Tru-Fit: Only Method to Comply with HSE Good Practice Vs. Visual/Gauge Inspection of SBT Fitting Faults Required for ALARP and EI Guidelines

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***Abstract*— Small Bore Tubing (SBT) connector faults cause >£500M in lost production in hydrocarbon industries annually in the UK alone. Risk-Based Inspection (RBI) is commonly performed, where HSE and Energy Institute (EI) require risk to be kept to ALARP legally, demonstrated by adopting HSE and industrial Good Practice. Industrial literature shows close visual inspection and gap gauges fail to meet HSE and industry good practices of 80%CRR-20%FCRR or a 90% Probability of Detection (PoD) at 95% confidence, resulting in 75% of inspected under-tight fittings unnecessarily opened with significant risk, but are used due to lack of alternatives. Tru-Fit, a novel SBT fault grading system, has been developed to fill this valuable gap, allowing informed RBI by plant duty holders.**

In this work inspections of 183 laboratory samples representing 4 main fault conditions and healthy SBT fittings from several manufacturers were performed to ENIQ-61 using Tru-Fit, Visual, and Gauge inspection. TPR(CRR), and FPR(FCRR) were calculated and compared with industry figures and good practice requirements.

Tru-Fit was the only method to meet HSE and EI Guidelines good practice for ALARP with TPR >99% and FPR<0.5%, critical for integrity management using RBI, whereas Visual and Gauges both fell short with TPRs of 46% and 30% respectively, commensurate with industrial datasets.

Tru-Fit for new construction, RBI, in-service inspection, and maintenance for industrial plant and equipment is strongly recommended to build an effective strategy for management of SBT and ensure Duty Holders good practice obligations required by regulatory bodies, health & safety and the Energy Institute Guidelines are being complied with. Using Tru-Fit can enhance safety, reduce risk, and save significant costs by minimising downtime, maintenance, lost production, and safety issues.

Keywords—Visual Inspection, Non-Destructive Testing, Risk Management, Probability of Detection,-SBT Inspection

I. Novelty of This Work

This work presents an independent assessment of the novel Tru-Fit small-bore tubing (SBT) fitting inspection system in detecting common faults in a laboratory setting compared against existing methods of close visual and gauge inspection. The results are compared against industrial field data for visual and gauge methods to assess generality in this study.

This work shows visual and gauge inspection methods fall short of good practice in laboratory and field results, and that Tru-Fit exceeds defined good practice, being suitably accurate for SBT risk based inspection, should be adopted by plant duty holders, the competent person, technical authorities (TA's) and inspectors to improve safety, emissions, and profitability.

II. Introduction

A. Small Bore Tubing Connection Failures

SBT failures are amongst the highest causes of hydrocarbon releases in the oil and gas industry [1]. A recent study from an industry task force set up to assess industry losses in the energy sector found corrosion under insulation to be the major cause with SBT following closely behind and one of the main causes of production loss with SBT causing £500 million annually in the UK sector with 250,000 tons CO2e released [2], [3], [4].

Industry safety alerts and experience has shown that the root cause of many SBT failures is due to poor assembly practice. Major operators have also identified that a key contributing factor to small bore system integrity issues was a lack of competency surrounding the makeup and installation of SBT fittings and instrument pipework. The UK HSE and Energy Institute Guidelines both recognise SBT assemblies as one of the largest contributors to the incidence of loss of process containment in potentially hazardous plants and that there is considerable room for improvement in terms of inspection practices [5].

There are around 45 million tube fitting assemblies installed in the UK and the North Sea alone. Statistics show that as many as 26% of these may have the potential for allowing a leak or worse [6]. Incorrectly fitted equipment, improper orientation, and non-compliance with procedure (i.e. human factors) were the most widespread operational causes [7], [8]. SBT assemblies are vulnerable to failure due to poor installation practice and lack of effective inspection programmes. If good practice is not being applied throughout the whole SBT assembly life cycle, there is a relatively high probability that an integrity failure event will occur at some time during service [5].

The need to recognise SBT assemblies as potentially being high risk is also evident from incident statistics for the offshore UKCS collated by the Health and Safety Executive (HSE). HSE statistics collated for the period 2016 to 2020 indicate that 10 % of all reported hydrocarbon leaks recorded on the Hydrocarbon Release (HCR) database were SBT related. Of these events, 23% of major releases were SBT related and 13% of significant releases were SBT related [5].

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SBT assemblies require regular inspection and maintenance to ensure ongoing integrity throughout their entire service life, thus avoiding situations developing that are hazardous to personnel and to the plant operations [5].

B. Risk Based Inspection

It is the purpose of risk-based inspection to select the techniques that are most effective for the type of in-service defects predicted. For inspection to be an effective part of integrity management, the techniques and procedures used must be capable of achieving a reliable examination. The techniques and procedures must therefore be matched to the potential defects identified [9]. High-risk equipment requires high inspection performance and reliability to be demonstrated [9]. Inappropriate or incorrect application of RBI has the potential to dilute safety standards and can result in dangerous plant failures [10].

Improper selection can have the following impacts:

- **Impact on risk assessment:**
  RBI relies on accurate data from inspections to calculate the probability of failure (PoF). If the inspection method is not thorough enough to identify potential issues, the PoF will be inaccurate, potentially underestimating the actual risk.
- **Missed defects:**
  A less effective inspection method might miss critical defects or degradation, leading to failure, especially if the inspection technique is not suited to the specific type of defect or damage mechanism.
- **False negative results:**
  If an inspection fails to detect an existing problem (false negative), it can lead to complacency and a false sense of security, increasing the risk of failure.

The performance and reliability of the inspection needs to be commensurate with the risk of failure of the components/equipment inspected. Inspection method selection should be based on the capability to detect and assess the deterioration types anticipated/sought in the parts of interest. The Duty Holder and/or Competent Person should have evidence of this capability, together with knowledge of any significant limitations [9].

Both HSE and the Energy Institute guidelines for small bore tubing require risk to be kept as low as reasonably practicable (ALARP) to ensure risk is managed effectively. Compliance with ALARP can generally be demonstrated by utilising industry good practice [11]. Good practice inspection methods can be verified by performing PoD trials and capability assessments [9].

The latest edition EI guidelines also have the requirement that *"risk assessments should take into account the probability of failure"*. The inspection should then be targeted at the high/medium risk items with a view to reducing the probability of failure and hence the risk [12]. However, it is then even more important that the correct inspection technique is used [12]. The use of inspection is a way of reducing the risk by reducing the probability of failure by detection of the defects before the item fails. A less effective inspection method directly affects the probability of failure in risk-based inspection (RBI) because it can lead to undetected defects, ultimately increasing the likelihood of equipment failure, even if the risk assessment initially identified a high-risk component.

C. Defined Good Practice

HSE guidance document Offshore Technology Report 2000/18 [13] defines a good inspection performance as: Correct Rejection Rate (CRR), or True Positive Rate (TPR), or Probability of Detection (PoD) >=80% and False Call Rate in Rejection (FCRR) or False Positive Rate <= 20% [14].

Other industries onshore where SBT are used such as hydrogen or nuclear or where there is a greater risk to the general public may require a higher POD of 90% with 95% confidence [9], [15], [16], more typical in many standards and guidelines.

Good practice may change over time because, for example, of technological innovation which improves the degree of control (which may provide potential to increase the use of elimination and of engineering controls), cost changes (which may mean that the cost of controls decreases) or because of changes in management practices. Good practice may also change because of increased knowledge about the hazard and/or a change in the acceptability of the level of risk control achieved by the existing good practice [11].

D. Plant Manager/Owner Obligations

Owners and users of industrial plant ('Duty Holders' within this study) manage the risk of plant failure for many reasons. The common goal is to prevent failure that could cause danger and damage. Failures almost always have a direct or indirect effect that is harmful to the business of the Duty Holder. For example, health & safety issues, lost production, costs of follow-up to an incident, replacement of equipment, loss of public image, higher insurance premiums, financial consequences, and costs of legal action [9].

Duty holders are under a legal duty to control and reduce risks to ALARP in accordance with UK HSE regulations and the Energy Institute Guidelines for Small Bore Tubing. Duty Holders are expected to apply good practice as a minimum to demonstrate achievement of ALARP [5], [11]. EI Guidelines provide good practice for the management of integrity of SBT [5]. Inspection good practice for SBT can be determined by performing probability of detection (PoD) trials [9] which are well defined [11]. Where there is relevant, recognised good practice, HSE expect duty-holders to follow it. If they want to do something different, they must be able to demonstrate to HSE satisfaction that the measures they propose to use are at least as effective in controlling the risk [17]. In judging compliance, HSE expects duty-holders to apply relevant good practice as a minimum [11].

A universal practice in industry, such as using manufacturer gap gauges for SBT in service inspection, may not necessarily be good practice or reduce risks ALARP. Duty holders should not assume that it is so [18].

E. Problem Summary

SBT fitting failures are not well managed, despite the widespread adoption of RBI principles, as the currently available universal inspection methods of close visual inspection and gap gauges are not accurate enough to perform RBI effectively. This presents major concerns to duty holders both in terms of safety, and profitability.

Industry figures show 75% of connections indicated by the close visual and gauging methods as being under tight and

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opened for further evaluation had no further defects [5]. Unnecessary opening of connectors is not recommended by the connector manufacturers as this may create further issues with parts that are in service such as leaks, re-assembly issues and uncertainty of correct re-assembly [19]. Unnecessary opening of connectors is also a significant safety hazard to personnel requiring depressurising and opening of hydrocarbon systems and subsequent reinstatement and pressure testing alongside the additional time spent in hazardous areas for personnel.

These issues can be mitigated by effective RBI, facilitated by an accurate and appropriate inspection method for which novel techniques have been developed to replace current substandard methods that are assessed in this work.

III. Scope of This Work

This study aims to highlight the appropriate inspection methods to achieve reliable SBT inspection. The application, capability, and limitations of available inspection methods are reviewed. A laboratory sampling of industrial fittings will be made, and inspected with close visual, manufacturers gap gauges, and Tru-Fit inspection methods. These results will be compared with relevant industry figures to generalise them, concluding in a recommendation for an appropriate inspection technique for RBI and ALARP principles in good practice.

IV. Methodology

Standard methods for SBT fitting inspection, including close visual and gap gauges, were applied to a variety of SBT fittings with a range of known artificial fault conditions according to standard industry practice [20]. A concurrent inspection using Tru-Fit, with appropriate measurement heads, was made on each fitting and results compared. The materials used in this study are shown in Figure 1.

A. *Inspection Methods for Comparison*

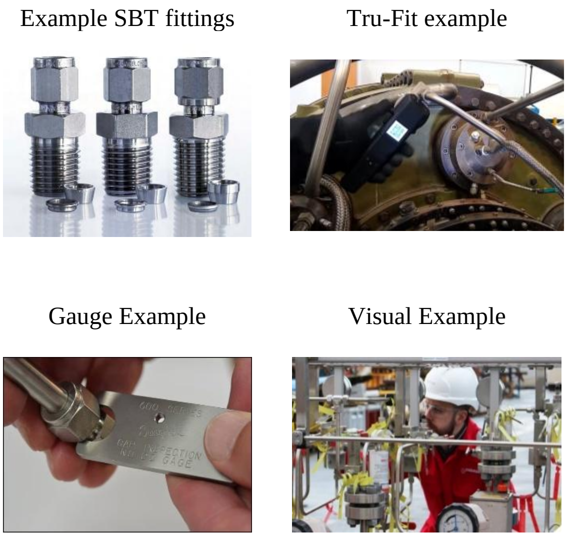

Figure 1 - Materials used in this study. A) SBT fittings from 3 manufacturers covering 3 common sizes. B) Tru-Fit SBT Fault Grading system. C) Fitting Manufacturer Gap Gauge, D) Close Visual Inspection

1) Tru-Fit

Tru-Fit is a non-invasive inspection method that uses sensor information and proprietary data analysis software to determine if the connector has been assembled correctly or an anomaly is present. The anomaly may be external or internal. The analysis software produces an assembly grade for the connection ranging from 1 to 5 with 5 being the most severe. The grading is produced by the software independent of the operator, reducing human interpretation and reporting errors. The numerical grading simplifies interpretation and can also be used to directly feed into risk-based inspection programmes, maintenance management systems or predictive maintenance programmes helping to prioritise risks and ensure the safety and reliability of the industrial plant. In addition to uploading the grading and inspection data the Tru-Fit mobile application used to read the Tru-Fit tool also includes the capability to perform and upload visual inspection results for anomalies that may be encountered during inspection or possible in-service deterioration mechanisms such as corrosion.

2) Gap Gauges

Using manufacturers gap gauges as go no-go gauges during SBT inspection is a commonly used inspection practice. Many manufacturers recommend their gauges are used only at first make-up assembly of the connector and not used after this for inspection or for re-make of the connector when the connector is disassembled. The inspector tries to insert the gauge into the connector gap, if the gauge enters a possible anomaly is reported, if the gauge does not enter the connection is assumed to be correctly assembled. The connectors that fail the gauge check are then subsequently depressurised, disassembled, cleaned and further inspected (break and remake inspection). Connectors that pass are reassembled and pressure tested, connectors that fail may be replaced or repaired.

Faults such as under tight connectors are assessed by experience or sometimes manufacturers gap gauges although most major manufacturers do not recommend gap gauges are used for this purpose, rather only for first assembly make-up of the connector [21], [22].

3) Close Visual Inspection

Visual inspection, with the use of optical aids, is performed with the aim of detecting surface-breaking flaws or highlighting anomalies that may be visually detectable. Hand-held magnifiers are used to perform a close visual inspection of the connector assembly. The capability of visual inspection is heavily dependent on the surface condition of the component, level of lighting available and inspector experience. Capability is limited unless special optical aids are used. This method usually requires supplementing with other methods/techniques such as break and re-make of the connector to confirm the presence of flaws.

B. *SBT Fittings Tested*

Commonly used industry twin ferrule connections were used for this study. Samples were from the three largest connector manufacturers with a range of three of the most used sizes in industry. All connectors were manufactured from stainless steel which is the most used material in industrial plant. Each of the methods is agnostic to material type so material type was not considered significant.

183 twin ferrule small bore tubing connector samples were inspected with each of the close visual, gauging and Tru-Fit inspection methods. 132 samples had assembly defects typically found in industry with 51 samples having no

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defects. The sample number met or exceeded industry requirements to determine PoD.

C. Tested Fault Conditions

Energy Institute Guidelines require information from experience gained from sources such as incident reports, safety or technical bulletins and improved technology should feed into the activity [5]. Defects were introduced during sample assembly typical of assembly defects encountered in service that had led to various industry failures. Anomaly types specified in EI guidelines and industry safety alerts were selected. Particular attention was paid to industry safety alerts or notifications where assembly anomalies had caused in-service failures, unplanned shutdowns or loss of containment or injury to personnel. These defects were selected as the type of defect that would be considered higher risk or have a higher probability of causing a loss of containment failure in service. These typical defects that had caused failures in-service would need to be detected by the inspection method with sufficient reliability and confidence to be considered good practice.

The flaw population derived from the EI guidelines and safety alerts consisted of:

- **Overtight connections**:
Overtightening can deform the ferrule and tube; stress may also increase on the connector components contributing to increased likelihood of stress corrosion cracking19 and vibration related fatigue failures 20.
- **Under tight connections**:
Under tightness may cause leaks due to incorrect sealing and potential tube blowout failures. Under tightening severity may vary.
- **Reversed internal ferrules**:
Internal anomaly, the rear ferrule is installed backwards, a common cause of connector sealing issues and leaks. Reversed back ferrules also produce less vibration resistance.
- **Missing internal ferrules:**
Internal anomaly, one or more of the ferrules is missing causing sealing issues producing leaks, and less vibration resistance, potentially the grip of the tubing may be affected with a higher probability of tube blowout.
- **Extra ferrules:**
Internal anomaly, too many internal ferrules installed causing improper deformation of the internal components leading to poor seals and leaks.

D. Data Collection

Hit-Miss Data was used in this study. Data resulting from an inspection where only the determination of whether an indication is present or not is recorded. Thus, the data at each measurement point corresponds to either a yes or no or is sometimes represented numerically as a 1 (i.e., indication present) or 0 (no indication). No signal measurements from any NDE sensor output are recorded.

Tru-Fit inspection personnel were trained and certified by Paragon. Gauging checks were performed in accordance with manufacturer's instructions. Tru-Fit inspection and gauging was performed independently by university staff in blinded trials. In this work, a Tru-Fit grade of 2-5 (where number indicates the fault type) was taken as a fault indication, and a grade 1 taken as no indication.

To ensure additional independence, close visual inspection was performed by an independent third-party company utilising an experienced inspector.

SBT fitting samples were created and assembled with known faults by Paragon, or by TUV SUD from previous independent TUV SUD assembly and testing of the Tru-Fit system [23]and were blinded in this work.

E. Data Analysis

Demonstration of performance shall be in accordance with HSE document Offshore Technology Report 2000/18 good inspection performance: Correct Rejection Rate >= 80% and False Call Rate in Rejection <= 20% [13], [14].

In addition, each method to be assessed against common industry PoD rates 90% PoD at 95% confidence [9], [15], [16], [24], [25] was assessed in accordance with HSE document Best Practice for Risk Based Inspection as a part of plant integrity management and numerous industry standards [26]. Unlike the Tru-Fit method the visual and gauging methods are incapable of determining the severity and/or defect type. Therefore, PoD calculations at 95% confidence were derived for each method using the full set of 183 samples as a broad method capability assessment.

V. Results

The results of the inspections using the 3 methods of interest are shown in Figure 2. HSE good practice targets are indicated by the dashed box, where a method is good practice if the TPR and FPR fall within the box, indicating a high correctness and low mistakes. Values close to the line of unity, or random guess line indicate that a method is little better than a random guess. Values below the random guess line have negative predictive value and so are useless.

Here the TPR or CRR measures the proportion of faults correctly identified as faults, where a higher number indicates that more faults are correctly found. The FPR or FCRR measures the proportion of healthy fittings incorrectly labelled as faults, where a higher number indicates the number of unnecessary system openings.

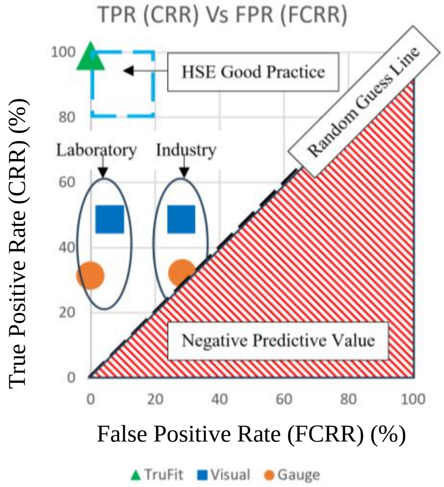

Figure 2 - Experimental results. True Positive Rate (CRR) Vs. False Positive Rate (FCRR) Percentage for each inspection method on all samples. Tru-Fit meets good practice, other methods do not even in ideal laboratory settings. Results concur with industry studies in non-ideal settings.

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Tru-Fit was the only method tested that met HSE and industry good practice with TPR > 99% and FPR < 0.5%, indicating a very high positive predictive value, compared with existing universal methods of close visual and gauge inspection that fall far short of good practice with TPRs of 46% and 30% respectively. Tru-Fit was also the only method found to meet 90% PoD with 95% confidence. Visual inspection performed better than Gauges, as expected given that gauges are not recommended for this purpose by their manufacturers [21], [22].

Comparing the laboratory results with industry figures, TPRs are roughly equivalent, indicating the good generality of this study, with the industry figures showing higher FPRs for visual and gauges of approximately 26%. [27], [28] typically owing to the non-ideal lighting, cleanliness and access conditions of in-service fittings as shown in Figure 3 and inspection human factor errors with both methods being subjective. Even if TPRs were 100%, the high FPR of visual and gauge methods lead them to fall short of good practice and not be suitable for RBI.

VI. Discussion

From the results it is clear that existing universal methods of close visual inspection and gap gauges fail to live up to the expectations of industry good practice, and so would not promote effective RBI. Tru-Fit met and exceeded HSE and EI good practice guidelines, and so would be effective in RBI implementing ALARP principles.

The TPR, and therefore the number of faults correctly identified were similar between the laboratory and industry figures, and the FPR for industry figures is significantly worse for the industrial site data than for the laboratory primarily due to the non-ideal nature of lighting and access in typical plant as shown in Figure 3. This means that close Visual inspection, and particularly gauges, in practice have minimal positive predictive value. This is likely mirrored by the manufacturers not recommending their use for this type of in-service inspection.

Figure 3 - Examples of SBT applications in plant. (Right: https://www.ecitb.org.uk/) Poor lighting and tight access make visual and gauge inspection have a high false positive rate

Considering the high Tru-Fit positive predictive value obtained in the study, and that the method is not impacted by lighting (as in close visual) or a subjective inspector decision as other methods are, it is reasonable to suggest that the expected increase in FPR in practice onsite will be far less than that experienced by close visual and gauge inspection.

In regards to HSE and EI good practice, the target values of >=80% and <=20% for TPR and FPR respectively attempt to balance risk with the feasibility of implementing high accuracy inspection methods in all instances. These values should be considered the bare minimum for an effective RBI strategy, with results better than these translating directly into financial, environmental, and safety benefits for those responsible for plant maintenance.

VII. Industrial and Commercial Impact

As the Tru-Fit inspection method is non-intrusive this reduces costs and additional safety risks as connectors do not need to be depressurised and opened for further evaluation then subsequently re-assembled and pressure tested prior to entering service again. EI guidelines show 75% of connectors highlighted as under-tight with visual and gauging methods had no internal defects [5], [11] and were opened unnecessarily increasing risk, costs and additional time spent in high-risk hazardous areas by inspection personnel. This can be further expanded to show that 26% of all plant connectors that were inspected were unnecessarily opened [28], which given the large amount of connections in the smallest plant represents significant labour cost and downtime.

Manufacturers of SBT connectors recommend avoiding unnecessary disassembly of fittings [19]. Many sections of industry use gauging as an inspection method for in-service SBT connectors whilst many SBT connector manufacturers state that the gauges provided should only be used at original make-up of the connector [21], [22]. Although the PoD obtained for the gauge method will not increase if used at initial make-up, the low PoD may explain why manufacturers do not recommend gauges for inspection.

Installation operators should continue striving for proactive improvements in their programmes building upon and sustaining previous successes and ultimately moving from a position of hydrocarbon release reduction to one of prevention. Good practice performance measures should consider insights from weeps, seeps and non-reportable hydrocarbon releases to further improve hydrocarbon release prevention performance and regular discussions on broader integrity threats that would not necessarily be apparent [8].

The UK Net Zero Technology Centre has priorities around fugitive emissions leak prevention from fittings as part of its integrity management emissions reduction programme as industry moves towards net zero and recognises Tru-Fit as an emissions reduction technology [29]. A recent study concluded that Tru-Fit system adoption would save 1000 tons CO_2e per asset in the UK sector [3].

VIII. Conclusion

Tru-Fit inspection method is the only method recommended for SBT connector assembly inspection for both initial installation alongside manufacturers gap gauges, for confirming adequacy of new construction during inspection and for in-service inspection. A combination of Tru-Fit inspection for connector assembly faults and visual inspection for any deterioration mechanisms such as corrosion etc. and overall integrity checks is considered best practice.

Duty holders should review their requirements around fugitive emissions reduction and consider if Tru-Fit would also help with moving towards hydrocarbon release prevention, insights from weeps and seeps, broader integrity threats such as SBT, data to be managed more effectively e.g. with weighting factors summarised and equated to a single score [8] such as the grading system that form part of the Tru-

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Fit inspection system. A greater accuracy and PoD allows a more effective inspection allowing defect detection at an earlier stage. Earlier stage detection allows predictive targeted maintenance to take place before a leak occurs. Re-assessment is appropriate as new inspection methods and techniques become available and offer Duty Holders the prospect of obtaining information not previously available. This should consider the differences in capability between previous inspection techniques and future possibilities.

The results of this study may assist all personnel involved with the design, installation, inspection and maintenance of SBT assemblies across multiple industry sectors including renewables, oil and gas, hydrogen, transportation, nuclear, energy, shipping etc. including those involved in operations, site management, and those having specific safety and integrity roles with their organisation to evaluate the effectiveness of their inspection methods and help ensure compliance with regulations and with effective risk management and risk-based inspection practices. This study provides the Duty Holder, Competent Person and TA evidence of the capability of each available inspection method with knowledge of any significant limitations as required by HSE. This study has been made available to industry to allow Duty Holders and relevant personnel ensure ALARP, risk based inspection and health and safety good practice obligations required by regulatory bodies and the Energy Institute Guidelines are being complied with.

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