).

3.7 ASME B31.12 Option A provides a conservative stress-based screening approach but does not explicitly assess crack stability. As such, it is not considered sufficient for assessing complex valve geometries in high-pressure hydrogen service (See Section 6.3.3).

3.8 [redacted]

[redacted] (See Section 6.4.4 and Figures 12–16).

3.9 The fracture assessment results indicate that, from a structural integrity perspective, the valve pressure boundary is tolerant to small defects under the assessed loading conditions when evaluated using conservative fracture toughness assumptions (See Section 6.4.4).

3.10 Hydrogen service suitability cannot be fully confirmed without material-specific fracture toughness and fatigue crack growth data, particularly for welds and heat-affected zones, which are likely to govern failure behaviour (See Section 5.5.5).

3.11 [redacted] (See Section 7.3.3 and Section 7.4).

3.12 Hydrogen's smaller molecular size, higher diffusivity, and lower ignition energy increase both leak propensity and consequence. [redacted]

3.13 Seat sealing degradation within NTS valves is driven by wear, scoring, elastomer degradation, and particulate contamination. Legacy valve designs present increased long-term reliability risks in hydrogen service (See Section 7.3.4).

3.14 [redacted] (See Section 7.4.2 and Section 7.4.4).

3.15 [redacted] (See Section 7.5).

3.16 [redacted] (See Section 8.3.4).

3.17 WP4 testing demonstrated that cyclic operation using forming gas did not result in measurable degradation in valve sealing performance under the conditions assessed (See Section 8.3.3).

3.18 The use of forming gas during testing provides valuable and practical insight into valve performance in hydrogen service, particularly with respect to leakage behaviour and detection sensitivity. However, forming gas does not fully replicate the physical properties of pure hydrogen, and therefore introduces uncertainty in the direct applicability of results to 100% hydrogen service conditions. As such, while forming gas testing is considered a suitable intermediate and safer validation method, testing using 100% hydrogen would provide a more representative assessment of valve performance (See Section 8.3.3 and Section 8.4).

3.19 [redacted] (See Section 8.1.2).

3.20 Overall, the combined findings of WP1–WP4 demonstrate that structural failure of valve pressure boundaries is unlikely to be the primary limiting factor for hydrogen service under the assessed conditions (See Sections 5–8).

3.21 The dominant risks associated with hydrogen repurposing of NTS valves are related to leakage performance, detection capability, maintenance strategy effectiveness, and long-term degradation mechanisms (See Sections 7 and 8).

3.22 The transition to hydrogen service represents a shift from a strength-based integrity problem to a leakage and defect management problem, requiring changes to design philosophy, testing, and operational practices (See Sections 5.6 and 7.4).

3.23 [redacted].

3.24 [redacted] (See Sections 8.3.3 and 8.4).

3.25 [redacted] (See Sections 8.3.4 and 8.4).

4.0 RECOMMENDATIONS

4.1 A hydrogen-specific leakage acceptance philosophy should be developed for NTS valves. Existing leak-rate thresholds and asset health scoring methodologies, which are based on natural gas behaviour, shall be revised and redefined for hydrogen and hydrogen-blend service to reflect increased leak propensity, reduced ignition energy, and higher consequence of release. Revised criteria shall ensure that valves currently classified as acceptable under natural gas service are not misclassified under hydrogen conditions.

4.2 A structured hydrogen qualification framework should be implemented for both new and repurposed valves. This framework shall align, where practicable, with ASME B31.12 and API 6D Annex M, incorporating hydrogen-relevant test media, acceptance criteria, and performance requirements.

4.3 NGT leak-rate health bands should be redefined for hydrogen and hydrogen-blend service. Revised criteria should ensure that valves currently classified as acceptable under natural gas service are not misclassified when operating with hydrogen, where lower leakage tolerances are required.

4.4 A structured hydrogen qualification framework should be implemented for both new and repurposed valves. This framework should align, where practicable, with ASME B31.12 and API 6D Annex M, incorporating hydrogen-relevant test media, acceptance criteria, and performance requirements.

4.5 Gas seat testing for hydrogen service shall be undertaken in accordance with API 6D Annex M as a minimum requirement. Where hydrogen tightness is critical, the use of more representative test media, such as helium and/or forming gas, should be adopted as a supplementary measure to provide enhanced sensitivity and improved representation of hydrogen leakage behaviour. This approach is aligned with hydrogen-focused standards and emerging industry practice and should be considered to augment, rather than replace, the baseline requirements of API 6D.

4.6 Dedicated validation testing should be undertaken using 100% hydrogen. Comparative testing against forming gas should be conducted to quantify differences in leakage behaviour, sealing performance, and diagnostic response, thereby establishing the applicability and limitations of surrogate test media.

4.7 Where legacy valve designs are expected to remain in service within the NTS, further cyclic seat degradation testing should be undertaken on configurations representative of the installed population. Focus should be given to two-piece seat designs incorporating elastomeric O-Ring Seals as seats and carbon steel / ENP trim, to characterise degradation mechanisms and performance limitations under hydrogen-relevant conditions. However, these legacy configurations are not considered optimal for long-term hydrogen service, and results from such testing should be used to inform risk-based decisions on continued operation, refurbishment, or replacement with modern valve designs incorporating polymer-based seating and corrosion-resistant trim.

4.8 Future test programmes should incorporate valves with engineered or known leakage paths within the ball to seat interface. This will enable robust validation of diagnostic techniques, particularly at low leakage rates relevant to hydrogen service, and allow determination of detection sensitivity and repeatability.

4.9 Acoustic Emissions (AE) technology, including Score's Midas Meter, should be subject to a formal hydrogen validation program. This shall include calibration against known leakage rates, a range of valve geometries, and multiple operating conditions, to establish a validated hydrogen-specific acoustic response database.

[redacted]

4.13 [redacted], and ancillary systems to ensure early identification of degradation mechanisms.

[redacted]

4.15 Valve seat and trim material selection should be reviewed as part of hydrogen readiness assessments. Legacy configurations, including carbon steel with ENP coatings and elastomeric sealing elements, should be evaluated against modern stainless steel and polymer-based designs to determine long-term suitability and maintenance implications.

4.16 Hydrogen suitability assessments should incorporate fracture mechanics-based evaluation. Material designation, hardness, and strength alone should not be used to infer hydrogen compatibility. Assessments should be conducted in accordance with the principles of ASME B31.12 Option B for critical applications.

4.17 Ageing NTS valves should be prioritised for hydrogen-readiness assessment. Assets exceeding nominal design life should be subject to enhanced scrutiny due to increased likelihood of degradation, material ageing, and sealing performance uncertainty.

4.18 OEM engagement should be strengthened through formal data requirements. Vendors should be required to provide evidence of hydrogen performance, including leakage behaviour, cyclic degradation, maintenance requirements, and design limitations, to support qualification and procurement decisions.

4.19 Valve specifications that are used for procurement should be updated to explicitly include hydrogen service requirements. These should address leakage performance, testing protocols, maintenance considerations, and diagnostic compatibility to ensure future valves are inherently hydrogen-ready.

4.20 Hydrogen-specific maintenance and emergency procedures should be incorporated into NGT standards. These should include requirements for isolation, inerting, personnel training, and contingency planning to manage the increased risks associated with hydrogen systems.

4.21 A risk-based valve assessment and prioritisation framework should be developed for the NTS. This should consider valve age, design, materials, duty cycle, maintainability, and criticality to identify assets suitable for continued operation, refurbishment, enhanced monitoring, or replacement in a hydrogen transition scenario.

4.22 Material qualification and inspection requirements defined within API 6D Annex M should be considered as a baseline; however, additional NDE and defect assessment may be required to ensure alignment between inspection capability and the flaw sizes assumed within fracture mechanics-based hydrogen integrity assessments.

5.0 WP1 – VALVE MATERIALS LITRATURE REVIEW

The scope of WP1 is to develop a detailed understanding of the materials currently used for valve bodies, closures and internal components within the NTS, with a specific focus on their behaviour and suitability when exposed to high pressure hydrogen environments

The work package considers a structured review of mechanical properties, fracture toughness and allowable stress limits of the primary materials present across the NTS valve population, drawing upon available NGT materials records and historical PMI data.

5.1 Common Valve Materials

Pipeline valves are critical pressure-containing and controlling elements within the NTS, providing the means to isolate and control fluid flow and ensure safe operation under both normal and abnormal conditions. Given their critical function within the system the selection of the correct materials is critical and fundamental to achieving structural integrity and operational reliability.

Metallic material requirements for trunnion-mounted ball valves are typically categorised into two primary groups based on their functional role within the valve assembly:

- Pressure boundary components, including the valve body, adaptors, bonnet and associated bolting

- Pressure controlling components, comprising of internal parts such as the obturator (ball), trunnions, stem and seat carriers.

The material requirements for these material groups are usually specified on the client valve datasheet or documentation package; however, this information is not always available and may not include any changes or upgrades made during the valves service life. NGT do not typically specify material within their Valve Datasheet (VDS), although GIS/V6 [1], Specification for Steel Valve for use with Natural Gas at Normal operating pressures above 7 Bar and sizes above DN15, does state that metallic materials for pressure containing parts must be listed within ASME B16.34 [2] and conform to the requirements within the GIS/V6 specification.

In a conventional pipeline service, the selection of valve materials is governed primarily by operating conditions (pressure, temperature and service media), the applicable industrial standard, and operator requirements. In most pipeline applications, valve pressure boundary components—including the body, bonnet or cover, body joints, and associated bolting—are manufactured from materials listed in ASTM specifications referenced by ASME B16.34, which defines pressure–temperature ratings for metallic valves [3].

The material groupings within ASME B16.34 are based upon an extensive industrial experience and represent materials that have demonstrated acceptable performance for defined operating envelopes. However, ASME B16.34 does not explicitly define material degradation mechanisms or suitability for emerging service environments, such as hydrogen, and therefore material selection remains the responsibility of the end user [3]. Additionally, this also presents a challenge when considering the use of legacy equipment such as valves for use on new services such as hydrogen.

5.1.1 Criteria for Valve Material Selection

While ASME B16.34 identifies acceptable material specifications, it does not provide detailed guidance on material selection beyond pressure – temperature limits [2]. The evaluation of material suitability for a given service must therefore consider potential degradation mechanisms, inspection requirements and long-term performance risks associated with both the operating environment and the service media.

Examples of degradation mechanisms that may influence material selection include:

- Reduction in ductility and fracture toughness of carbon steels at low temperatures
- Embrittlement due to Hydrogen exposure
- Corrosion and oxidation
- Susceptibility of austenitic stainless steels to intergranular corrosion and chloride stress corrosion cracking
- Grain boundary attack and environmental cracking in nickel-based and high-alloy materials
- High temperature strength reduction

Among these factors the operating pressure and temperature alongside the service media chemical composition are the driving criteria for material selection. For a non-corrosive service media at ambient temperature, carbon steel is generally considered the most cost-effective solution. While corrosive, high temperature or aggressive environments may necessitate the use of stainless steel or higher-alloy materials.

5.1.2 Material Groupings in ASME B16.34

Materials listed within Table 1 of ASME B16.34 [2] can be broadly categorised into four practical groups commonly used in pipeline valve manufacture:

- Carbon Steels
- Low-alloy steels
- Stainless Steels
- Exotic and high- alloy metals

While ASME B16.34 provides guidance on allowable temperature ranges for these materials, such guidance should be treated as indicative rather than definitive, where service conditions extend beyond conventional hydrocarbon service applications.

5.1.3 Carbon Steels for Valve Bodies

Carbon steel is the most widely used material for pipeline valve bodies due to its favourable balance of strength, manufacturability, availability and cost. Carbon steels typically contain between approximately 0.05% and 2.5% carbon, with increasing carbon content contributing to higher strength and hardness. While carbon steels provide excellent pressure containment capability, they are susceptible to corrosion and may exhibit reduced toughness or increased brittleness depending upon composition, heat treatment and service temperature. These characteristics necessitate careful consideration in low-temperature or aggressive service environments.

Typical carbon steels used for valve bodies:

- ASTM [redacted] cast steels (Grades WCA, WCB, WCC)
- ASTM [redacted] Forged carbon steel
- Low-temperature carbon steels, such as ASTM [redacted] Grades LCB & LCC (cast) and ASTM [redacted] Grade LF2 (forged)

5.1.4 Forged versus Cast Valve Bodies

Valve bodies may be manufactured using either forged or cast steel, depending upon valve size, pressure class and design requirements. For a given specification and grade, corresponding forged and cast materials typically exhibit similar nominal chemical composition and mechanical properties. However, forged steels generally offer improved material uniformity and structural integrity. The forging process promotes metallurgical re-crystallisation and grain refinement through controlled deformation and heat treatment, resulting in enhanced toughness, impact resistance and shear strength. Directional grain flow achieved during forging further improves resistance to crack initiation and propagation, particularly in high pressure or cyclic service. As a result, forged steel valves are commonly employed on long-distance transmission pipelines and other demanding applications where enhanced fracture resistance and reliability are required.

5.1.5 Low Temperature Carbon Steels

ASTM [redacted] is the most widely specified forged carbon steel for pressure-containing components such as valves, flanges and fittings. It is typically suitable for ambient and elevated temperature service and is commonly selected where assured mechanical performance and structural integrity are required. ASTM [redacted]N denotes material that has been supplied in the normalised condition. Normalising refines grain structure, improves toughness and produces more consistent mechanical properties compared with the as-forged condition. For low-temperature service, ASTM [redacted] Grade LF2 is commonly specified and is suitable for operation down to approximately -46°C. This grade is typically selected where process conditions may result in temperatures below -29°C.

5.1.6 Stainless & Austenitic Stainless Steel

Stainless steels are iron-based alloys containing a minimum chromium content of approximately 10-20%, providing resistance to corrosion and oxidation while maintaining mechanical integrity across a wide temperature range. Austenitic steels like Type 304 stainless steel is one of the most widely used austenitic stainless steels and is often referred to as an “18/8” alloy due to its nominal composition of 18% chromium and 8% nickel. Type 304L is a low-carbon variant with improved weldability and reduced susceptibility to carbide precipitation. Types 304 and 304L offer excellent corrosion resistance and are non-magnetic and non hardenable except by cold working.

However, they are susceptible to chloride stress corrosion cracking under certain environmental conditions. Type 316 and 316L stainless steels, containing molybdenum, provide enhanced resistance to pitting and general corrosion, particularly in chloride-containing environments. These alloys exhibit one of the widest temperature operating ranges of commonly used valve materials, typically from -254°C to 816°C, and are widely used for valve bodies in corrosive and offshore environments.

5.1.7 Duplex and Super Duplex Stainless Steel

Duplex stainless steels, such as ASTM [redacted] Grades [redacted] and ASTM [redacted] possess a mixed austenitic – ferritic microstructure that provides higher strength and improved resistance to chloride stress corrosion cracking compared with conventional austenitic stainless steels. Typical compositions include elevated chromium, increased molybdenum, reduced nickel content, and nitrogen additions.

The combination of high strength and corrosion resistance means they are well suited for use in oil and gas, petrochemical and subsea valve applications. Super duplex stainless steels (e.g. Grades F53, F65 and F60) represent higher-alloyed variants with increased chromium and molybdenum contents. These materials offer superior resistance to both organic and inorganic acids and enhanced performance relative to standard duplex grades, making them suitable for highly aggressive environments.

5.1.8 Materials of Construction within the NTS

The 36” Class 600 Ball valve that was the subject of the project, NIA_NGT0227, Hydrogen Impact on the National Transmission System (NTS) Valves & Maintenance [3] was disassembled and all component materials identified. Positive Material Identification (PMI) was performed on all metallic components from the disassembled 36” Class 600 Robert Cort ball valve to identify the materials and enable them to be assessed for their suitability to be used with Hydrogen. The findings of the PMI study have been summarised in Table 1, detailing both the PMI and hardness test results.

In general, the pressure containing components, such as the valve body, adaptors and bonnet, were found to be manufactured from ASTM [redacted] or equivalent grades with hardness values typically below 6HRC. This is a high-strength carbon manganese steel commonly specified for forged pipeline components. Including API 6D valves and fittings in high-pressure gas transmission service. From a valve materials perspective, ASTM [redacted] therefore sits within the carbon steel valve material group, alongside grades such as ASTM [redacted], ASTM [redacted]0 LF2, and ASTM [redacted]WCB, albeit at the upper end of the strength range for this category. ASTM [redacted] [redacted]2 has a specified minimum yield strength of approximately [redacted]MPa (52 ksi) and is typically supplied in a quenched and tempered processed condition to achieve the required combination of strength and toughness. The use of F52 material is consistent with historical gas transmission practice where higher strength steels were employed to enable reduced wall thickness while maintained pressure containment and fatigue performance under cyclic loading.

Additionally, hardness testing was performed on the valve body, a measured hardness of 6 HRC. This value is relatively low when compared to many quenched and tempered pipeline steels and indicates a relatively soft and ductile material condition, consistent with a steel supplied with an emphasis on fracture resistance rather than maximum strength. The measured hardness is well below the typical hardness limits commonly applied for hydrogen service screening (typically <22 HRC), suggesting a reduced susceptibility hydrogen-assisted cracking when compared to higher hardness steels. However, while the PMI and hardness results provide confidence in the general material class and indicate a favourable hardness condition, they do not in themselves demonstrate a suitability for hydrogen service. Neither

ASTM A694 material designation nor hardness alone address hydrogen-induced degradation of fracture toughness.

Published literature and hydrogen-specific standards demonstrate that fracture toughness in hydrogen environments (K_{IH}) can be significantly lower than air measured fracture toughness, even for relatively low hardness carbon and low alloy steels. Accordingly, for the identified ASTM A694 F52 valve material, hydrogen integrity cannot be inferred solely from material identification or hardness. Demonstration of hydrogen readiness requires explicit consideration of fracture-controlled failure mechanisms, including the use of conservative lower bound fracture toughness values or material specific hydrogen fracture toughness date, in accordance with the fracture mechanics philosophy defined within ASME B31.12 Option B.

Description	PMI Result	Hardness Test	Notes	Suitability for H_2
Gland Plate Capscrew	No Match	39 HRC	Ties in with B7 composition Hardness unsuitable.	Unsuitable
Adaptor Plate Capscrew	4140	41 HRC	Ties in with B7 composition Hardness unsuitable.	Unsuitable
Body Stud	4140	307 HV - 333 HV (35 HRC)	Ties in with B7 composition Hardness unsuitable.	Unsuitable
Body	A694 F52 / F60 / F65	155 HV (1 HRC)		Suitable
Adaptors	A694 F52 / F60 / F65	Adaptor A - 170HV (6 HRC) Adaptor B - 134 HV (< 1 HRC)		Suitable
Gland Plate	A694 F52	229 HV, 20 HRC		Suitable
Stop Collar	Grade X52	154 HV, 1 HRC		Suitable
Adaptor (T-Plate)	No Match	278 HV (29 HRC)	C -0.351%, Mn - 1.41%, Cr - 0.038%, Mo - <0.005%, Ni - 0.041%	Unsuitable

Table 1 : PMI & Hardness Results from 36" Class 600 Ball Valve [3]

5.2 Current Standards Relating to Materials in Hydrogen Service

The effect of hydrogen on metallic materials for pressure equipment and valves is well documented with most attention currently given to the presence of Hydrogen Sulphide (H_2S) in the upstream oil and gas sector. Industry standards for materials in sour H_2S service have been produced by the National Association of Corrosion Engineers (NACE) [4]. Although the focus of the standards is sulphide stress cracking, a form of hydrogen embrittlement which occurs in the presence of sulphide, similarities can be drawn from the failure mechanisms caused by hydrogen alone. API 6D Annex M specifically states that all components should be in accordance with NACE MR0175 / ISO 15156 [4]. Austenitic stainless steels are stated by the EIGA guidelines to be suitable for hydrogen service, particularly for high pressures. Stainless steels (ferritic, martensitic, duplex or precipitation hardened) are stated to be suitable for use if they are used at low stress and at the low end of their strength ranges. However, it should be noted that "low stress" and "low strength" are not quantified within the guideline. Nickel and copper alloys are considered susceptible to hydrogen damage, and it is stated that care should be taken if used, although beyond general guidance on limiting applied stresses and hardness there are no specific requirements. Cobalt alloys (e.g. Stellite hard facing coatings on valves) are also considered acceptable [5].

ASME B31.12 [6] refers to carbon steels as being "listed materials" for pipelines. Additional reference is made to ASTM A381 which does allow the use of low alloy steels by agreement; however, this does not appear to be the intent of B31.12 (5). Notably B31.12 is significantly more open for piping and piping components, with various low alloy and austenitic steels being listed (5). The draft API 6D Annex M is written for valves specifically with a maximum temperature of up to 347°F(175°C) [7]. For valves above this temperature, it refers to API RP 941 [8]. It states that all metallic materials shall conform to either NACE MR0175 / ISO 15156 or to the requirements within API 6D Annex M Section M.4.1.3 [7]. The material groups of API 6D Annex M are as defined by NACE MR0175 / ISO 15156. In general, the recommended materials for pressure containing, pressure controlling parts and bolting for both ASME B31.12, EIGA and API 6D Annex M are generally aligned [5] [7] [6]. API 6D Annex M lists the below materials as permitted for use as pressure containing parts on Hydrogen service:

- Carbon steel
- Low allow carbon steel
- Austenitic stainless steel

The following materials can be recommended for pressure-containing parts, pressure-controlling parts and bolting in hydrogen service if materials are acceptable based on testing protocols and acceptance criteria as agreed between the manufacturer and the purchaser:

- Highly alloyed austenitic stainless steel
- Cold worked solution annealed or cold worked annealed nickel-based alloys
- Ferritic stainless steel
- Martensitic stainless steel
- Duplex stainless steel
- Precipitation-hardened stainless steel

Materials listed as acceptable with additional testing are not necessarily immune to failure mechanisms under all service conditions. The standards (API 6D Annex M, ASME B31.12 and EIGA) place the responsibility on purchasers to select the materials suitable for the intended service. API 6D Annex M does provide some guidance on recommended material testing for hydrogen service but doesn't explicitly state the testing to be used in a specific scenario. If the valve body is a casting, there is an additional risk of through wall leakage due to porosity, voids or other inclusions that may not have been found when first placed in service. Where a casting is required, or where a cast valve is being re-purposed for hydrogen service, appropriate NDE with a suitable acceptance criterion should be completed to verify the basic integrity of the casting and ensure it is free from defects. Similarly with pressure controlling elements of the valve assembly such as the ball, if they are a cast material additional checks will be required to ensure suitability for use within a hydrogen environment. As discussed, the qualification of metallic materials for hydrogen service is dictated by a combination of pipeline, pressure vessel and valve standards, none of which independently provides a complete framework for hydrogen valve integrity. The reviewed literature consistently demonstrates that hydrogen introduces fracture-controlled mechanisms, primarily through hydrogen assisted cracking and degradation of fracture toughness, which is not wholly addressed by conventional allowable stress based design codes [9] [10].

ASME B31.12, Hydrogen Piping and Pipelines, represents the most comprehensive hydrogen specific design code currently available. Although its formal scope is limited to piping and pipelines, it establishes the dominant material qualification and fracture control philosophy for hydrogen service [6]. B31.12 defines two design routes: Option A which is prescriptive and Option B which is performance based. Option A relies on conservative stress limits and material screen to control fracture risk indirectly, whereas Option B explicitly requires the use of hydrogen affected fracture toughness and fatigue crack growth data to demonstrate structural integrity. The fracture mechanics requirements embedded within ASME B31.12 are technically underpinned by ASME Boiler and Pressure Vessel Code Section VIII Division 3, Article KD-10, which provides explicit guidance on hydrogen specific fracture toughness testing, threshold stress intensity factors and crack growth behaviour. The hydrogen standards review confirms that this fracture control framework forms the technical basis for modern hydrogen integrity assessment across multiple international codes. [10].

European guidance, notably DVGW G464, adopts a similar fracture mechanics-based approach, incorporating Failure Assessment Diagrams (FADs) and hydrogen dependent fatigue crack growth laws for lifetime and integrity assessment of hydrogen pipelines [11]. While valves are not explicitly addressed, the governing mechanics and assessment methodologies are directly applicable to valve pressure retaining components. For pipeline valves specifically, API 6D Annex M provides hydrogen specific qualification requirements, including material controls, testing and leakage verification (API 6D Annex M) [7]. Annex M supplements the base API 6D valve specification but does not introduce fracture mechanics-based design rules. Consequently, Annex M should be regarded as a valve qualification and verification standard, rather than a complete hydrogen integrity code. In practice, hydrogen valve integrity must therefore be demonstrated through an integrated application of standards combining:

- ASME BPVC Section VIII Division 2 for stress, deformation and collapse assessment
- ASME B31.12 for hydrogen facture control philosophy
- API 6D Annex M for valve specific hydrogen qualification

5.3 Impacts to Fracture Toughness for Valve Materials

The available literature consistently identify reduction in fracture toughness as the dominant material degradation mechanism in hydrogen service. Hydrogen does not necessarily cause a proportional reduction in yield strength or ultimate tensile strength; instead, it suppresses crack tip plasticity, thereby reducing the material resistance to crack initiation and propagation [10] [9].

Fracture toughness measured in hydrogen environments, commonly denoted as KIH is systematically lower than air measured toughness (K_{IC}) and must be used for integrity assessment in hydrogen service at stress levels well below yield when crack like defects is present, particularly under high stress triaxiality [10] . This behaviour is especially critical for pipeline valves. Valve bodies, bonnets and closures, inherently contain geometric discontinuities that act as stress concentrators such as seat pockets, bonnet opening and injection points. Additionally weld overlays and welded joints also present areas that will be susceptible to hydrogen assisted cracking. Hydrogen assisted cracking is shown to be highly localised and defect driven, with weld metal and heat affected zones frequently governing fracture resistance rather than parent material.

The 55MPa√m lower bound fracture toughness referenced within ASME B31.12 Option B is widely used as a screening threshold but is recognised in the literature as a pragmatic design value rather than a universal material property. [6] [10] Reliance on traditional Charpy impact energy or air based fracture correlations alone is therefore insufficient to demonstrate hydrogen valve integrity.

5.4 Potential Locations for Fracture in Valve Bodies

In hydrogen environments, the degradation of fracture toughness and increased susceptibility to hydrogen-assisted cracking shifts valve integrity from a stress-controlled problem to a defect-controlled problem. Consequently, fracture assessment must focus on local features rather than global stresses and must explicitly consider postulated flaws at governing locations. There are a number of locations within the valve body pressure boundary that need to be considered as possible areas for crack initiation. Although nominally thick-walled valve bodies experience multiaxial stress states under internal pressure and elevated triaxiality compared to straight pipe. Fracture assessment is required were local membrane plus bending stresses approach design limits, thickness transitions exist or where defects exist from forging / casting processes. Seat pockets represent one of the more fracture critical valve features due to the sharp geometric discontinuities, local stress intensification and high through thickness stress gradients. These features often generate elevated stress triaxiality at the fillet roots and localised plasticity even when stresses are low. In Hydrogen service these conditions are particularly adverse because crack initiation and propagation are driven by local tensile stress and constraint. The removal of material required to accommodate the bonnet introduces a large structural discontinuity in the pressure boundary, resulting in combined membrane and bending stresses under internal pressure and pressure end loads. Internal fillets and thickness transitions in this region frequently govern local stress and strain response, particularly under pressure cycling. Fracture assessment is therefore required at the bonnet-to-body interface, with postulated corner or surface cracks used to represent potential crack-like defects at internal corners or threaded regions adjacent to the pressure boundary.

Where valves incorporate welded end adaptors or girth welds, fracture assessment must explicitly consider weld metal and heat-affected zone (HAZ) behaviour. Welded regions are widely recognised as preferential sites for hydrogen-assisted cracking due to locally reduced fracture toughness, residual stresses from welding, and hydrogen trapping effects. In many cases, the HAZ governs fracture resistance rather than the parent material. Weld overlays and hardfacing layers applied for wear or corrosion resistance introduce additional fracture-critical interfaces within the valve. These overlays create metallurgical and mechanical property mismatches at the fusion line and associated HAZ, which can elevate crack driving force under pressure and thermal loading. Hydrogen exposure further exacerbates this risk by reducing fracture toughness at the overlay interface.

Threaded and studded features cut into the pressure boundary also require fracture assessment, even where bolting materials themselves are replaced for hydrogen service. Threads introduce sharp notches, high local tensile stresses, and reduced ligament thickness, all of which promote crack initiation. For valves manufactured from cast materials, fracture assessment becomes particularly important due to the increased likelihood of embedded volumetric defects such as shrinkage porosity or inclusions. These defects may be benign in natural gas service but can act as crack initiation sites in hydrogen environments. Fracture assessment of cast valve bodies should therefore assume embedded flaws of conservative size and be supported by enhanced non-destructive examination to verify baseline material integrity. Across all valve types and features, weld metal and heat-affected zones must be treated as potentially governing fracture locations. Even where parent material properties appear favourable, local toughness reductions, residual stresses, and hydrogen diffusion effects in weldments can dominate fracture behaviour. Consequently, fracture assessment should always include weld and HAZ regions using conservative hydrogen-affected fracture toughness assumptions unless material-specific test data demonstrate otherwise.

5.5 Fracture Toughness of Valve Materials

Fracture toughness is the governing material property controlling resistance to crack initiation and propagation in pressure-containing components. For valve bodies operating in hydrogen service, fracture behaviour is defect-driven and therefore requires explicit consideration of fracture toughness rather than reliance on conventional strength-based parameters. As established in Section 5.3, hydrogen exposure alters the fracture response of steels, reducing resistance to crack propagation without necessarily affecting yield strength.

The primary materials used in NTS valve pressure boundaries, including ASTM [redacted] F52, are directly comparable to API 5L pipeline steels such as X52 and X60. These materials have been extensively studied and provide a reliable basis for fracture toughness estimation.

For API 5L X52 grade materials, representative hydrogen fracture toughness values (K_{IH}) are typically in the range of 60–100 MPa√m under pipeline operating conditions. Lower-bound values of approximately 55 MPa√m are widely adopted for design in accordance with ASME B31.12 Option B, while weld heat affected zones may exhibit reduced fracture resistance in the range of 30–60 MPa√m. Accordingly, fracture assessment should consider both conservative lower-bound values and realistic material behaviour to demonstrate adequate flaw tolerance.

A lower-bound conservative hydrogen fracture toughness value of 30 MPa√m has been adopted in line with industry practice and the fracture control philosophy underpinning ASME B31.12 Option B. This value represents a conservative screening threshold derived from pipeline validation data and ASME Section VIII Division 3 guidance, rather than a material-specific property.

5.6 Design Analysis Methodologies

5.6.1 Role of ASME BPVC Section VIII Division 2

Pipeline valves are commonly analysed using ASME BPVC Section VIII Division 2 Design-by-Analysis (DbA), employing elastic analysis or elastic–plastic analysis depending on the design complexity and allowable deformation [12]. Division 2 provides a rigorous framework for evaluating primary stresses, local plasticity, ratcheting, and collapse behaviour under combined pressure and mechanical loading.

However, ASME VIII Division 2 does not address hydrogen embrittlement or hydrogen-affected fracture toughness. Compliance with stress, strain, and collapse limits alone implicitly assumes that material fracture resistance remains adequate — an assumption explicitly challenged by hydrogen fracture literature [6] [10] [9]. Consequently, while ASME VIII Div 2 is necessary for demonstrating pressure containment and structural stability, it is not sufficient on its own for hydrogen service.

5.6.2 Engineering Implementation of ASME B31.12 Option A

ASME B31.12 Option A adopts a prescriptive approach intended to control fracture risk indirectly through conservative limitation of stress and material strength [6]. When applied to pipeline valves, Option A is implemented through:

- Elastic stress analysis, typically performed in accordance with ASME VIII Div 2 Part 5, to determine primary membrane and bending stresses.
- Verification that primary membrane plus primary bending stresses remain below allowable limits, consistent with Option A stress fractions.

- Demonstration that no progressive deformation or ratcheting occurs.
- Verification of pressure containment and leak integrity, commonly via helium leak testing as a hydrogen surrogate, consistent with API 6D Annex M [7]
- Option A does not explicitly assess crack stability and is therefore best suited to lower-stress hydrogen applications where conservative stress limits provide sufficient margin.

5.6.3 Engineering Implementation of ASME B31.12 Option B

ASME B31.12 Option B adopts a performance-based philosophy in which structural integrity is demonstrated explicitly through fracture mechanics using hydrogen-affected material properties (ASME, 2023a). For valves, this is implemented as follows:

- Elastic–plastic finite element analysis is performed to characterise realistic stress–strain fields and extract reference stress or limit load parameters.
- Postulated crack-like flaws are assessed using stress intensity factor or J-integral formulations in accordance with BS 7910 or API 579-1/ASME FFS-1
- Failure Assessment Diagram (FAD) evaluation is undertaken using hydrogen-affected fracture toughness (K_IH) rather than air-measured toughness [6] [11]
- Fatigue crack growth assessment is performed where cyclic loading exists, integrating hydrogen-relevant crack growth rates to determine allowable flaw sizes and inspection intervals [11] [6]
- This approach provides an explicit demonstration of flaw tolerance and structural integrity under hydrogen service conditions.

5.7 Discussion of WP1

The findings of WP1 demonstrate that the materials currently used within the National Transmission System (NTS) valve population are broadly consistent with established pipeline practice and are aligned with recognised material groupings defined within ASME B16.34. Carbon and carbon–manganese steels, particularly grades such as ASTM [redacted], [redacted] WCB and higher-strength materials such as ASTM [redacted], dominate the pressure boundary construction of NTS valves. These materials have historically provided reliable performance in natural gas service due to their favourable balance of strength, ductility, manufacturability and cost. However, the transition to hydrogen service introduces degradation mechanisms that are not explicitly addressed within traditional valve material standards, creating a fundamental gap between historical design intent and future service requirements.

A key outcome of the material review is the confirmation that material classification and allowable stress-based design alone are insufficient to demonstrate hydrogen suitability. ASME B16.34 provides an effective framework for defining acceptable material specifications and pressure–temperature ratings; however, it does not consider hydrogen-specific degradation mechanisms such as embrittlement or fracture toughness reduction. This limitation is particularly significant when assessing legacy NTS valves, where material selection was undertaken without consideration of hydrogen service. As such, the responsibility for demonstrating material suitability for hydrogen lies with the end user and must be supported by additional assessment beyond code compliance.

The Positive Material Identification (PMI) and hardness testing undertaken on the 36” Class 600 ball valve provide a representative insight into the NTS valve population. The identification of ASTM [redacted] F52 for pressure boundary components, combined with low measured hardness values (typically ≤6 HRC), indicates that the material is in a relatively ductile condition with low susceptibility to hydrogen-assisted cracking when assessed using traditional hardness screening criteria. This is consistent with industry guidance, which generally considers carbon steels below approximately 22 HRC to be suitable from a hydrogen embrittlement screening perspective. However, WP1 clearly demonstrates that hardness and material identification alone do not provide sufficient evidence of hydrogen integrity, as they do not account for hydrogen-induced reductions in fracture toughness.

The literature review confirms that hydrogen fundamentally alters the fracture behaviour of metallic materials, with the dominant degradation mechanism being a reduction in fracture toughness rather than a reduction in yield strength. Hydrogen suppresses crack-tip plasticity, increasing the likelihood of crack initiation and reducing resistance to crack propagation. This effect is particularly important for valve bodies, which inherently contain geometric discontinuities such as seat pockets, bonnet openings, and threaded features that promote local stress concentration and high stress triaxiality. Under these conditions, fracture behaviour becomes defect-driven, and the presence of small crack-like flaws can govern failure at stress levels well below those predicted by conventional allowable stress design methods.

The significance of this behaviour is reinforced by the observed material hierarchy within valve assemblies. While parent materials such as A694 F52 or equivalent X52 pipeline steels exhibit relatively high fracture toughness in hydrogen (typically in the range of 60–100 MPa√m), weld metal and heat affected zones (HAZ) often exhibit significantly lower resistance, typically in the range of 30–60 MPa√m. As a result, welded regions frequently represent the governing locations for fracture, rather than the bulk material. This has important implications for both new valve design and the assessment of legacy assets, where weld quality, residual stress, and HAZ properties must be explicitly considered.

The review of applicable standards highlights that no single code provides a complete framework for hydrogen valve integrity. API 6D Annex M defines hydrogen-specific qualification requirements for valves, including material controls and leakage testing, but does not incorporate fracture mechanics-based design rules. ASME B31.12 introduces a hydrogen-specific fracture control philosophy, particularly through Option B, which requires the use of hydrogen-affected fracture toughness and explicit crack stability assessment. However, its formal scope is limited to pipelines and piping systems. ASME BPVC Section VIII Division 2 provides a robust methodology for stress and deformation assessment but does not address hydrogen degradation mechanisms. Consequently, WP1 demonstrates that hydrogen valve integrity must be established through an integrated application of standards, combining stress analysis, fracture mechanics, and valve-specific qualification requirements.

The adoption of fracture mechanics-based assessment, as required by ASME B31.12 Option B, represents a fundamental shift in design philosophy. Traditional approaches based on allowable stress and Charpy impact energy are insufficient to demonstrate integrity in hydrogen environments. Instead, assessment must be based on crack-like defects, hydrogen-affected fracture toughness ($K_{(IH)}$), and explicit evaluation of crack driving force using methodologies such as Failure Assessment Diagrams (FADs). The commonly referenced lower-bound value of 55 MPa√m is widely used as a conservative screening threshold within industry; however, WP1 confirms that this value is not a universal material property, but a pragmatic design assumption derived from pipeline validation studies. More conservative values, such as 30 MPa√m, may be required to bound weld and HAZ behaviour.

Finally, the identification of fracture-critical locations within valve bodies reinforces the need for localised assessment. Features such as seat pockets, bonnet interfaces, welds, overlays, and threaded regions exhibit elevated stress and constraint conditions and must be explicitly evaluated. The governing failure location is therefore unlikely to correspond to regions of highest nominal stress, but rather to locations where geometry, material condition, and hydrogen effects combine to reduce fracture resistance.

In summary, WP1 demonstrates that while the materials used within the NTS valve population are broadly compatible with hydrogen service from a compositional and hardness perspective, their suitability cannot be assumed without explicit fracture-based assessment. Hydrogen introduces a defect-driven failure mechanism that is not addressed by conventional design standards, necessitating the adoption of a fracture mechanics-based approach. This finding directly informs the subsequent work packages, which focus on quantitative fracture assessment, validation testing, and the development of hydrogen-specific integrity criteria for NTS valves.

6.0 WP2 – VALVE DESIGN ANALYSIS

The purpose of Work Package 2 (WP2) is to evaluate the structural integrity and hydrogen service readiness of a representative National Transmission System (NTS) valve through a combination of finite element stress analysis and fracture-based assessment. This work package builds directly upon the findings of WP1, which established that hydrogen exposure fundamentally alters the governing failure mechanisms of metallic components. In conventional natural gas service, valve integrity is typically assessed using allowable stress-based criteria, whereby compliance with design code limits is considered sufficient to demonstrate structural adequacy. However, as demonstrated in WP1, hydrogen introduces fracture-controlled behaviour, whereby crack initiation and propagation govern failure at stress levels well below those associated with yielding or plastic collapse.

Accordingly, WP2 adopts a combined structural and fracture mechanics approach, integrating the stress classification framework of ASME BPVC Section VIII Division 2 with the hydrogen-specific philosophy of ASME B31.12. The intent is not only to demonstrate whether the valve satisfies conventional design criteria, but to determine whether these criteria are sufficient to support hydrogen service, or whether additional fracture-based assessment is required. The scope of the work is focused on the pressure-containing components of the valve, including the body, adaptors, bonnet, transition plate, welded end connections and associated bolting. Internal components such as the ball, seats and sealing systems are excluded, as the primary objective is to assess pressure boundary integrity under static loading conditions. The assessment considers internal pressure, external piping loads and assembly-induced bolt preload, representing the dominant loading mechanisms experienced during service. The outputs of WP2 include identification of critical stress locations, evaluation of code compliance, assessment of hydrogen fracture susceptibility and definition of the requirements for further fracture mechanics-based assessment.

6.1 Valve Details

The valve selected for assessment is a 36" Class 600 full-bore trunnion-mounted ball valve manufactured by [redacted] (See Appendix A). This valve is representative of legacy transmission valves installed within the NTS and therefore provides a suitable basis for evaluating hydrogen repurposing feasibility. The valve is of welded-end construction, with the body and adaptors forming the primary pressure boundary and load path between upstream and downstream pipework. The principal pressure containing components are manufactured from ASTM [redacted] F[redacted], a high-strength carbon-manganese steel commonly used in gas transmission systems. As established in WP1, this material offers a favourable combination of strength, toughness and manufacturability, and is typically supplied in a quenched and tempered condition. Hardness measurements obtained during earlier work indicated relatively low hardness values, consistent with a material condition prioritising fracture resistance over maximum strength. This is generally favourable from a hydrogen compatibility perspective; however, as discussed in WP1, hydrogen-induced degradation of fracture toughness cannot be inferred from hardness or material grade alone.

The transition plate is manufactured from AISI 4140, a higher strength low-alloy steel, while the bolting is consistent with ASTM [redacted] material, which exhibits significantly higher hardness levels. The presence of high-strength bolting is notable, as such materials are typically more susceptible to hydrogen-assisted cracking, particularly in high constraint regions. However, the focus of the present assessment is the pressure boundary behaviour rather than detailed bolting material requalification. The valve is designed for operation at a maximum design pressure of 102.1 barg, with a normal operating pressure of approximately 70 barg, and a temperature range between -20°C and +50°C. These conditions are representative of NTS service and are assumed to remain unchanged for hydrogen operation. The geometry of the valve is also assumed to remain unchanged, meaning that any hydrogen-related integrity concerns arise from changes in material behaviour rather than design modification.

Summarised Valve details

[redacted]

Size:	[redacted]"
Class:	[redacted]#
Bore:	Full Bore
End Connection:	Welded
Body:	ASTM [redacted]
Adaptor:	ASTM [redacted]
Bonnet:	ASTM [redacted]
Transition Plate:	AISI [redacted]
Body/Adaptor Bolting:	ASTM [redacted]
Body/Bonet Bolting:	ASTM [redacted]
Service Medium:	Natural Gas
Design Pressure:	102.1 Barg
Design Temp:	-20°C to + 50°C
Operating Pressure	70 Barg

6.2 Model Set-up – Pressure Containing Parts

6.2.1 Study Definition

The Finite Element (FE) study has been conducted in accordance with ASME VIII Div 2, Section 5 and ASME 31.12 option A & B it investigates the structural response of the valve's pressure containing parts and associated bolting at the both the design and test pressure as well as external piping loads. The pressure containing parts are defined as below:

- Body
- Adaptors
- Pipe Pups
- Bonnet
- Transition Plate

As the valve is of a weld end design, the model considers pipework up and downstream of the valve as well as the weld between the valve Adaptors and pipework. A request for information was raised to develop an understanding of the pipe loads observed in an installation. A report carried out by Murphys at AGI [redacted] was used to generate estimated pipe loads and design pressure within the FE model. The below table shows the load cases used within the stress analysis.

Load Case	Name	Description
1	[redacted]	[redacted]
2	[redacted]	[redacted]
3	[redacted]	[redacted]
4	[redacted]	[redacted]
5	[redacted]	[redacted]

Table 2 - Load Cases for Stress Analysis

6.2.2 Geometry and Meshing

A detailed three-dimensional finite element model of the valve pressure boundary was developed in SolidWorks Simulation to characterise the stress distribution under representative loading conditions. The model includes all primary load-bearing components, ensuring that load transfer between the valve body, adaptors, bonnet and connected pipework is accurately represented. Welded end connections were explicitly modelled through the inclusion of pipe pup sections, allowing realistic application of external piping loads. The geometry was simplified (See Figure 1) to remove non-structural features that would otherwise degrade mesh quality without contributing meaningfully to stress prediction. However, all key geometric features influencing stress concentration, including thickness transitions, internal radii, bolt interfaces and pressure boundaries, were retained. Particular attention was given to the bonnet opening, adaptor interfaces and transition plate regions, as these are known to introduce significant stress concentration and constraint.

[redacted]

The model was discretised using higher-order tetrahedral elements, with local mesh refinement applied to regions of anticipated high stress gradient. This included the bonnet bore, adaptor-to-body interfaces, bolt holes and welded pipe connections (See Figures 2, 3 and 4).

[redacted]

The mesh density was selected to ensure sufficient resolution through wall thickness and across contact interfaces, enabling reliable stress linearisation and accurate identification of peak stress locations. Multiple elements were ensured through thickness at all critical sections to support subsequent fracture assessment (See Table 3).

[redacted]

Figure 3 : Meshing Around the Body Bonnet Area & Bonnet, Transition Plate

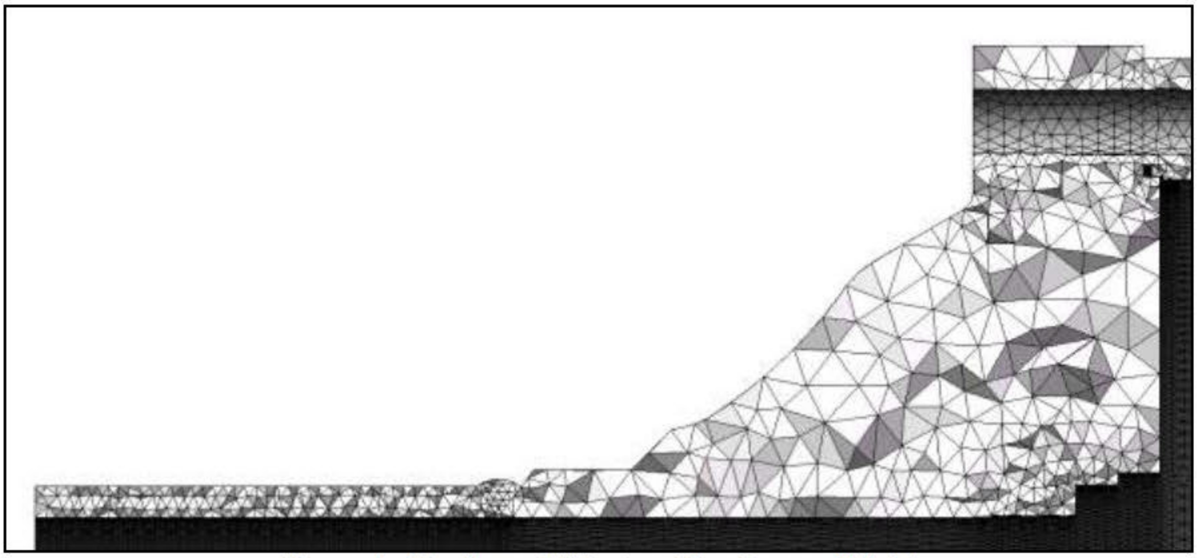


Figure 4 : Meshing of Adaptor, Pipe Pup and Weld

Component	Element Size (mm)
Global – Blended Curvature based	Max 30.0
Body – General	Max 26.5
Body – Adaptor Contact	8.5
Body – Adaptor Seal Area	5.50
Body - Adaptor Bolt Holes	10.5
Body – around bonnet bore	17.5
Body – Bonnet Bore	8.50
Body – Bonnet Bolt Holes	8.0
Body – Mesh Control Seat Pocket	9.0
Body -Bonnet Seal Area	5.5
Adaptor - General	Max 30.0
Adaptor Mesh Control Weld Prep	8.0
Body – Bonnet Contact	6.50
Bonnet - General	10.5
Bonnet – Transition Plate Contact	6.50
Pipe Pup – Mesh Control	7.20

Table 3 : Mesh Details of Simulation Model

6.2.3 Boundary Conditions

The FE models are linear static with non-linear contact used to model the interaction between components. Contact between pressure containing parts (e.g. body – adaptor) has been modelled as frictional, with a coefficient of friction of 0.2 to represent conservative steel on steel contact. The bolting has been modelled using the inbuilt bolting connection feature within the simulation package, whereby a pre-load is applied.

[redacted]

Internal pressure has been applied to all wetted areas (See Figure 5) within the valve; the pressure cases considered in each study are the working pressure and design pressure (See Table 4). Equivalent reaction loads due to the stem ejection have been applied to the relevant areas.

Element	Load Case				
	1	2	3	4	5
Internal Pressure psi	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Stem Ejection Load kN	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Piping Load X, N	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Piping Load Y, N	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Piping Load Z, N	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor to Body Bolting kN	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Bonnet to Body Bolting kN	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Transition Plate to Body Bolting kN	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 4 : Load Case Details

[redacted]

Bolt pretension loads (See Figure 6) have been applied to the models to represent the bolt pretension implemented on valve assembly (using bolt torque / tensioning equipment). The bolt load applied within the model is the force required to generate a stress equal to 50% of the bolt material specified minimum yield stress.

6.2.4 Material

Material properties were defined as linear elastic isotropic, consistent with ASME Section II Part D data. While this assumption is appropriate for stress classification and code compliance assessment, it does not capture plastic deformation or fracture behaviour and therefore requires careful interpretation when assessing hydrogen service. It is important to note that the model does not account for residual stresses arising from welding or manufacturing processes, nor does it include embedded defects or hydrogen diffusion effects. The results should therefore be interpreted as providing the stress state within an idealised structure, which must subsequently be used as input to fracture-based assessment rather than as a standalone demonstration of integrity. The material properties detailed below are based on ambient conditions, details of allowable stresses are detailed within Section 6.2.5.

Part	Material	σ_{yield}, (MPa)	UTS, (Mpa)
Body	ASTM A694 F52	360	455
Adaptor	ASTM A694 F52	360	455
Bonnet	ASTM A694 F52	360	455
Transition Plate	AISI 4140	515	690
Bolting - All	ASTM A193 B7	725	860

Table 5 : Material Properties

6.3 Assessment Methodology

[redacted]

6.3.1 Acceptance Criteria ASME VIII Div 2

[redacted]

- [redacted]
- [redacted]

[redacted]

Part	Material	σ_{yield}, (MPa)	UTS, (MPa)	Allowable Stress (MPa)
Body	ASTM A694 F52	360	455	189.58
Adaptor	ASTM A694 F52	360	455	189.58
Bonnet	ASTM A694 F52	360	455	189.58
Transition Plate	AISI 4140	515	690	287.50
Bolting - All	ASTM A193 B7	725	860	358.33

Table 6 : Allowable Stresses Used for ASME VIII Div 2 Assessment

6.3.2 Pathlines Used for Assessment

[redacted]

[redacted]

6.3.3 Acceptance Criteria ASME 31.12 Option A

[redacted]

For Use with Option A	
Location Class	Design Factor
1	0.5
2	0.5
3	0.5
4	0.4

Table 7 : Option A Location Class Values

Part	Material	σ_{yield}, (MPa)	Allowable Stress (Class 1-3) (MPa)	Allowable Stress (Class 4) (MPa)
Body	ASTM A694 F52	360	180	144
Adaptor	ASTM A694 F52	360	180	144
Bonnet	ASTM A694 F52	360	180	144
Transition Plate	AISI 4140	515	257.5	206

Table 8 : Allowable Stresses for Class 3 & 4 Locations)

6.3.4 Acceptance Criteria ASME 31.12 Option B

[redacted]

[redacted]

6.4 Results

6.4.1 Stress & Displacement Distribution

The finite element analysis demonstrates that the valve pressure boundary exhibits stable structural behaviour across all assessed load cases (LC1–LC5) (See Figures 8 – 12). The predicted displacements are small relative to the overall geometry and are localised primarily at regions of geometric discontinuity, including the bonnet opening, adaptor interfaces and pipe pup connections. There is no evidence of global instability, excessive deformation or loss of structural load path integrity.

The stress distribution within the valve is non-uniform and is governed by localised constraint effects. Elevated stresses are consistently observed at:

- Body-to-bonnet interface
- Body bore region (PL10, PL11, PL18, PL19)
- Adaptor transition regions
- Pipe pup connections under combined loading

These regions are characterised by steep through-thickness stress gradients and elevated triaxiality, which are known to promote fracture-controlled behaviour, particularly in hydrogen environments. Away from these localised regions, the stress distribution within the bulk of the valve body remains relatively uniform and well within allowable limits (See Appendix C). This confirms that the structural response of the valve is not governed by global loading effects, but rather by localised stress concentrations associated with geometry and load transfer. The governing stress locations identified in this analysis are used consistently in the subsequent code-based and fracture-based assessments.

[redacted]

[redacted]

6.4.2 ASME VIII Div 2 Assessment

The stress linearisation results show that primary membrane stresses are generally within the allowable limits defined by ASME VIII Division 2, with maximum values approaching but not significantly exceeding the allowable stress of approximately 189 MPa. This indicates that the valve pressure boundary can sustain the applied loads without risk of gross plastic deformation or collapse. Primary membrane plus bending stresses exceeds the nominal limit of 1.5S at certain localised regions, with peak values approaching approximately 360 MPa. These elevated stresses are confined to areas of geometric discontinuity and are associated with localised stress concentration effects rather than global structural behaviour. In the context of ASME VIII Division 2, localised elevated stresses may be acceptable if they are classified as secondary or peak stresses and do not contribute to progressive deformation or instability. However, the presence of these elevated stresses is significant in the context of hydrogen service, as they represent locations where crack initiation and propagation may be more likely. Overall, the ASME VIII Division 2 assessment demonstrates that the valve is structurally adequate under conventional design criteria but highlights the criticality of local stress concentrations in determining hydrogen integrity.

Load Case	Governing Location	Max Pm (MPa)	Max Pm+Pb (MPa)	Acceptance
LC1 – Working Pressure	Body (PL18 / PL11)	[redacted]	[redacted]	[redacted]
LC2 – Design Pressure	Body (PL18 / PL11)	[redacted]	[redacted]	[redacted]
LC3 – Pipe Loads	Adaptor (PL21)	[redacted]	[redacted]	[redacted]
LC4 – WP + Pipe Loads	Body (PL11 / PL18)	[redacted]	[redacted]	[redacted]
LC5 – DP + Pipe Loads	Body / Pipe Pup	[redacted]	[redacted]	[redacted]

Table 9 : Summary of ASME VIII Division 2 Assessment

6.4.3 ASME B31.12 Assessment – Option A

[redacted]

[redacted]

Load Case	Minimum Class 3 Ratio	Minimum Class 4 Ratio	Assessment
LC1 – Working Pressure	[redacted]	[redacted]	[redacted]
LC2 – Design Pressure	[redacted]	[redacted]	[redacted]
LC3 – Pipe Loads	[redacted]	[redacted]	[redacted]
LC4 – WP + Pipe Loads	[redacted]	[redacted]	[redacted]
LC5 – DP + Pipe Loads	[redacted]	[redacted]	[redacted]

Table 10 : ASME B31.12 Option A Summary Results

[redacted]

[redacted]

[redacted]

[redacted]

6.4.4 ASME B31.12 Assessment Option B

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]

Load Case	Governing Location	[redacted]	[redacted]	[redacted]	[redacted]
LC1 – Working Pressure	Body (PL11)	[redacted]	[redacted]	[redacted]	[redacted]
LC2 – Design Pressure	Body (PL11)	[redacted]	[redacted]	[redacted]	[redacted]
LC3 – Pipe Loads	Adaptor (PL21)	[redacted]	[redacted]	[redacted]	[redacted]
LC4 – WP + Pipe Loads	Body (PL18)	[redacted]	[redacted]	[redacted]	[redacted]
LC5 – DP + Pipe Loads	Body (PL11)	[redacted]	[redacted]	[redacted]	[redacted]

Table 11 : ASME B31.12 Option B Summarised (All Flaw Sizes)

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted].

Load Case	Location	Pathline	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC1	Body	11	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC1	Body	18	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC1	Body	10	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC1	Body	19	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC2	Body	11	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC2	Body	18	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC2	Body	10	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC2	Body	19	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC3	Adaptor	21	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC3	Adaptor	36	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC3	Adaptor	40	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC3	Adaptor	8	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC4	Body	18	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC4	Body	11	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC4	Body	19	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC4	Body	10	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC5	Body	11	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC5	Body	18	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC5	Body	19	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
LC5	Body	10	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 12 : Summarised Values of Load and Fracture Ratio

[redacted]

Figure 12 : Failure Assessment Diagram LC1

[redacted]

Figure 13 : Failure Assessment Diagram LC2

[redacted]

Figure 14 : Failure Assessment Diagram - LC3

[redacted]

Figure 15 : Failure Assessment Diagram LC4

[redacted]

Figure 16 : Failure Assessment Diagram LC5

6.4.5 Selection of Postulated Flaw Sizes and NDE Basis

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

6.5 WP2 – Discussion

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

7.0 WP3 – FUNCTIONAL REQUIREMENTS

The scope of WP3 is to develop a clear understanding of the current limitations, methodologies, and industry standards related to through valve leakage and maintenance within the National Transmission System (NTS), with a specific focus on hydrogen readiness.

The scope of work considers a review of acceptable in-line leak rates and valve seat sealing performance, examining current NGT operational parameters for both critical and general isolation valves, as well as identifying any knowledge gaps in maintenance documentation and existing industrial standards.

WP3 also investigates the diagnostic techniques currently employed by NGT for monitoring through-valve leakage, assessing their effectives when applied to hydrogen service and identifying any supporting data from valve OEMs. A further element of this work package is a critical review of available academic and industrial methodologies for testing valve seat wear, sealing degradation, and cyclic performance, particularly under conditions simulating real-world NTS operating pressures, and hydrogen exposure. Consideration is also given to environmental factors such as corrosion and abrasive particles within the line.

7.1 Request for Information (RFI)

7.1.1 Valve Information

To acquire the relevant information on the NTS, various RFIs were raised with NGT. The majority of the RFIs concerned the gathering of maintenance and diagnostic information held by NGT.

7.1.2 OEM Engagement

RFIs where also raised with the valve OEMs from NGTs Qualified Vender Database (QVD) as part of an engagement study reviewing what work has been conducted by OEMs in relation to valve degradation and maintenance in hydrogen service. An RFI survey sheet (see Appendix E) was developed to investigate the following areas:

- Hydrogen Leak Detection
- Seat Degradation Testing
- Maintenance
- Design

Ultimately the aim of the survey was to understand what the current marketplace considerations are with regards to valve maintenance in hydrogen service.

7.2 Challenges Relating to Hydrogen Leak Detection

Transportation of gaseous molecular hydrogen (H_2) presents several different technical challenges that must be carefully considered with respect to valve design, material selection, pressure testing and long-term maintenance. Molecular hydrogen (H_2) is the smallest and lightest element in existence, it is colourless, odourless, and tasteless, while it is non-toxic it is a highly combustible substance and as such presents significant risk with respect to transportation and storage.

The small molecular size of hydrogen in comparison to other molecules such as Nitrogen or Methane, makes maintaining an effective pressure boundary seal challenging. Additionally, atomic hydrogen (H) can permeate into and through materials which can affect the structural integrity of the material, in particular metallic materials.

Typically, failure mechanisms associated with metallic materials are the result of diffusion of atomic hydrogen (H) into the metal. The process typically involves the adsorption of molecular hydrogen (H_2) into atomic Hydrogen (H) onto the metallic surface, which is then absorbed into the metallic structure. The temperature, pressure, surface condition and chemical composition of materials will all influence the rate of adsorption, it is therefore critical to consider these factors as part of the process for repurposing or specifying new equipment.

The main failure mechanisms relating to metallic materials in hydrogen service are:

- Hydrogen embrittlement
- Hydrogen blistering
- Hydrogen induced (stress) cracking
- High-temperature hydrogen attack

7.3 Valve Seat Sealing and Degradation

7.3.1 Considerations for the Testing of Hydrogen Valves

Gas leak testing is currently conducted primarily with the use of nitrogen gas as it is inert and non-flammable, unlike air which contains approximately 21% oxygen. The molar mass of nitrogen is less than that of air meaning it can detect smaller leaks. However, given the even smaller molar mass of hydrogen, a valve which successfully passes nitrogen testing may not necessarily be leak tight on hydrogen service. The most stringent leak-testing currently involves the use of helium as the test medium. Like hydrogen, helium is lighter than air, however, unlike hydrogen, it is inert and non-flammable, making it far safer for testing purposes. Discussions are currently ongoing within the valve industry as to how to standardise the testing of valves for hydrogen service. Preliminary discussions lead us to believe that testing with helium will be acceptable, however, there is still the potential for testing with a gas mixture containing hydrogen. The testing of valves for use in hydrogen service is discussed in ASME B31.12 where the requested test medium is helium.

As per guidance from ASME B31.12 [6], all valves purchased to API 6D requirements for use in hydrogen service pipelines must be qualified against the requirements of API 6D (22nd edition) Annex C, paragraph C.4, using helium as the test medium. This means that valves are to be subject to high pressure gas seat tests at a minimum of 1.1 times the valve pressure rating, using helium as the test medium, in place of nitrogen. As per guidance from ASME B31.12, all valves not purchased to API 6D requirements for use in hydrogen service pipelines should be qualified against the testing.

API 6D Annex M includes requirements for type approval and Factory Acceptance Testing (FAT) for valves intended for hydrogen service. The level of testing required is dictated by Hydrogen Specification Level (HSL) although they are generally in line with the current API 6D requirements with an increase in the duration of the testing time and a reduction in the allowable leakage (for metal seated designs). The testing specified within API 6D Annex M utilises nitrogen gas for gas testing although though provision for testing with helium or forming gas (nitrogen with hydrogen) is also included. Additionally, provision is made for the addition of Fugitive Emission (FE) testing depending on the SLH.

7.3.2 NTS Operating Parameters

[redacted]

[redacted]

[redacted]

7.3.3 In-line Leakage Rates

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Leakage Rate (L/s)	Asset Health Score	Description
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 13 : NGT Acceptable In-Line Leak Rates

[redacted]

7.3.4 Seat Degradation Mechanisms / Contributing Factors

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

7.3.5 NGT Valve Specification

Currently, NGT procure valves according to the [redacted] which is additional to the Gas Industry standard GIS/V6. To qualify a valve design to this standard, it must undergo a type test procedure. As part of the type test procedure, the valve is subject to cyclic testing at atmospheric pressure to establish any change in breakout torque as well as breakout testing at 100 barg differential pressure. Following the cyclic and breakout testing, the valve is subject to hydrostatic seat testing to highlight any deterioration in performance. No gas seat testing is performed as part of the type test procedure.

7.3.6 Industry Standards

Various available industry standards provide guidance on cyclic and endurance testing of ball valves e.g. API 6D, API 17D. Dynamic pressure testing in API 6D Annex M [6] stipulates a minimum of 160 operations are completed, whilst pressure cycling testing in API 17D stipulates that a minimum of 200 operations are completed. These far exceed the expected number of operations for the valves on the NTS over their whole service life.

7.3.7 Academia

Various academic sources have studied the effects of cycles on seat sealing ability. Teles, D.B. et al. (13) conducted a study on the "identification of leakage in ball valves by analysis of pressure and torque signatures in cyclical tests under critical operating conditions". The seat material of the valves used in the study was RPTFE, a common material that can be specified for valves on the NTS. The valve was subject to 1205 cycles at a differential pressure of 92 bar. It was found that on cycle 202, a positive seal was lost between the seat and ball. Following the cyclic testing, the valve was disassembled where damage was noted to the polymer seat insert

7.4 NTS Valve Maintenance

7.4.1 Current Valve Maintenance Instructions / Strategy

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

7.4.2 Current Overhaul Strategy

[redacted]

7.4.3 Diagnosis of Valve Faults

[redacted]

7.4.4 Maintenance Procedure Gaps

[redacted]

7.4.5 Industry Recommended Best Practice for Hydrogen

ASME B31.3 Section GR-5.11 provides recommended valve maintenance for valves fitted in hydrogen piping systems. It states that valves that are required to be operated during an emergency shall be examined periodically and partially operated at least once a year to provide safe and proper operating conditions. Routine valve maintenance procedures shall include, but not be limited to, the following:

- Servicing in accordance with written procedures by adequately trained personnel.
- Accurate system maps for use during routine or emergency conditions.
- Valve security to prevent system interruptions, tampering etc. as required.
- Employee training programs to familiarise personnel with the correct valve maintenance procedures.

Emergency valve maintenance procedures are to include:

- Written contingency plans to be followed during any type of emergency.

- Training personnel to anticipate potential hazards.
- Furnishing tools and equipment as required, including auxiliary breathing equipment, to meet anticipated emergency valve servicing and/or maintenance requirements.

Section GR-5.11.2 relates to distribution system valves and states that valves shall be checked and serviced, including lubrication where necessary, at sufficiently frequent intervals to assure their satisfactory operation. It states that valves in hydrogen service shall be checked and serviced at least annually, although does not stipulate the extent of servicing this should entail. The European Industrial Gases Association states that due to the risk of ignition from a hydrogen leakage, maintenance shall only be done after positive isolation of the concerned installation, followed by inerting. The process of inerting involves displacing the oxygen from the pipeline using an inert gas to remove the risk of ignition.

7.5 Diagnostic / Leak Detection Techniques

7.5.1 Acoustic Emissions

The primary method for establishing in line valve leakage rates is via Acoustic Emissions (AE) technology. Acoustic methods, such as Score's Midas® meter, detect high frequency acoustic emission signals generated by fluid leaking across the valve seat. AE readings are quick to take and give an estimation of the actual leak rate at the time of test.

Leakage noise is produced by the varying pressure field associated with turbulence caused by the leakage flow and the disturbance of the fluid on the low-pressure side of the valve. This pressure field propagates through the fluid; when the field encounters a solid barrier such as the valve body or pipe wall the field is transformed into elastic waves within that solid. These elastic waves are known as Acoustic Emissions (AE) and can be detected on the external surfaces of that solid barrier by suitable sensors.

The amplitude and frequency spectrum of the AE in a leaking valve are dependent on a range of variables, several of which have complex interactions with each other. These variables are:

- The leaking fluid type and its properties such as viscosity, density and compressibility.
- Upstream and downstream pressures and potential, with gas, for choked flow to occur.
- Geometry of the leak path: cross-sectional shape, length and number of leak paths.
- Transmission path length and attenuation from noise source to sensor location.
- Valve type, geometry and size.

Various researchers have tried to establish some form of theoretical relationship between the leakage rate, the AE signal spectrum and some of the above variables. The theoretical studies have been limited to very specific cases; however, they show that the Average Signal Level (ASL) of the AE spectrum is a good indicator of the leakage and that an empirical approach can provide a representation of this relationship.

This empirical approach requires a database to be established of ASL measurements versus measured leak rates for a wide range of valve types, sizes, pressures, fluids with varying forms of damage. Score have established such a database from leakage simulator test rigs, tests on valves with deliberately damaged seats, from valves returned to Score for overhaul and from valves tested in-situ.

In the hydrogen space, acoustic emissions technology has generally been tested for external leakage only, however, the results are positive and are transferable for internal leaks.

7.5.2 Hydrogen vs Natural Gas Acoustic Emissions

The speed of sound in hydrogen is about three times higher than in natural gas, whilst the resonance frequency is also higher, leading to sharper, higher-pitched acoustics for hydrogen leakage. The leakage of natural gas produces sound in both the audible and ultrasonic ranges, however, the leakage of hydrogen typically produces sound in the ultrasonic range meaning it can be more difficult to hear, especially in noisy environments.

7.5.3 Existing NGT Leak Detection Techniques

[redacted]

[redacted]

Table 15 : NGT Dines Scale

[redacted]

[redacted]

[redacted]

[redacted]

7.5.4 Midas Meter / Sensors

The Midas meter is a portable, non-invasive diagnostic tool used to detect, quantify and monitor valve leaks in live process plants. The tool was developed by Score after 15 years' experience of AE valve leak detection. It works by measuring acoustic emissions from the valve body while it is under pressure. The high frequency noise generated from the leaking fluid at the valve seat to ball interface is converted to a leakage rate to determine the extent of through seat leakage. The use of a Midas meter requires contact with the exterior body of the valve hence is unsuitable for valves that are buried.

The Midas Meter comprises two main components:

- An intrinsically safe handset that detects AE signals from leaking valves and employs digital processing to give the Average Signal Level (ASL) in decibels (dB) of the AE signal from the leakage source.
- A PDA which receives the AE ASL from the handset via Bluetooth and records this against the specifically input valve data before using the data to quantify the leakage present.

Midas sensors use the same acoustic technology as the Midas meter; however, they are affixed semi-permanently to the valve body and provide a constant read out of the valve acoustics.

7.5.5 Fibre Optic Leak Detection

Fibre optic leak detection uses a fibre optic cable to continuously monitor vibrations or temperature changes. Fibre optic leak detection can be used for underground installations as the optic cable is attached to the pipeline and transforms into a series of virtual sensors, detecting continuous changes in the surrounding environment due to leaks. The fibre optics detect changes in pressure, temperature and noise that may occur due to leaks.

7.6 OEM Engagement

All OEMs detailed on NGT's current Qualified Vendor Database (QVD) were contacted regarding their current work on valve internal leak detection and maintenance with regards to use on hydrogen, or hydrogen blend, service. A Request for Information (RFI) questionnaire was developed to gather the required information from the vendors. The questions were set against the following areas:

- Hydrogen Leak Detection
- Testing
- Maintenance
- Design

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

7.7 WP3 – Discussion

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

8.0 WP4 – TESTING ASSESSMENT

The scope of WP4 is to validate and evaluate the degradation of a selected ball valve and diagnostic techniques through structured testing. Forming gas (95% N_2, 5% H_2) is used as a hydrogen surrogate to simulate conditions anticipated in a hydrogen-ready NTS. The scope of work builds upon the findings of WP3 and focusses on the physical validation of valve performance and leakage detection methodologies under conditions representative of hydrogen service.

8.1 Valve Selection Process

[redacted]

8.1.1 Valve Details

[redacted]

8.1.2 Materials of Construction

[redacted]

8.2 Test Methodology

A bespoke test methodology [19] was created with forming gas being used as a hydrogen surrogate.

8.2.1 Forming Gas

Forming gas is a mixture of H_2 and nitrogen (N_2), with a common ratio of approximately 5% H_2 and 95% N_2. The dilution of the H_2 reduces the safety risks of testing with a greater percentage of H_2. The maximum content at which H_2 becomes flammable in air (when mixed with N_2) is noted as 5.5% as per ISO 10156:2017 (Table 2). Although a seemingly low concentration, H_2 is still detectable using appropriate instrumentation and therefore a viable alternative to the standard gas helium (He) for fugitive emissions testing. A mixture of 5% H_2 and 95% N_2 is therefore to be used in this instance.

8.2.2 Methodology Overview

Discussions were held between Score and NGT where it was confirmed that the valve would undergo cyclic seat testing. The valve was to be subject to a total of 320 breakout tests at a differential pressure of 3 bar with seat tests at 70 barg, 80 barg and 90 barg being undertaken on every tenth cycle. These test pressures were specifically requested by NGT to match their typical operating parameters. During the seat tests, the leakage rate at both the cavity and end to end was to be measured using a flow meter. End to end leakage was also to be comparatively measured using Score's Midas Meter. The Extrima leak detector, manufactured by Inficon, was to be used to detect external hydrogen leakage from the stem as well as internal hydrogen leakage via the cavity vent port. A schematic of the test set up for the cyclic seat tests is provided in Appendix G.

NGT also supplied Score with one of their PRIs for comparative testing. On completion of the cyclic seat testing, the intention was to inflict damage to the valve seat such that a leakage could be engineered and the PRI would be used alongside Score's flow meter to record the valve internal leakage rate and the results compared for accuracy.

8.3 Test Results

8.3.1 Test Set-Up

Due to acoustic technology being used during the testing, the test set-up consisted of 3-off 10" x 600# ball valves in series. This was done to reduce noise and turbulence before and after the main valve seat sealing interface to ensure accuracy of the acoustic results. The [redacted]

Figure 17: WP4 Test Set Up

8.3.2 Pre Testing

Initial pre-testing was completed on the valve to benchmark its performance. Tests were undertaken using both inhibited water and nitrogen gas as the test media at the full ASME B16.34 test pressures for the body and seat. No leakage was observed over the full test durations. A Norbar was fitted to the valve to carry out torque testing at zero differential pressure. The torques were compared with the OEM torques at full differential pressure where no concerns were raised. The valve was then deemed suitable to proceed with testing with forming gas.

The assembly was subject to a body test at the full ASME B16.34 gas test pressure of 113 barg, using forming gas as the test medium. No leakage was observed over the full test duration. The test results are summarised in Table 16 and Table 17, below.

Pre Trial Pressure Tests				
Test	**Medium**	**Pressure (barg)**	**Duration (mins)**	**Result**
Body	Inhibited Water	154	15	Zero Leakage
Seat 'A'	Inhibited Water	113	5	Zero Leakage
Seat 'A'	Inhibited Water	113	5	Zero Leakage
Body	Nitrogen Gas	113	15	Zero Leakage
Seat 'A'	Nitrogen Gas	113	5	Zero Leakage
Seat 'B'	Nitrogen Gas	113	5	Zero Leakage
Body	Forming Gas	113	15	Zero Leakage

Table 16 : Pre Trial Pressure Test Results

Note: Torque testing completed at zero differential pressure			
Torque Results (Opening)			
Test	**Run 1 (Nm)**	**Run 2 (Nm)**	**Run 3 (Nm)**
Break to Open	277	278	277
Run to Open	7	12	19
End to Open	70	70	59
Torque Results (Closing)			
Break to Close	705	680	684
Run to Close	590	590	585
End to Close	550	550	541

Table 17 : Pre Trial Torque Test Results

8.3.3 Cyclic Seat Testing

A flow loop was connected to the test equipment, as per Appendix G, to begin cyclic testing. The assembly was first subject to seat tests with forming gas at 70 barg, 80 barg and 90 barg to benchmark the isolation performance. Total gas leakage was recorded at the cavity and end to end via a flow meter, whilst internal hydrogen leakage was recorded at the valve cavity and external hydrogen leakage was recorded at the stem area, using an Extrima leak detector. The valve was subject to a full suite of cyclic seat testing where 320 break out tests were completed at 3 barg differential pressure. Seat testing was completed on every tenth cycle to assess the leakage at 70 barg, 80 barg and 90 barg, respectively. The leakage rate results recorded were as per Figure 18 to Figure 20, below.

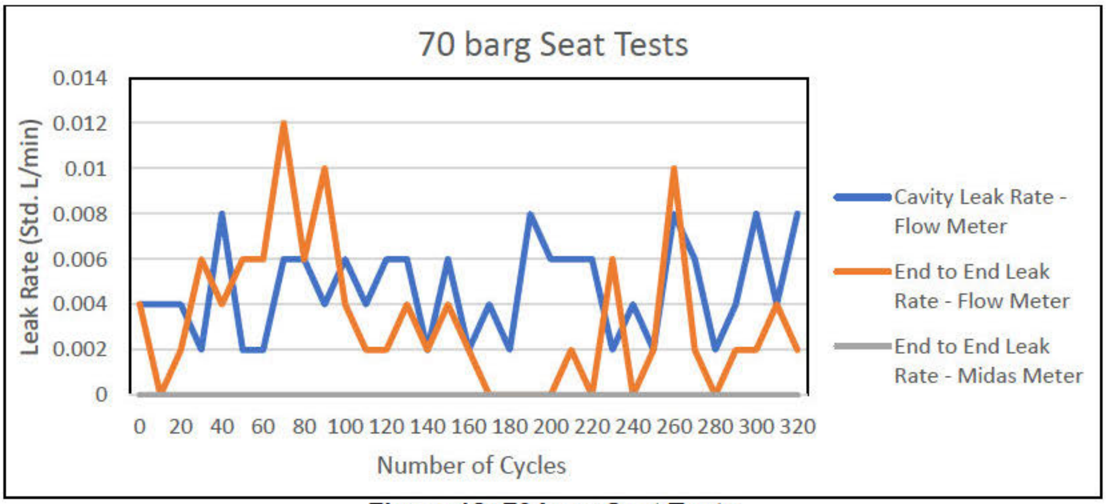


Figure 18: 70 barg Seat Tests

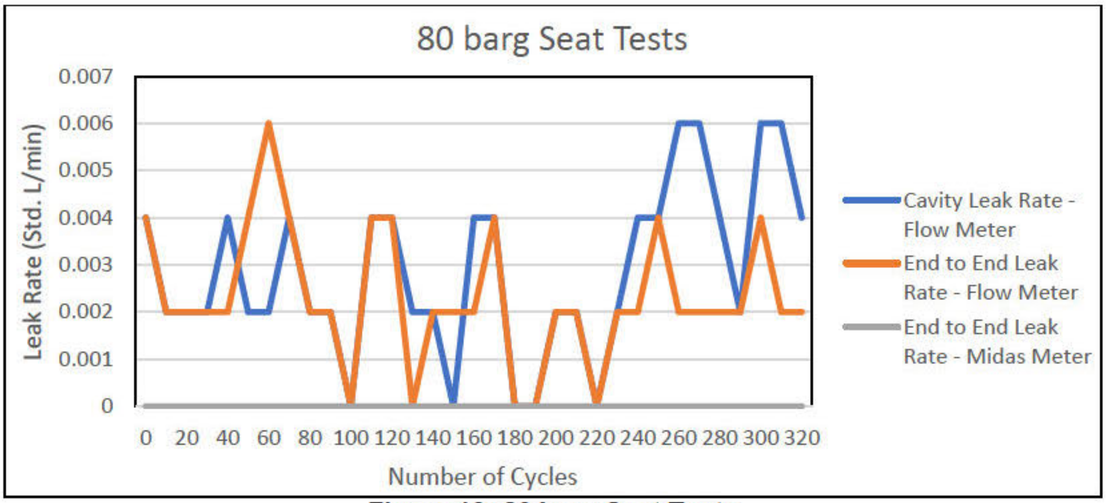


Figure 19: 80 barg Seat Tests

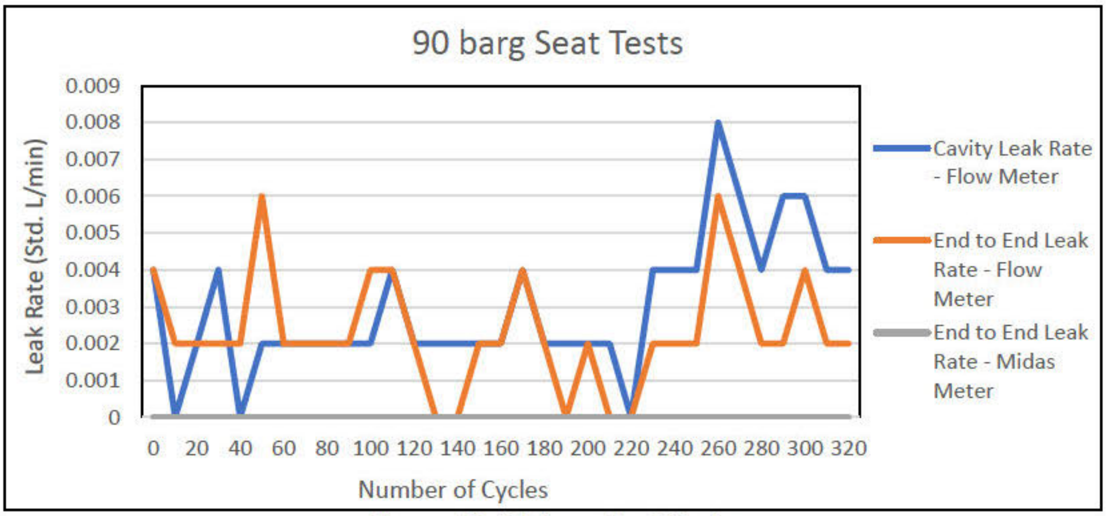


Figure 20: 90 barg Seat Tests

The results show that very small leakages were detected at both the cavity and end to end, none of a magnitude great enough to produce a pressure drop on the test gauge. The Midas Meter detected zero leakage throughout the suite of seat testing.

The hydrogen leakage at both the cavity and stem was measured during each seat test. The results were as per Figure 21 to Figure 24, below.

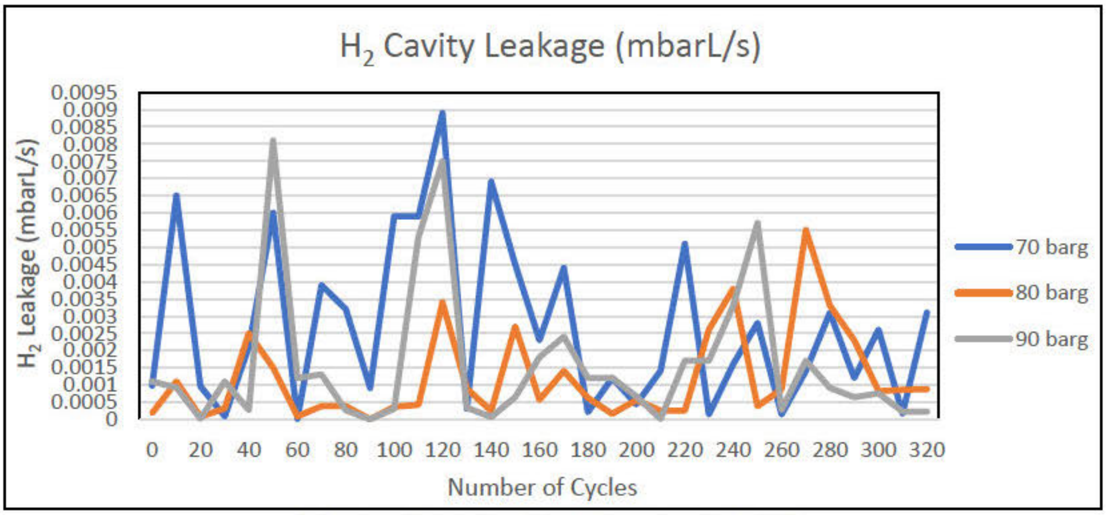


Figure 21: Cavity Hydrogen Leakage (1)

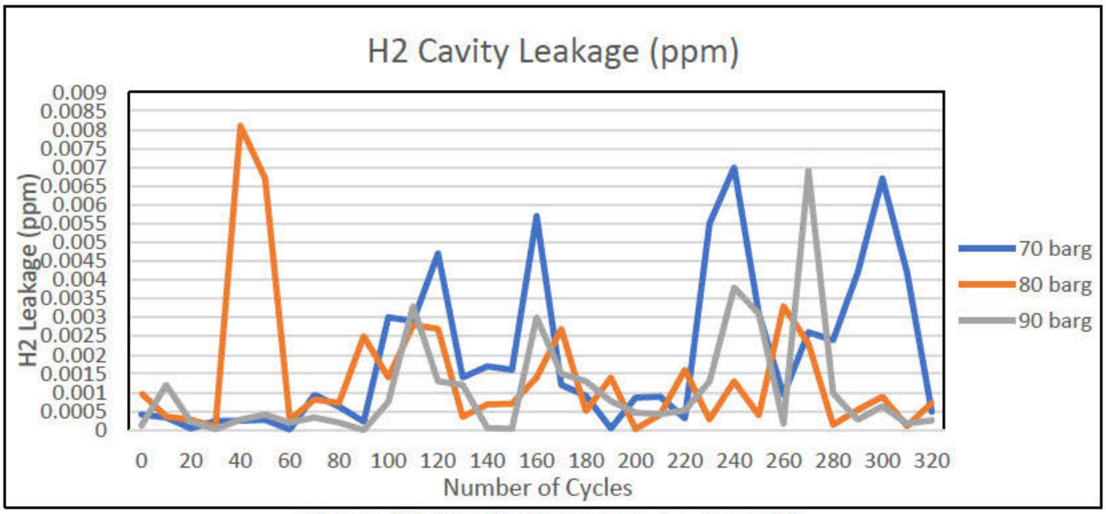


Figure 22: Cavity Hydrogen Leakage (2)

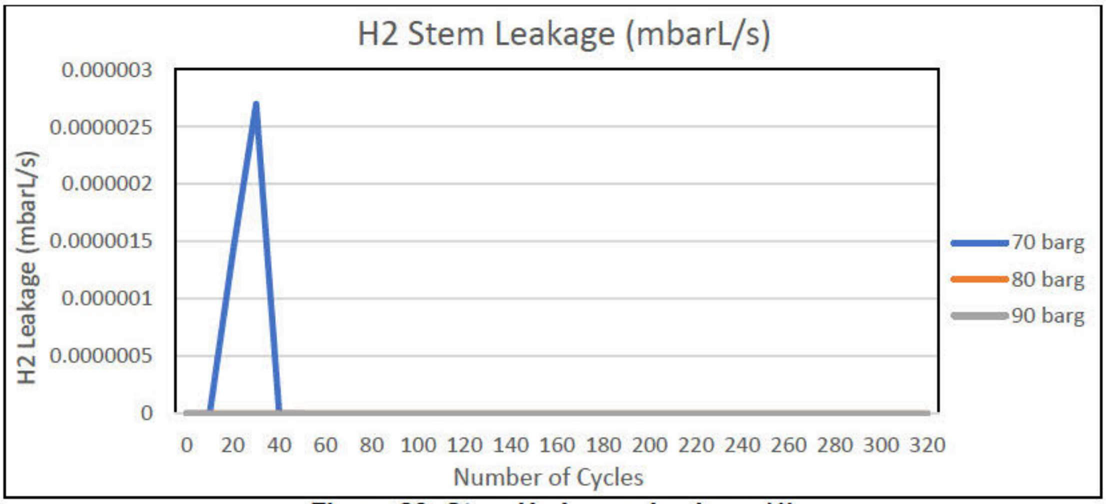


Figure 23: Stem Hydrogen Leakage (1)

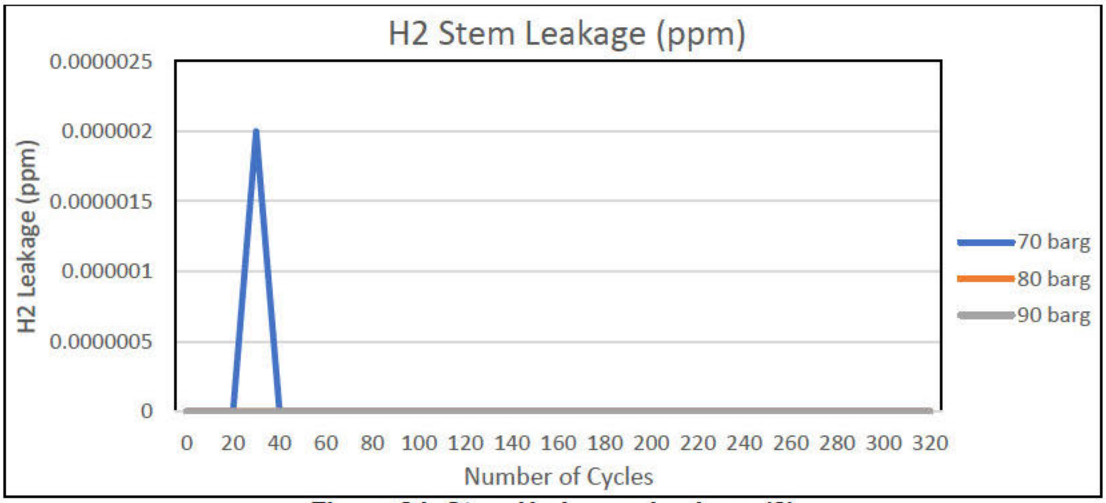


Figure 24: Stem Hydrogen Leakage (2)

No specific trend was found with the cavity hydrogen detection results, whilst no stem leakage was recorded apart form one unexplained spike on the 30th test cycle.

The break torque at 3 barg differential pressure was recorded on every 10th cycle where no notable concerns were raised. The results are as per the below figure.

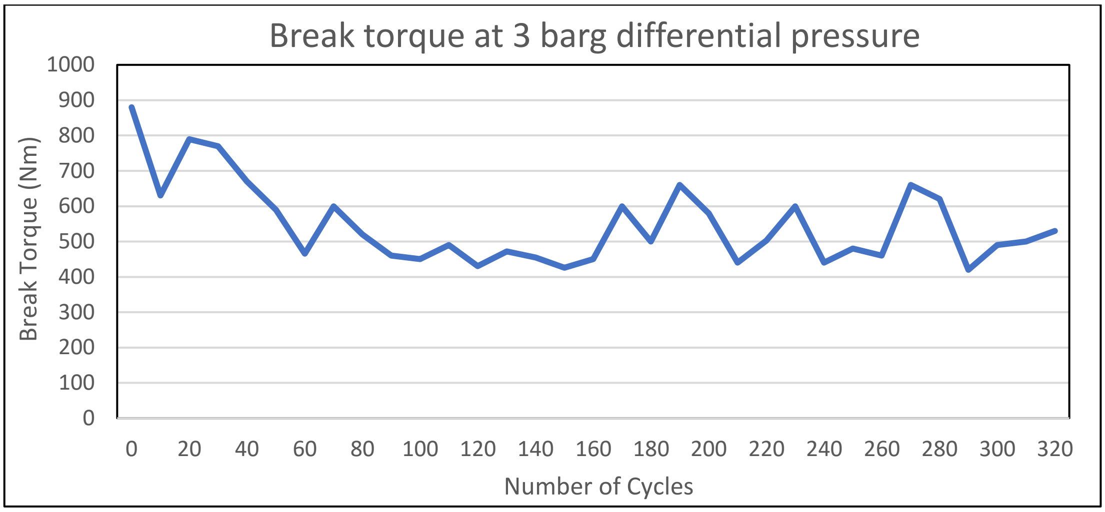


Figure 25: 3 barg DP Break Torque

8.3.4 PRI / Blowdown Tool Testing

[redacted]

[redacted]

8.4 WP4 – Discussion

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

9.0 DISTRIBUTION LIST

[redacted]

10.0 REFERENCES

[1] Energy Networks Association, “Steel Valve for Use with Natrual Gas at Normal Operating Pressures Above 7 bar and sizes above DN15,” *GIS/V6:2023,* 2023.

[2] American Society for Mechanical Engineers (ASME), “B16.34: Valves - Flanged, Threaded, and Welding End,” ASME, New York, NY, USA, 2025.

[3] K. Delaney, Hydrogen Impact on National Transmission System 3 - peice Ball Valves, Brighouse : Score , 2025.

[4] NACE, “NACE MR 0175/ISO 15156 FOR CORROSION RESISTANT ALLOYS FOR SULPHIDE SERVICE,” National Association of Corrosion Engineers , 2005.

[5] E. I. G. A. (EIGA), “Hydrogen Pipeline Systems,” European Industrial Gases Association, Brussels, 2014.

[6] ASME, “Hydrogen Piping and Pipelines ASME B31.12-2019 ASME Code for Pressure Piping,” The American Society of Mechanical Engineers,, New York, 2019.

[7] API , “API Specification 6D - Specification for Pipeline and Piping Valves - Annex M Draft,” American Petroleum Institute , 2024.

[8] American Pteroleum Insttute, “API RP 941 : Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants 8th Edition,” API, 2016.

[9] European Pipeline Research Group, Literature Study on Hydrogen Pipeline Steels, 2020.

[10] N. M. E. S. N. L. M. Sanchez, Standards and Codes for Hydrogen in Pipeline Infrastucture: Testing, qualification and integrity assessment, 2025.

[11] Deutscher Verin des Gas - und Wasserfaches, DVGW Code of Practice G464: Steel Pipelines for Hydrogen Gas, 2021.

[12] ASME, Boiler & Pressure Vessels Design Code Section VIII Division 2, 2023.

[13] S. Lueb and S. Delnooz, “Switching from a natural gas distribution grid to a 100% hydrogen distribution grid,” Banff, Canada, 2024.

[redacted]

[17] ISO, “ISO 15848-1 Industrial valves — Measurement, test and qualification procedures for fugitive emissions,” *2015.*

[18] ISO, “ISO 5208 Industrial valves — Pressure testing of metallic valves,” *ISO 5208 ,* 2015.

[19] J. Clacher, “Test Procedure for Hydrogen Trial Testing on a 10" Class 600 FG Valvole Ball Valve Rev 2,” 2025.

[20] J. Armstrong, R. Atkins and D. Karran, “IMPACT OF HYDROGEN ON NTS OILS & GREASES,” Wood, Aberdeen, 2023.

[21] K. Delaney, M. Burgess, M. Billington, S. Buchan and D. Gordon, “H2 Impact on NTS 3-Piece Ball Valves – Final Report,” Score Group Ltd., Peterhead, 2025.

[22] ASTM International, “D445 - Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity),” ASTM, West Conshohocken, PA, USA, 2024.

[23] ASTM International, “D4052 - Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter,” ASTM, West Conshohocken, PA, USA, 2022.

[24] ASTM International, “D3427 - Standard Test Method for Air Release Properties of Hydrocarbon Based Oils,” ASTM, West Conshohocken, PA, USA, 2025.

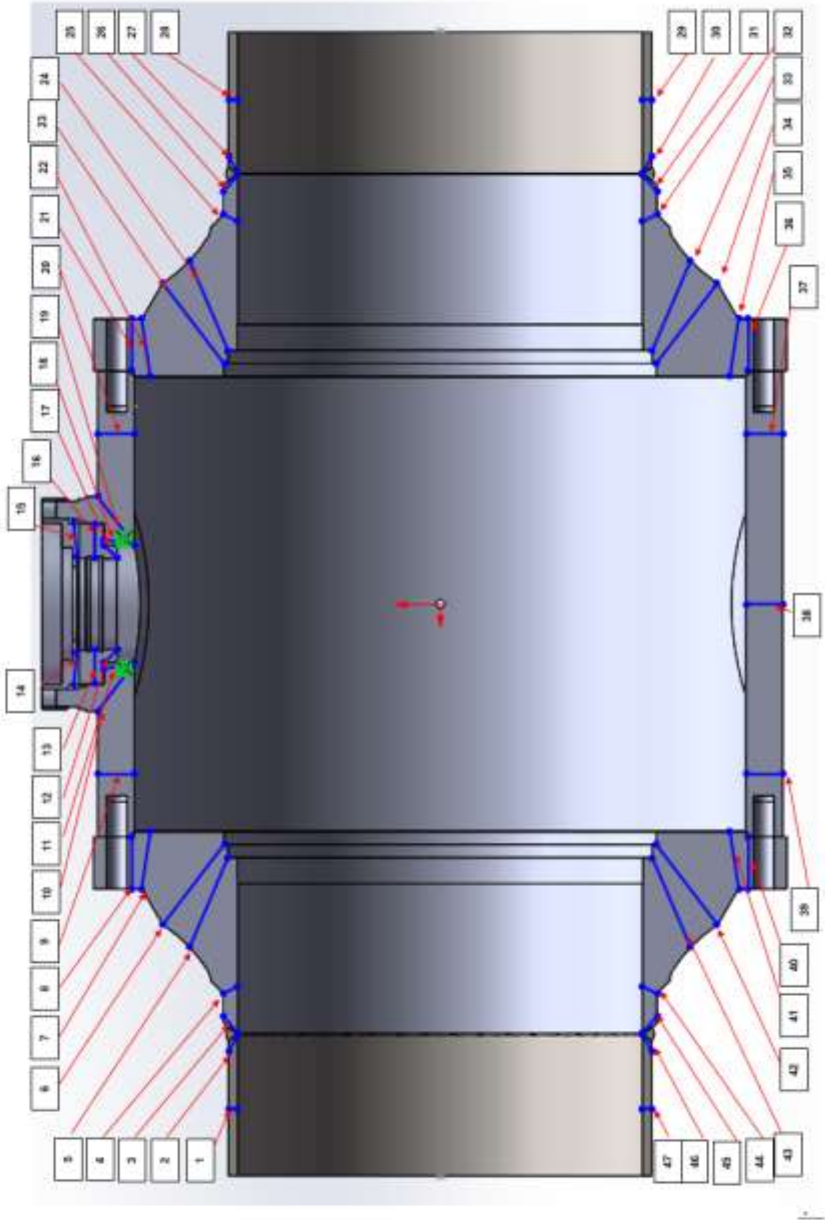
[25] ASTM International, “D892 - Standard Test Method for Foaming Characteristics of Lubricating Oils,” ASTM, West Conshohocken, PA, USA, 2020.

[26] ASTM International, “D4172 - Standard Test Method for Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method),” ASTM, West Conshohocken, PA, USA, 2025.
[27] ASTM International, “D7563 - Standard Test Method for Evaluation of the Ability of Engine Oil to Emulsify Water and Simulated Ed85 Fuel,” ASTM, West Conshohocken, PA, USA, 2023.
[28] ASTM International, “D92 - Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester,” ASTM, West Conshohocken, PA, USA, 2024.
[29] ASTM International, “D665 - Standard Test Method for Rust-Preventing Characteristics of Inhibited Mineral Oil in the Presence of Water,” ASTM, West Conshohocken, PA, USA, 2025.
[30] D. Gordon, N. Burgess and M. Burgess, “Test Procedure for Hydrogen Sealant Injection Trial Testing on 3-off Sealant Compounds,” Score, Peterhead, UK, 2025.
[31] D. Gordon, A. Milne and M. Allan, “Failure Investigation on a 6" Class 600# Petrolvalves Ball Valve,” Score, Peterhead, UK, 2025.
[32] Z. C, “Hydrogen Permeation Behaviour of Rubber Materials,” *Hydrogen Energy,* 2024.
[33] Z. Y, “Effect of Hydrogen on Rubber Sealing Materials Used in Hydrogen Infrastucture,” *Hydrogen Energy,* 2020.
[34] N. S, “Hydrogen Dissolution and Diffusion in Elastomeric Materials,” *Chemical Physics Letters ,* 2012.
[35] L. Z, “Failure Modes of Rubber O-Rings in Hydrogen Enviroments,” *Polymers,* 2025.
[36] Y. S, “Tribology of PTFE Sliding Contacts in Hydrogen Atmospheres,” *Tribology International,* 2025.
[37] Y. Sawee, “Wear behaviour of PTFE Composits in Hydrogen Compressor Applications,” *Tribology Letters,* 2021.
[38] J. Spora, “Tribological Systems in Hydrogen Enviroments,” *Hydrogen Energy,* 2026.
[39] M. Y, “Recent Advances in Tribology Research,” *Friction,* 2022.
[40] A. E. K Holmberg, “Global impact of Tribology on Energy Consumption,” *Tribology International,* 2017.
[41] J. Man, “Hydrogen Aging Effects on Ball Valve Materials,” *Hydrogen Energy,* 2025.
[42] H. Barthelemy, “Hydrogen Storage and Industrial Challenges,” *Hydrogen Energy,* 2012.
[43] B. S. C San Marchi, “Hydrogen Compatibility of Materials,” *Sandia National Laboratories.*
[44] R. Gangloff, “Hydrogen Assisted Cracking,” *Metallurgical Transactions .*
[45] H. Spikes, “Lubricant Additives and Boundary Lubrication,” *Tribology Letters,* 2016.
[46] A. Neville, “Tribochemistry in Lubricated Contacts,” *Tribology International ,* 2019.
[47] M. Ratoi, “Tribological Behaviour of Lubricated Contacts in Hydrogen”.
[48] American Petroluem Institute (API), “Specification for Valves, API SPECIFICATION 6D,” API Publishing Services, Washington DC, USA, 2025.
[49] American Petroleum Institute, “API 941: 2016 - Steels for Hydrogen Service at Elevated Temperatures and Pressures in,” API Publishings, Washington DC, USA, 2016.
[50] American Society of Mechnical Engineers, “B16.34 Valves Flanged Threaded and Welding End,” ASME, 2021.

Appendix A: General Arrangement Drawing

[redacted]

Appendix B: Pathlines



Appendix C: Additional Stress Plots

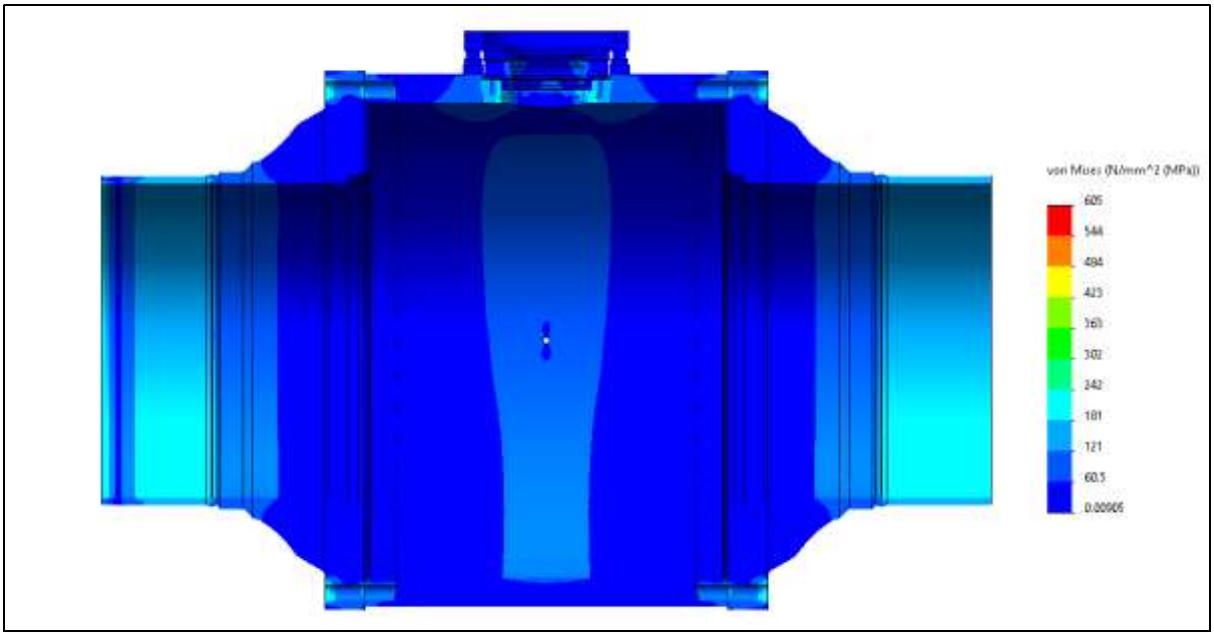


Figure 26 : LC1 Stress Plot Section

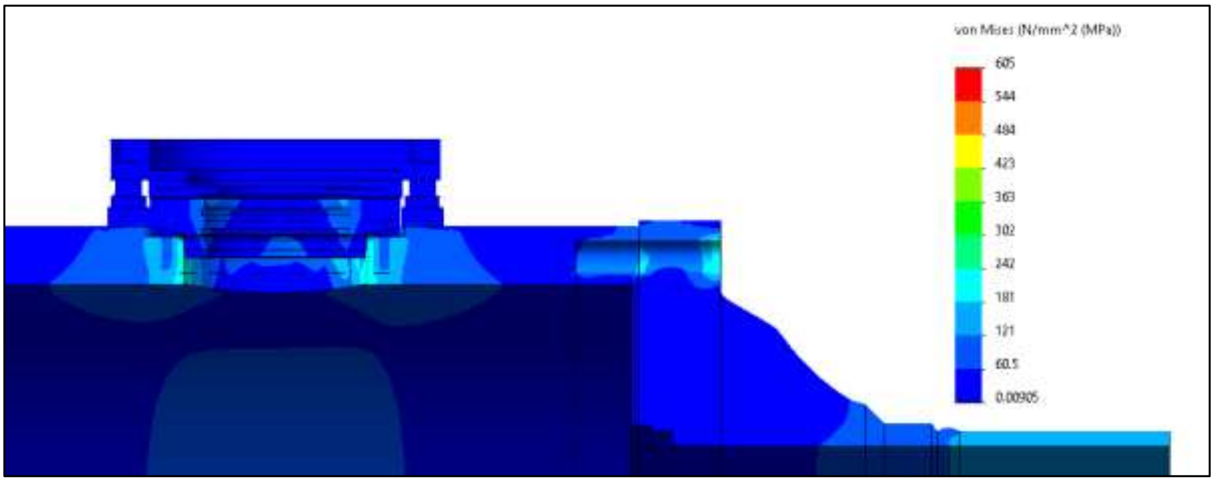


Figure 27 : LC1 Stress Plot Detail of Bonnet and Adaptor areas

Figure 28 : LC1 Stress Plot Detail of Pipe Pup area

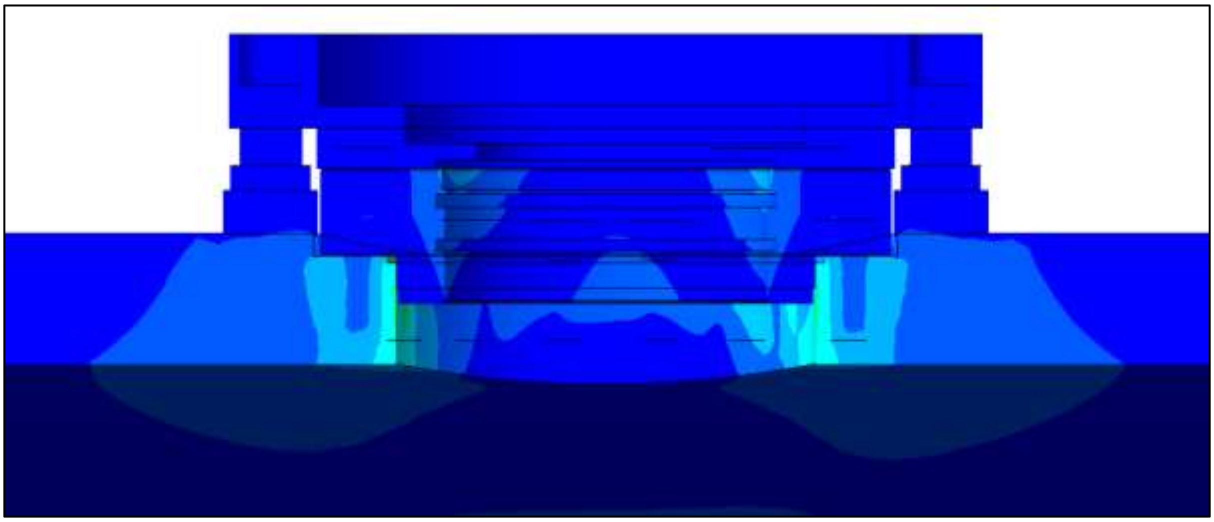


Figure 29 : LC1 Stress Plot Detail of Bonnet Area

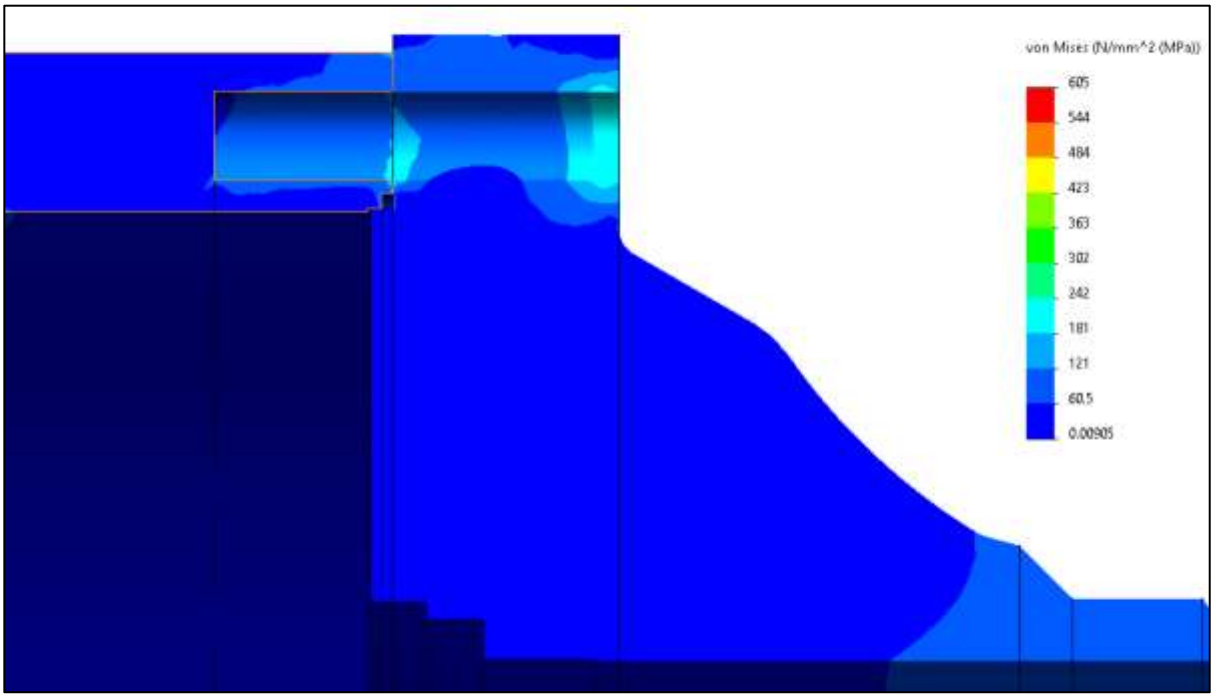


Figure 30 : LC1 Stress Plot Detail of Adaptor Area

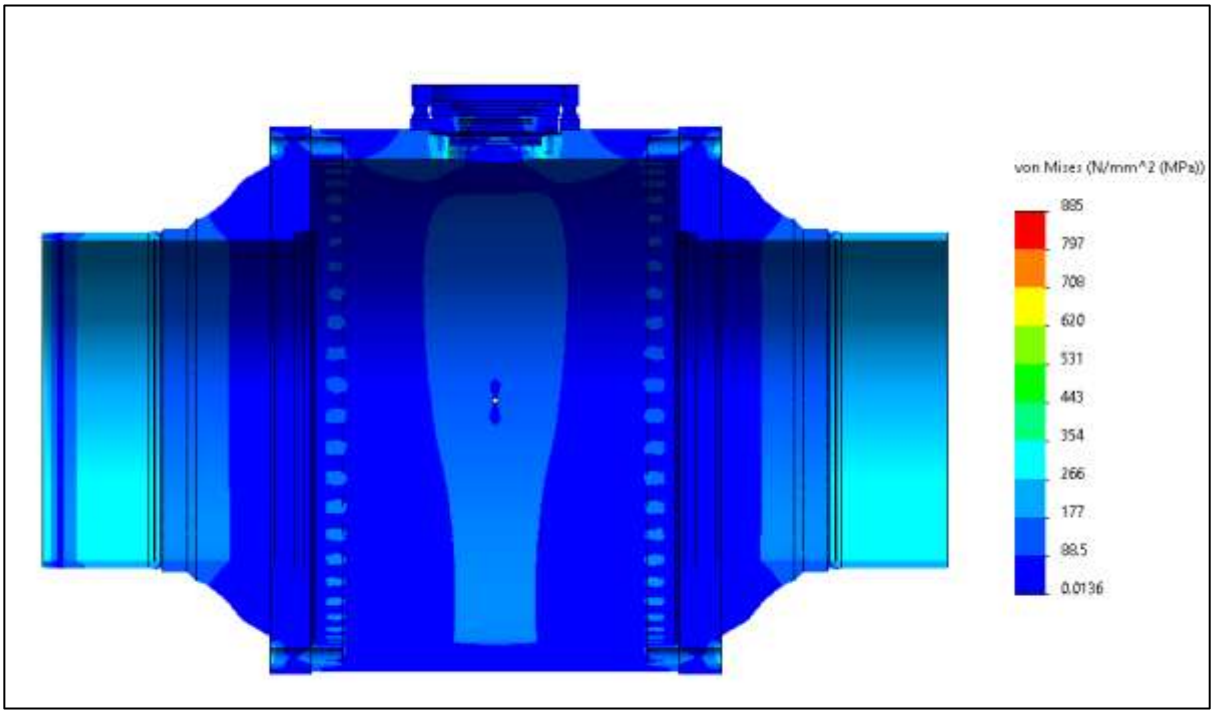


Figure 31 : LC2 Stress Plot Section

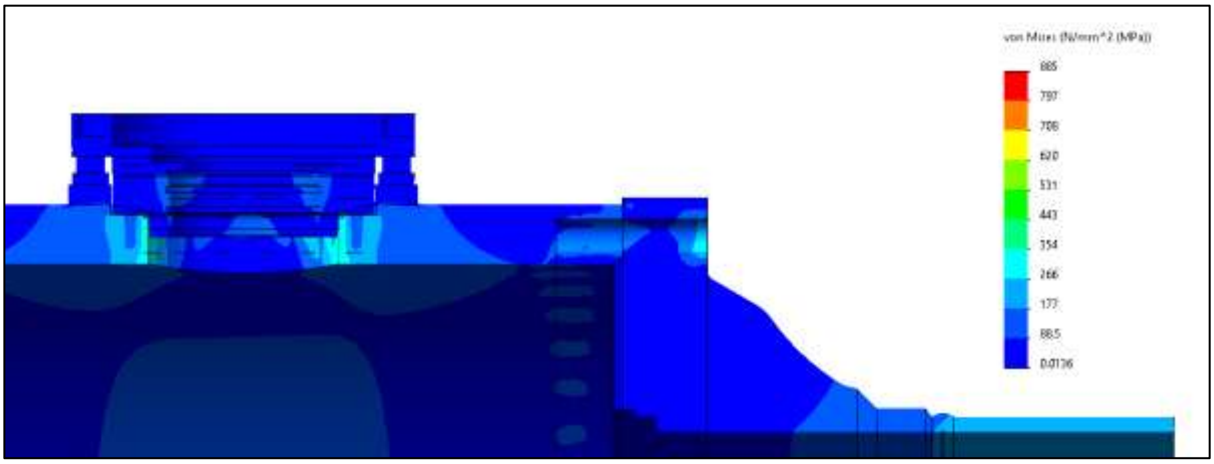


Figure 32 : LC2 Stress Plot Detail of Bonnet and Adaptor areas

Figure 33 : LC2 Stress Plot Detail of Pipe Pup Area

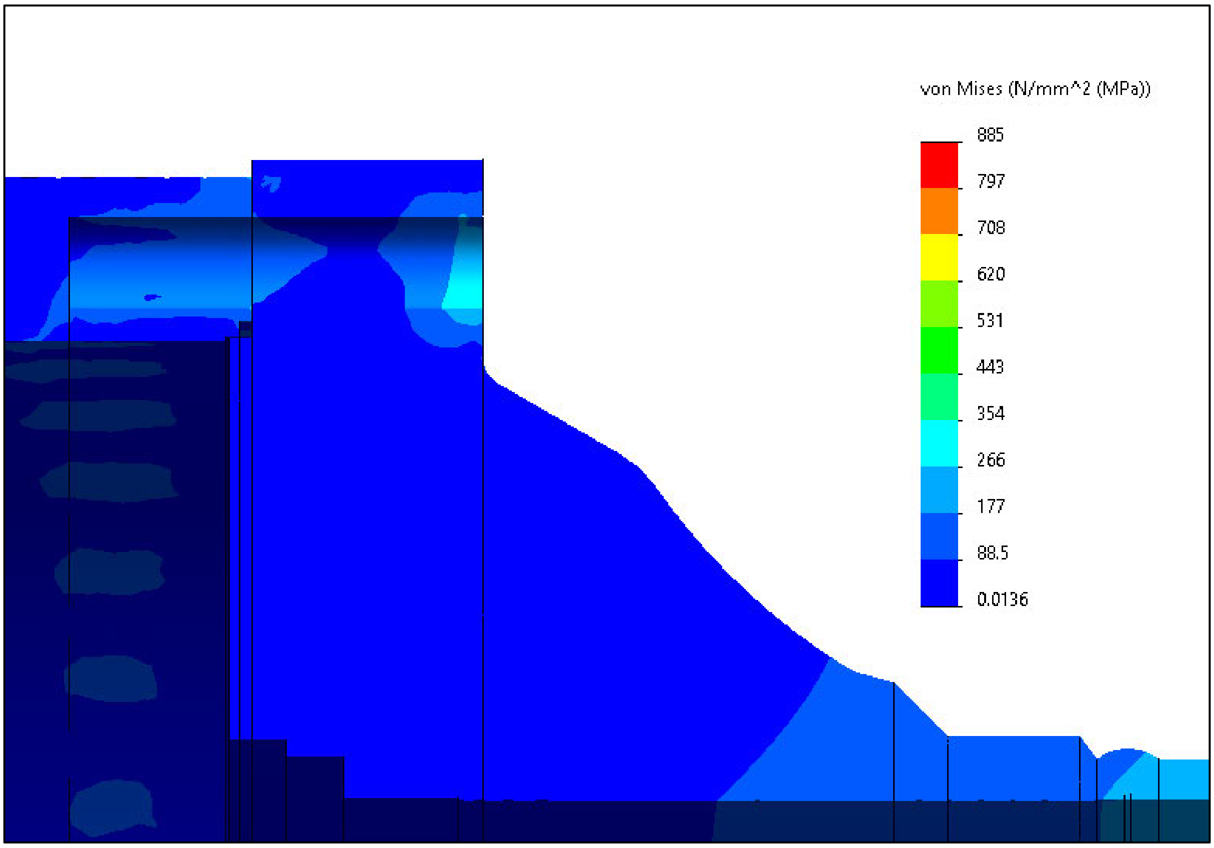


Figure 34 : LC2 Stress Plot Detail of Adaptor Area

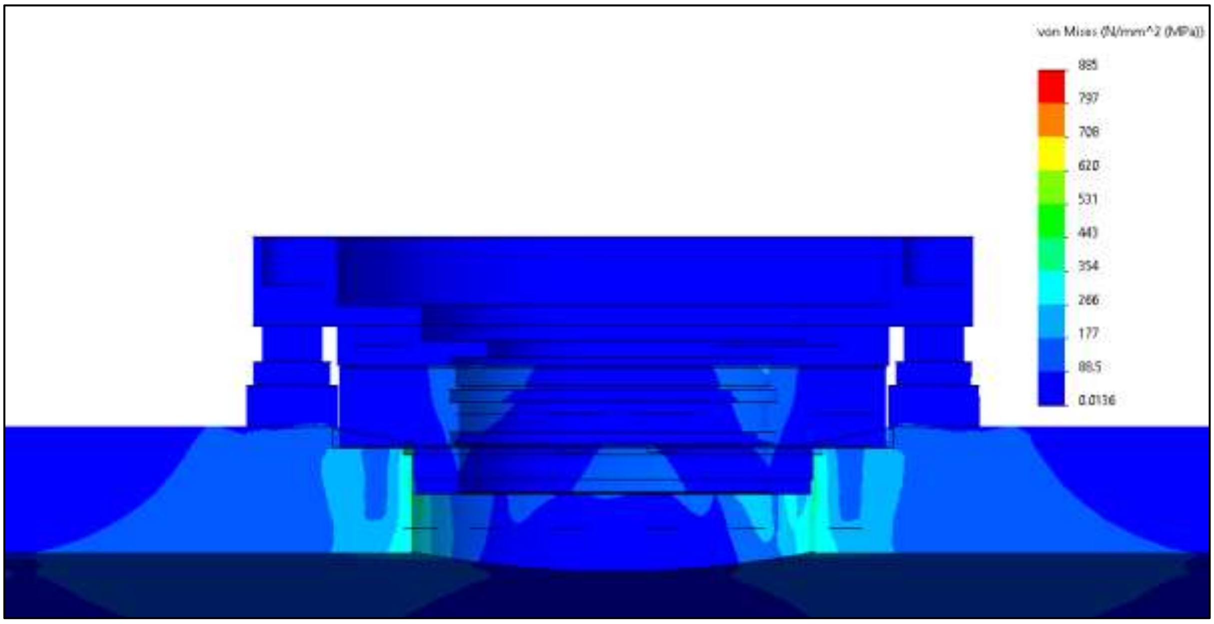


Figure 35 : LC2 Stress Plot Detail of Bonnet Area

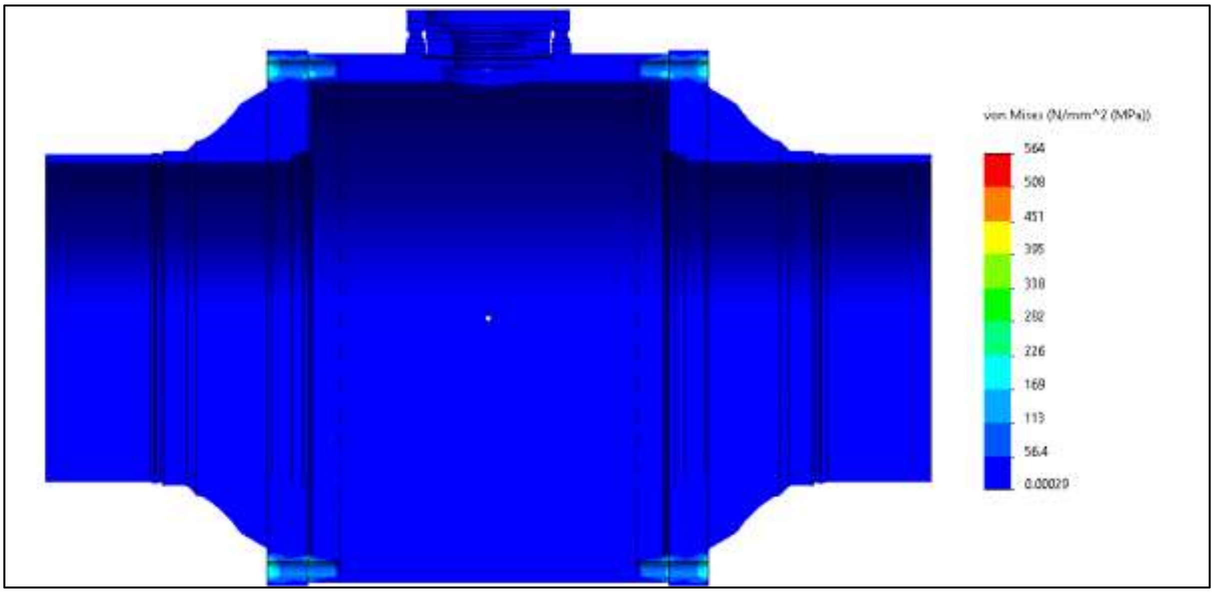


Figure 36 : LC3 Stress Plot Section

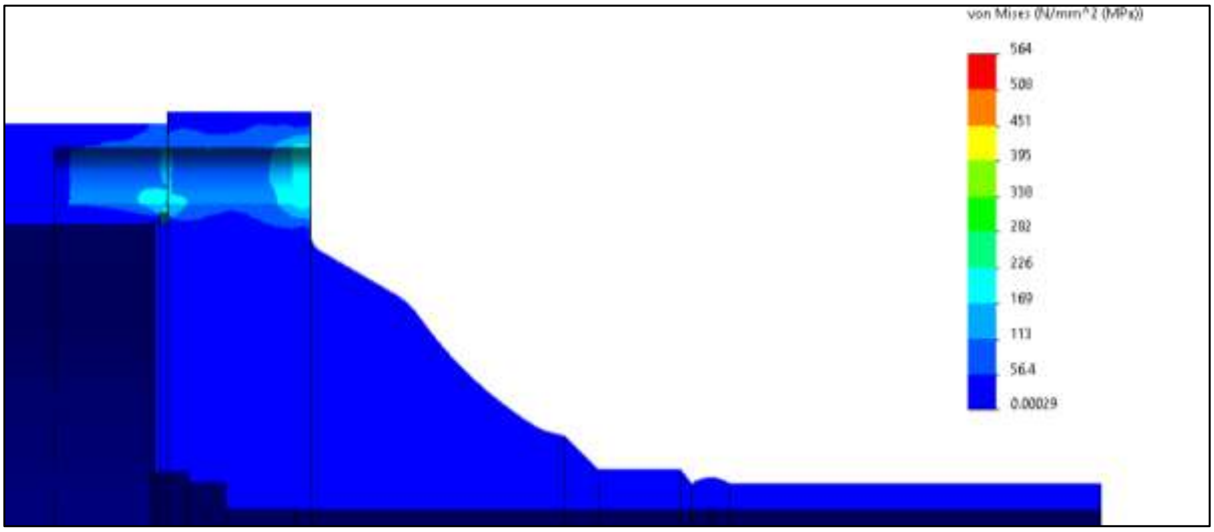


Figure 37 : LC3 Stress Plot of Adaptor and Pipe Pup Area

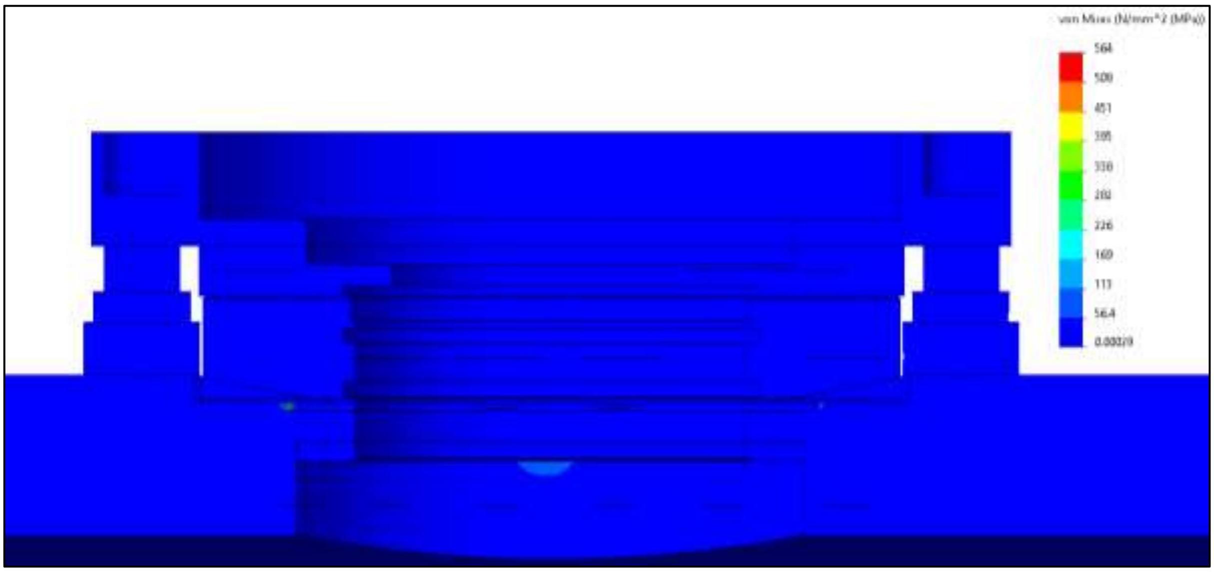


Figure 38 : LC3 Stress Plot of Bonnet Area

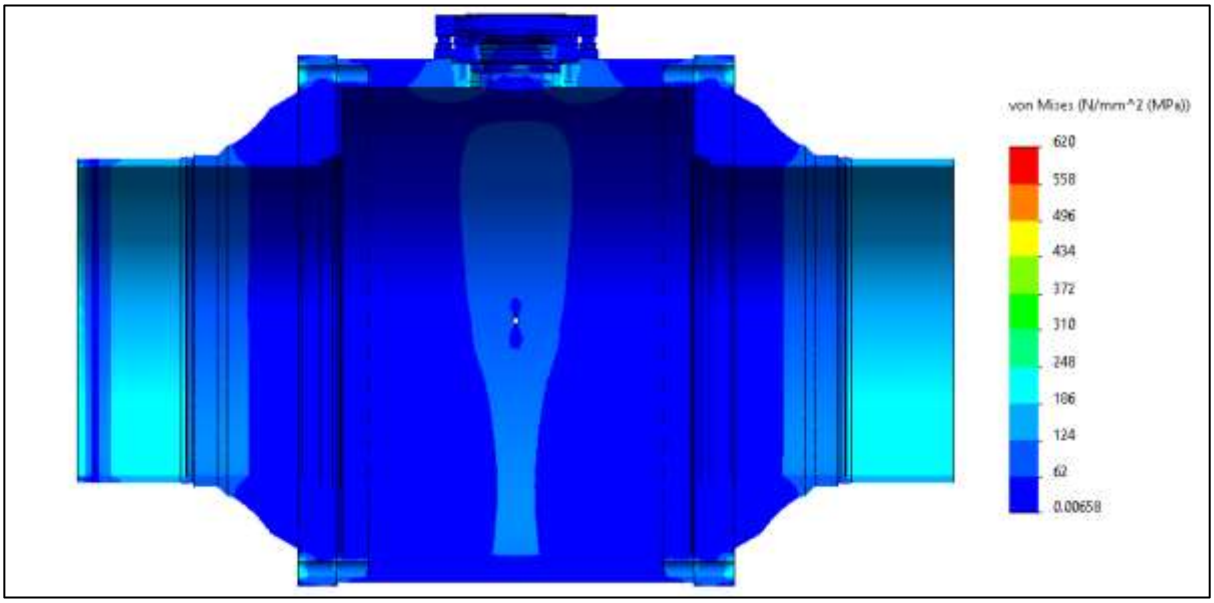


Figure 39 : LC4 Stress Plot of Section

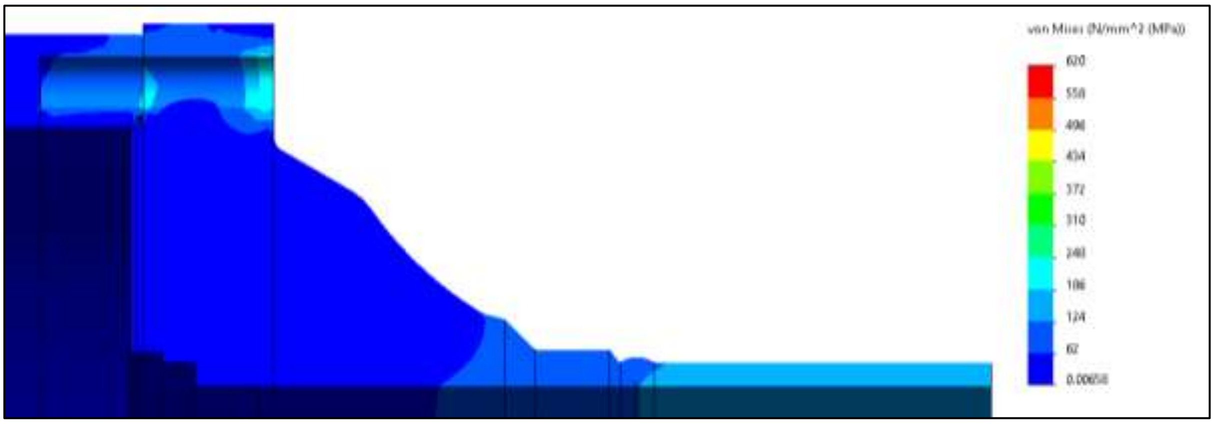


Figure 40 : LC4 Stress Plot of Adaptor and Pipe Pup Area

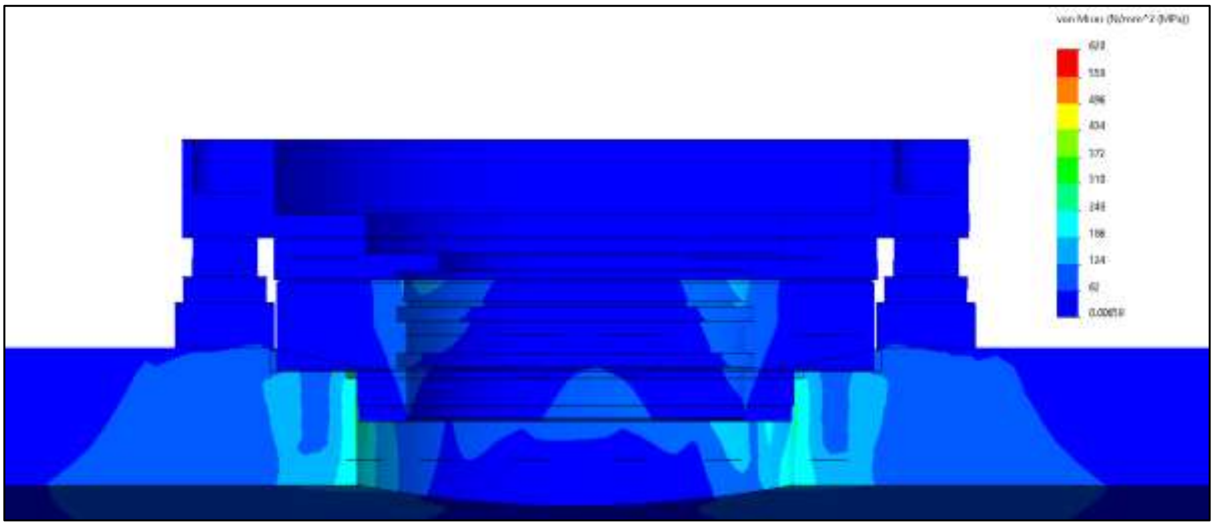


Figure 41: LC4 Stress Plot of Bonnet Area

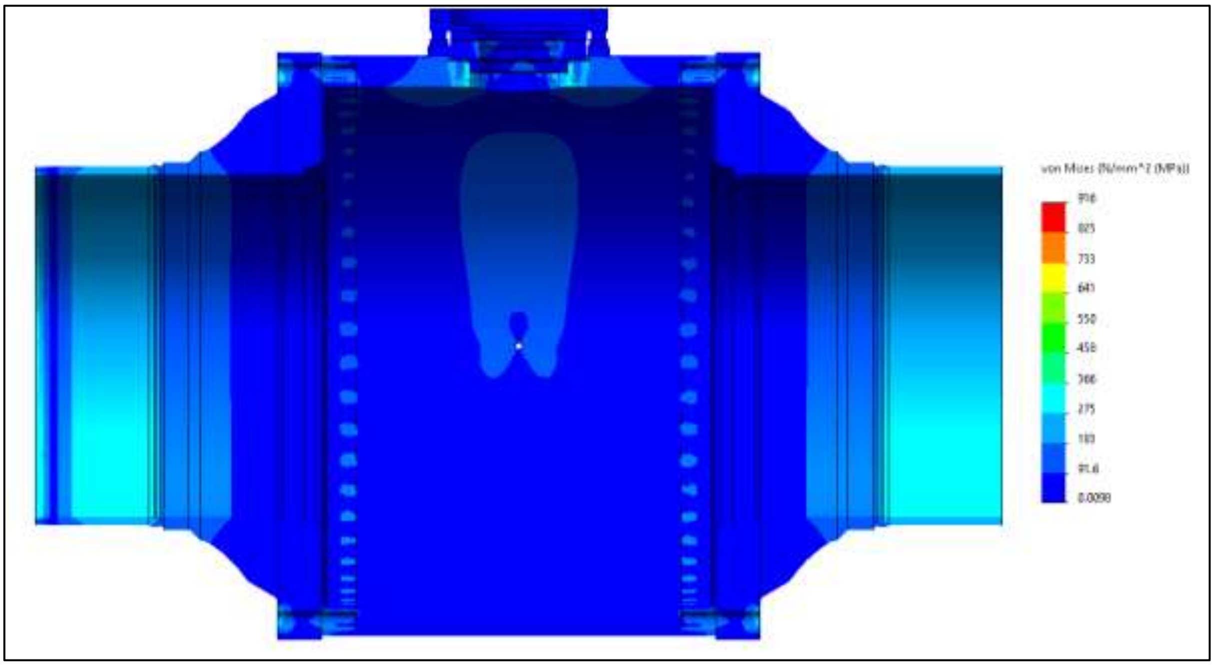


Figure 42 : LC5 Stress Plot of Section

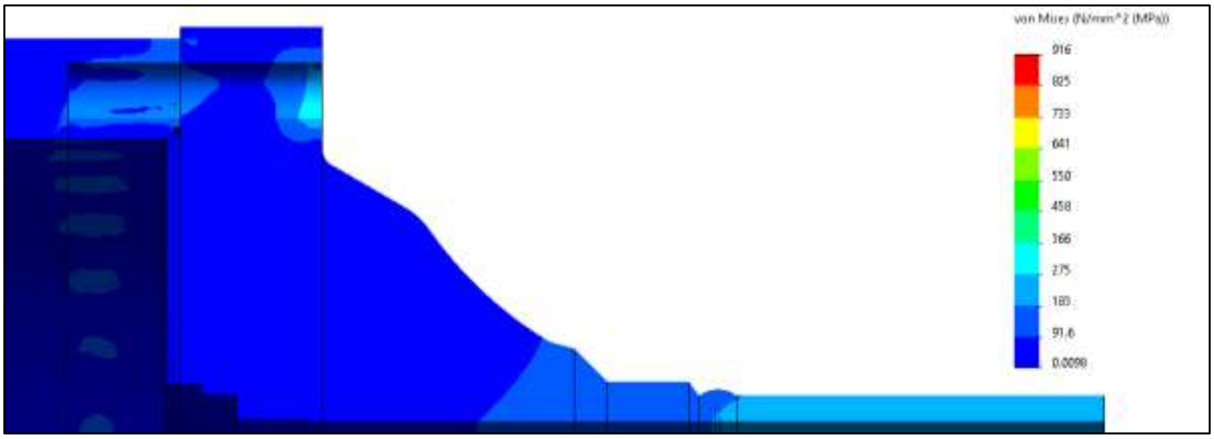


Figure 43: LC5 Stress Plot of Adaptor and Pipe Pup

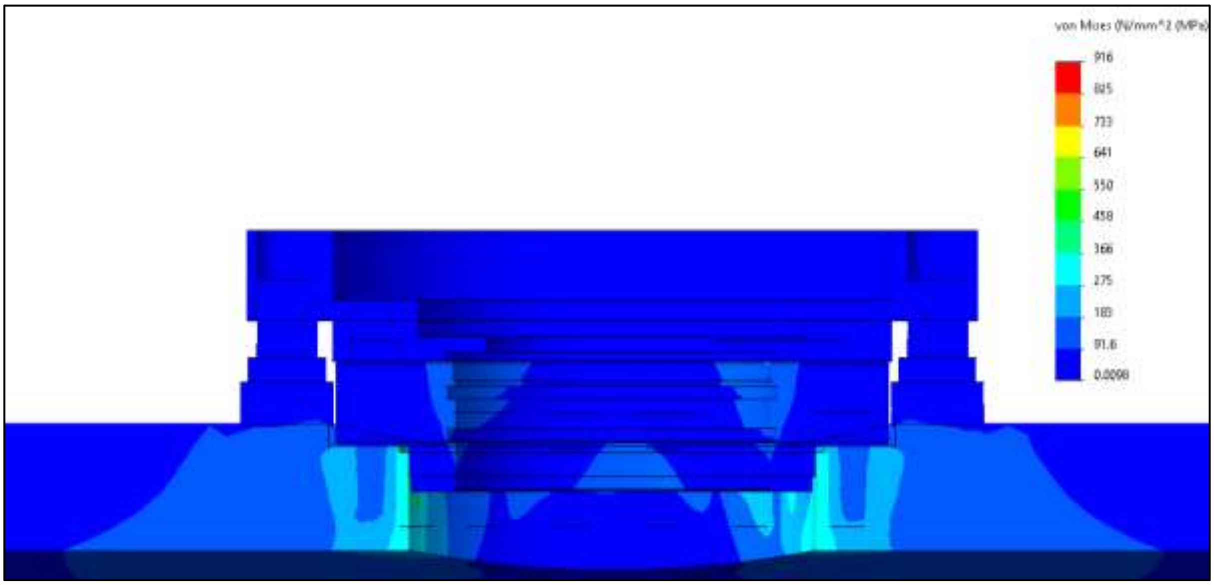


Figure 44 : LC5 Stress Plot of Bonnet Area

Appendix D: Summarised Results Tables Load Cases 1 – 5

Load Case 1					[redacted]		[redacted]		[redacted]			[redacted]		
Part	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Pipe Pup	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Pipe Pup	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Body	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Body	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Body	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Bonnet	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Bonnet	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Transition Piece	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Transition Piece	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Bonnet	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Bonnet	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Body	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Body	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Body	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Pipe Pup	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Pipe Pup	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Pipe Pup	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Pipe Pup	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Body	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Body	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Body	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Adaptor	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Pipe Pup	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Pipe Pup	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]					[redacted]		[redacted]		[redacted]			[redacted]		
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]					[redacted]		[redacted]		[redacted]			[redacted]		
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]					[redacted]		[redacted]		[redacted]			[redacted]		
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]					[redacted]		[redacted]		[redacted]			[redacted]		
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Appendix E: RFI for OEMs

[redacted]

[redacted]

Appendix F: Inficon Extrima Hydrogen Leak Detector Product Datasheet

INFICON

Calibration Leaks

The easy way to calibrate hydrogen leak detectors

Leak testing is a matter of quantifying leaks. To be able to correctly accept/reject test objects you need to measure to a set standard. You also need to calibrate your leak detector against a reliable reference leak. INFICON calibration leaks for hydrogen leak detectors cover a wide range of leak rates to suit your specific application.

For maximum accuracy, our calibration leaks are equipped with a specially developed diffuser nozzle. This nozzle allows the gas to spread evenly after leaving the leak without variations caused by air convection. The distinctive diffuser holder also eliminates the risk of varying or irregular readings depending on the way the probe approaches the leak. The calibration leaks are designed to suit INFICON Hydrogen Leak Detector Sensistor Sentrac, but can easily be used to calibrate most gas detectors. The INFICON family of calibration leaks for hydrogen leak detectors include bigger leaks (Types A-C) and smaller leaks (Types E and G). Leak Type A is intended for accumulation testing only. All leaks are traceable to NIST, NMIJ, NPL, PTB, etc., through the "Mutual Recognition Arrangement of the BIPM".

TYPES AND CONNECTIONS

A-C

- Sintered stainless steel
- Inlet: Compression connector for 6 x 4 mm and 1/4" x 5/32" tubing. ISO G1/8" internal behind connector
- Outlet: ISO G1/8" external
- Purge valve: Plug to be opened with 2.5 mm Allen key (hex drive). M5 internal behind plug. Fits also UNF10-32

E AND G

- Crimped metal capillary
- Filling connection: 1/4" male NPT, adapter for male ISO 1/4" included

ADVANTAGES AT A GLANCE

- Suitable for industrial applications
- Refillable and simple to use
- Special nozzles included for all INFICON hydrogen leak detector hand probes (not Leak A)
- Traceable to NIST, NMIJ, NPL, PTB
- Certificate included
- Available in different flows
- Suit different concentrations of hydrogen tracer gas

REFERENCE LEAKS

CONTENT AT DELIVERY

Type A

- Calibration leak assembly comprising leak and purge valve assembly
- Red G1/8" gasket
- Collet nut for connection to 1/4" tubing (marked red)
- Calibration certificate
- Delivery and storage case
- Manual

TYPE A

Type B and C

- Calibration leak assembly comprising leak and purge valve assembly
- Diffusor holder (for hand probe calibration)
- Diffusor filter (2 pcs)
- Probe guide rings, 8-11 mm diameter (4 pcs)
- Red G1/8" gasket
- Collet nut for connection to 1/4" tubing (marked red)
- 2.5 mm Allen key (hex drive) for purge valve and assembly of diffusor
- Calibration certificate
- Delivery and storage case
- Manual

TYPE B AND C

Type E and G

- Reference leak assembly
- Thread adapter (1/4" NPT- 1/4" ISO)
- Diffusor holder (for hand probe calibration)
- Diffusor filter (2pcs)
- Probe guide rings, 8-11 mm diameter (4 pcs)
- 2.5 mm Allen key (hex drive) for assembly of diffusor
- Calibration certificate

TYPE E AND G

SPECIFICATIONS AND ORDERING INFORMATIONS

Target flow for standard leaks:

Type	Part no.	Nominal flow** atm ml/s	Accuracy	Equivalent to g/yr (R134a)	For equivalent flow in: mbar.l/s or atm cc/s (air)	mbar.l/s or atm cc/s (5%H2/95%N2)
A*	590-420	5x10[illegible] (Air)	±2 %		multiply with 1	multiply with 1.04
B	590-421	5x10[illegible] (Air)	±2 %		multiply with 1	multiply with 1.04
C	590-422	5x10[illegible] (Air)	±2 %		multiply with 1	multiply with 1.04
E	590-427	7x10[illegible] ($5\%H_2/95\%N_2$)	±10 %	10	multiply with 0.96	multiply with 1
G	590-429	2x10[illegible] ($5\%H_2/95\%N_2$)	±10 %	3	multiply with 0.96	multiply with 1

A-C leaks are certified at 1 bar pressure, E and G leaks shall be pressurized according to certificate.

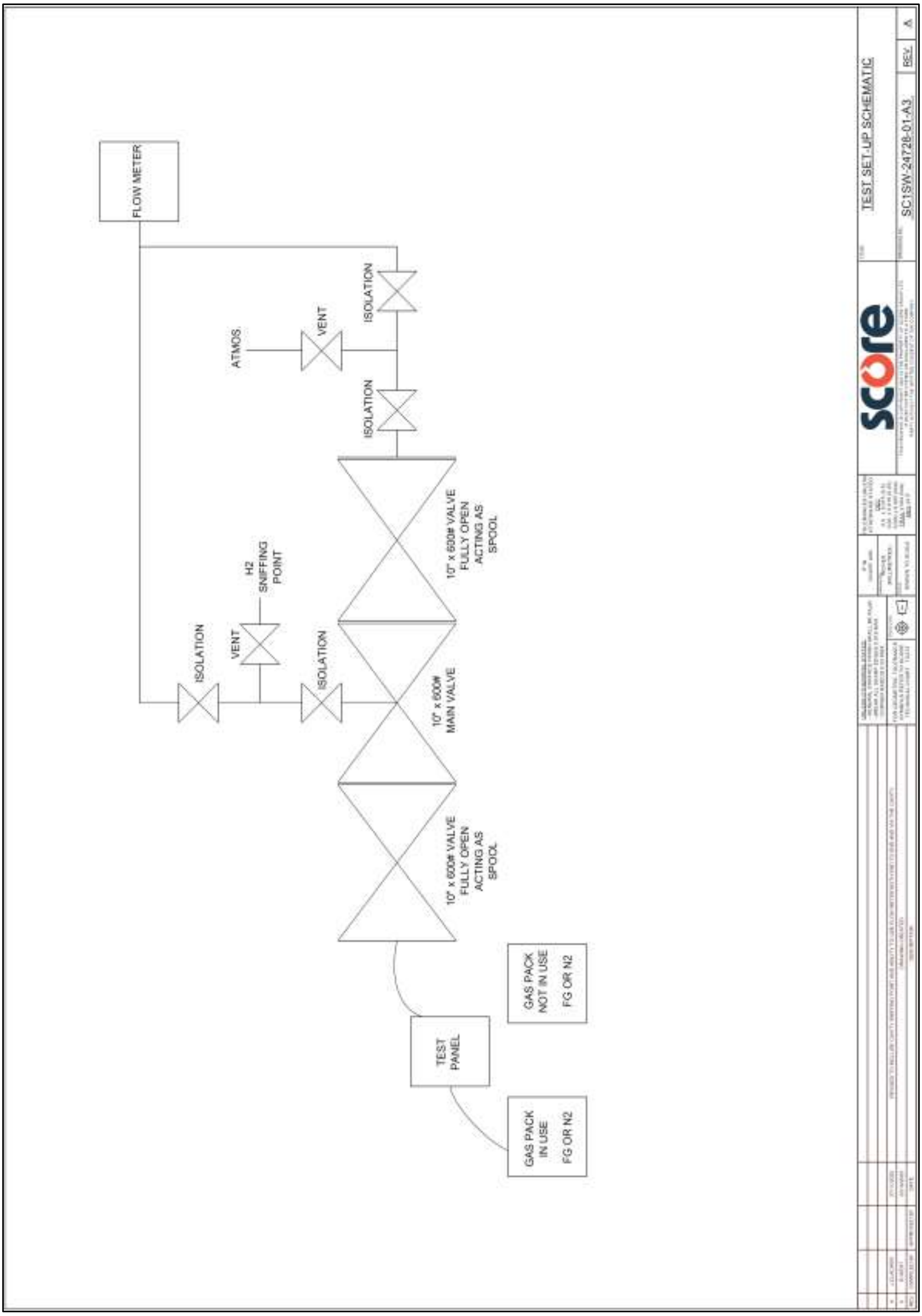
*Type A leaks are delivered without diffuser nozzle and are recommended for accumulation testing only.
They can not be used for calibrating hand probes with 5% H_2 / 95% N_2.

**A-C leaks are delivered with leak size within ±10% of nominal flow, E and G leaks with leak size within ±25% of nominal flow.

INFICON Inspired by visions. Proven by success.

www.inficon.com reachus@inficon.com

Appendix G:WP4 Cyclic Testing Schematic


FLOW METER
ATMOS.
VENT
ISOLATION
ISOLATION
H2 SNIFFING POINT
VENT
ISOLATION
ISOLATION
10" x 600# VALVE FULLY OPEN ACTING AS SPOOL
10" x 600# MAIN VALVE
10" x 600# VALVE FULLY OPEN ACTING AS SPOOL
GAS PACK NOT IN USE
FG OR N2
TEST PANEL
GAS PACK IN USE
FG OR N2
TEST SET-UP SCHEMATIC
SC1SW-24728-01-A3
REV
A

Appendix H: Blowdown Tool & Leakage Conversion Chart

[redacted]

[redacted]