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Advances in Offshore Corrosion and Integrity Management

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ABSTRACT

Corrosion and integrity management (C&IM) techniques have evolved well over the past decade or so and are quite well established for the onshore sector, and are being continually updated as new knowledge is validated and accrued. This is largely because access and direct inspection to such assets is reasonable and not an overbearing issue. In difficult cases cost related issues can be challenging but rarely insurmountable. In stark contrast, offshore and in particular deep subsea assets can present near insurmountable challenges and in that case corrosion and integrity management techniques and methodologies must engage a different mindset. Here one needs to apply good science, robust engineering and carefully re-assess the impact on Health, Safety and Environmental (HSE) details with respect to people, the environment and property, and also for cost, practicality, reputation, and indeed revenue value added. As a result, such challenges are best addressed on a risk-tolerance basis, to maintain good business sense and return on investment (ROI), and here the ALARP (As Low As Reasonably Practical) criteria is utilized. The revenue side and HSE side are often in conflict, but can be managed if the major proponents are kept separate and under an independent leadership, prior to final company decisions at the highest level.

Needless to say, with those decisions comes greater responsibility and accountability. This paper illustrates some of the multi-disciplinary approaches over the years. The case criteria and examples mentioned are from real world situations, and reveal the preferences of advancing and adapting existing technologies rather than implicitly brand-new ones. However, challenges still exist though with better knowledge management, and information exchange across assets and regions it is concluded that the industry overall will benefit. An 18 point check plan is offered to tackle the most prominent issues, plus direction and recommendations to facilitate fit for purpose solutions.

Keywords: Localized corrosion, degradation, performance, ALARP, risk, integrity management, KPI's, non-dimensional analyses, HSE, safety culture, intermediate testing, adaptive technologies.

INTRODUCTION

Many technical authorities (NACE, ASCE, SPE, IMECHE, IMAREST, ASME etc.) have expressed the importance of asset deterioration being by far the major threat to the integrity of onshore, offshore, and subsea projects, especially ageing assets, and indeed society in general regarding environmental interfaces, industry growth, water table pollution, etc. This paper is focused on the offshore and subsea side, where the risks and consequences are similar though more complex, magnified, and far harder to reconcile. The analogy of deep-sea exploration has been compared to outer space, except that outer space is assumed non-corrosive in the traditional sense.

Caveat: The references and bibliography are quite extensive in this field of endeavor, and the authors restrict themselves to directly relevant papers, conferences and sources, some of which remain by nature confidential or private correspondences, breaking down into Corrosion [1-11], Advanced Nano[12-16] HSE/safety oriented[17-21] Discrete external SME inputs[22] and Mechanical, Metallurgical, Welding observations. [22-27]

A very high number of offshore/subsea failures including major accident events (MAE's) have been linked to corrosion; and in particular the identification of major threats such as corrosion under insulation (CUI) and corrosion under pipe supports (CUPS) present significant challenges. Indeed, many operators have opined that CUI is the major single outstanding threat to their offshore assets. More generally the role of corrosion and metallic issues has been framed at up to 80% and possibly >90% for integrity and process safety. The role of internal corrosion for flow lines and risers has itself evolved into a premier topic of interest, in contrast to the high performance of cathodic protection (CP) and certain coatings such as the thermal spray aluminum (TSA) and other sacrificial types, although shielding issues can exist.[1,2,4-7] Overall corrosion assessment and control, is considered to be the critical step within Asset Integrity Management (AIM). Regarding the latter many corrosion mechanisms are understood relevant, but not always applied due to complexity and lack of predictability. Typically, such analyses tend to focus on uniform corrosion since that can be effectively modeled, and various software (private, JIP, public domain, etc.) exist to facilitate that. In real world applications however, problematic corrosion is almost entirely localized and multi-mechanistic; thus the disparity between modeling, predictions, laboratory testing, and field observations.[3-8,11] Historically that has been accepted via empowering greater conservatism to allow for 'pitting' or crevice type attack; but this is strictly less valid with the advent of deep subsea high pressure, temperature, velocity, stress (HP/HT/HV/ σ), conditions, variable flow regimes, transients, excursions, etc. The paper argues the case for more pragmatic 'fit for purpose solutions' tackling contentious and largely unresolved areas of corrosion management.

The argument centers on an evolving evergreen methodology, focused on the fundamental premise that prevention is always better than cure. To facilitate this means that design issues (pipeline/riser/pressure plant, etc.) must be attended as early as possible for best management of change (MOC). And most certainly at the project CAPEX (capital expenditure) stage rather than at the OPEX (operational expenditure) stage when it is too late and expensive to make meaningful changes, albeit operators usually but erroneously believe they have time. The same challenges are accentuated for brown field or ageing assets especially those operating into or beyond the last quarter of the design life, typically in the 25-35 year plus range, and appropriate meaningful actions can be taken to address such elderly assets as they 'need' to continue producing. The expectations can be met by the use of expensive new technologies, but since no one wants to be the first to try, this reluctance is usually met more cost effectively by modified or translated data culled from equivalent assets. Hence the trend to focus more on adapted existing technologies. Such advances of necessity invite new technology qualification challenges and the relevance per criteria for matching the DNV A203, and API 17N RP's (OTC 2017 [23]) can be navigated quite reasonably without onerous hindrance.

The idea of addressing critical corrosion mechanisms, including mixed mechanisms early is reflected in Figure 1 below. Here we see that the traditional potential failure versus time diagram can be translated to read initiation–propensity–failure diagram (IPF), with the emphasis on early recognition of corrosion and/or cracking phenomena. The 'I' is not always easily measurable but may be predicted (often at the design reappraisal), using forensic analyses, and non-standard angles or analogies such as on-site metallurgical 'replicas' via transmission electron microscopy (TEM), adaptive sensors (potential probes E-t) parallel bypass loops, etc. Contrast the case for brownfield (pre-corroded pipe) which is more challenging but has urgency, as the client will intervene only when really needed. Thereby putting the onus on better modeling and monitoring, with a positive feedback loop so results can be fine-tuned and algorithms revised for future projects. Hence this presents challenging but improving situations.

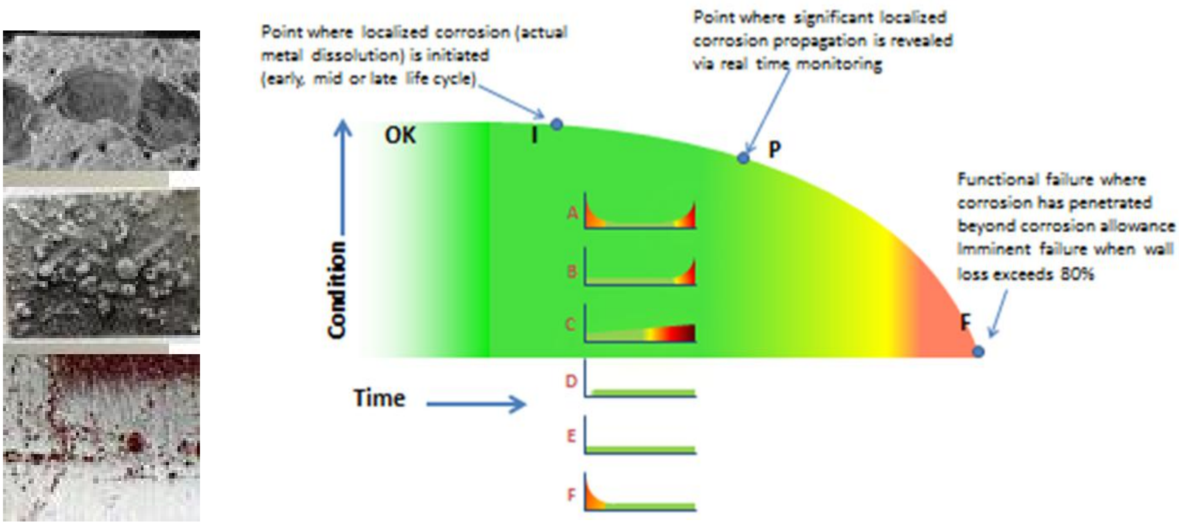

Figure 1: Traditional Potential–Failure (PF) curve translated to an Initiation–Propensity-Failure diagram (IPF).[24] Revealing that intervention is best at localized initiation (I) not always measurable but predictable by risk assessment, forensic methods, or analogy.

APPLICATIONS AND METHODOLOGY

For CAPEX, if the degradation mechanisms can be identified and caught early enough. This can be equated to prevention, and furthermore any mitigation actions such as inhibitor, biocide, or scale inhibitor injections, can be more confidently expected to work better. The logic is that clean surfaces will give better filming integrity, rather than pre-corroded (pre-roughened) surfaces. The method also allows for a better definition and reproducibility of the much-vaunted corrosion key performance indicators (KPI's). The situation for brownfield assets is more challenging but with well thought out corrosion management strategies (CMS) it can be addressed quite well.

As a rule, the established scientific method (rigor, proof, validation, repeatability, etc.) is understood and applied; in contrast the naturally evolved engineering method is not so well appreciated, but is by nature governing. Here industry utilizes a work process relying heavily on approximation, and so must be dependent on SME (subject matter expert) judgments. Fortunately, the early more formally trained corrosion scientists and engineers have now come of age and accumulated experience in depth, such that we can see a greater confidence regarding ALARP with emphasis on the following items, not necessarily in any order of importance:

Check Plan Listing

1. Utilize best practice ALARP criteria, PHAZOPs, with timely audits, and repeat HAZOP/FMECA's (Failure mode, effects and criticality analysis) (mandate corrosion SME's are invited for third party reappraisal).
2. Better material selection, coatings including TSA's and range of Nano coatings (major opportunities for internal pipe coatings, and CUI), and use of thermal imaging.
3. Insist on appropriate modeling (internal, external, and cracking) tackle pre-corrosion, storage, and preservation procedures (consider green vapor phase inhibitors, VPI's).
4. Adaptive technology, non-invasive (UT mapping), instrumented spools, established invasive (ER/LPR probes), creative sampling, potential-time (E-t sensors) etc.
5. Best practice benchmarks, calibration, verification, interpretation of history, big data.
6. Attend to 'new' mechanisms such as corrosion under excursions (CUE), applied R&D on site via 'intermediate' bypass loops, commissioned at system integration (SIT).
7. Better use of MOC, affordable empiricism and correlations (Chilton Colburn themes), and consider all known localized corrosion mechanisms (>15 off) not just pitting!
8. Lessons learned, benchmarking, precedence, judgment and risk scoring systems.
9. Quantifiable risk tolerance via consensus and KPIs, to support and deploy audits.
10. Variations of high-medium-low (HML) criteria to satisfy safety thresholds, productivity decision gates, and obviate roadblocks, with options for prefix V - very High/Low.
11. Encourage latest industry choices, and knowledge management, with better guidance on newer and project tested CRAs, tending towards cladding by Ni alloys.
12. Ensure project engineers, checkers, and verifiers including SME's are documented and validated at appropriate responsibility level.
13. Address all localized mechanisms, examine technologies for corrosion control, ideas on ROI, and 'monetization' for the life cycle, linking HSE to Revenues (HSEQ$).
14. Consider the use of the Corrosion potential (E_{Corr}) as a bone fide material property.
15. Encourage best applicable safe technologies, with measurable KPI's and appropriate knowledge management to enable translation across assets, systems, and circuits.
16. Accumulate history information, and utilize big data, machine data, artificial intelligentsia, better use of affordable adaptive small sensors.

17. Pay particular attention to fluid, geometry, stress upsets and corrosion initiation under excursions, focusing on specification breaks, mixed material interfaces, deadlegs, fatigue and vibration sites.
18. Expect the unexpected especially at weldments, occluded cells and coating interfaces. Entropy and gravity will ensure corrosion finds a way to thrive.

This is effectively an 18 point plan, which if addressed would go a long way to ensuring near zero C&IM failures. In practical terms many experienced practitioners (operators, class societies, Journals) have expounded the criticality of corrosion within the IM discipline (e.g. LR, DNV, BP, Shell, EOM, often via private communications). Nevertheless international codes, standards, recommended practices, project specifications or company 'go-bys' are often a reasonable means to progress, the latter allowing gaps in data to be filled. This provides the escape clause when things go awry, so the stakes and rewards are high, but still someone has to do the responsible 'sign off' when short cuts are taken for economic expediency. As a rule, the evolved steps must be in tune with the scientific method, but can be less rigorous, and often codified via proprietary algorithms, and company in house developed rulings (the engineering method); thus the criticality of bullet point 11 above. An example ALARP and Risk matrix is shown in Figure 2 below, and this can be used as the benchmark control when hard data are lacking, or indeed as a support tool when data does in fact exist. The importance of matching good empirical data to sound theory is always vital for high reliability results; and often possible to relate the criteria to KPI's, in terms of corrosion rates, potentials, pitting tendencies, erosion threats, etc. And in that regard independent engineering verification is critical, practical field validation preferred and technical qualification is always required in most jurisdictions.[9,10]

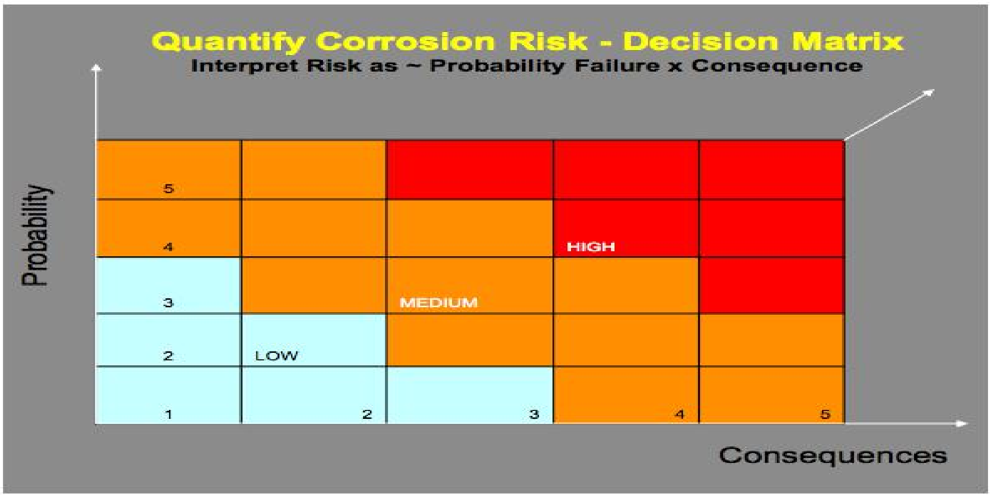

Figure 2: Adapted [2,24] Risk Matrix, with the ALARP condition normally described at Low zone, or occasionally at Medium zone on a client agreed case basis.

Nanotechnology Corrosion and Asset Management

Nanotechnology is the study and application of extremely small entities (1 to 100 nanometers) that can be used across all fields of science. The contribution of nanotechnology in the field of protective coatings for corrosion prevention and asset integrity management is not trivial. Here, a few examples on the application of nanotechnology in corrosion prevention is discussed. Silicon-based nano coatings applied on stainless steel and other alloys via chemical vapor deposition (CVD) fight corrosion while simultaneously easing design, fabrication, and integration of coated components.[12] The short-range atomic order of the amorphous material indicates that the coating is made up of nm-sized atomic clusters. The CVD method of coating application ensures that parts with complex geometries or narrow passageways such as valves and filters can be thoroughly treated both internally and externally. The coating is covalently bound to the base substrate to give durability and flexibility without flaking, while the thin profile has no impact on design tolerances.

Challenging Applications

Nanotechnology shows great promise in at least two major areas of application; firstly for corrosion under insulation (CUI); which is ostensibly the most severe form of corrosion that has been plaguing the petrochemical, refining and chemical industries for decades. The control of such CUI is extremely challenging due to the fact that water invariably seeps into the insulation, causing damage, which goes undetected for months until severe impairment has occurred. Recent advances in nanotechnology are aimed towards the prevention and mitigation of CUI. In the works performed by Noveiri et al,[13] nano-composite coating is used to prevent atmospheric corrosion and corrosion under insulation. This coating consists of 30% water based acrylic resin and 70% nano-composite, which constitute nanometer tunnels covering the surface completely. The morphology of the coatings, along with its hydrophobic properties, remove the moisture from the insulation surface, preventing moisture ingress onto the pipeline surface. Moreover, the semi-transparent coating ensures visibility of the underlying pipe, enabling early detection of CUI, although that needs to be tested properly under field conditions. The second major possibility is for internal pipe coatings. Here the challenge is to attain fully adherent and coherent coatings for all surfaces including field joints that are inevitably a problem area regarding preferential weld corrosion (PWC). So, a critical high integrity application is required; otherwise, one would accelerate localized corrosion cells at any coating damaged sites.

In principle, such self-healing coatings are considered to be efficient anticorrosion agents. These ‘smart’ coatings usually incorporate micro- or nanocapsules containing film-formers, which repair the damaged coating, when the integrity of the coating is compromised under mechanical stress or aggressive chemical environment.[14] For example, the introduction of calcium alumina fillers into polyphenylenesulfide coatings has been identified as an efficient method to seal and repair microcracks generated during exposure to hydrothermal environment at 200 ◦C, (Figure 3).[15] This shows a schematic of a typical coating containing microencapsulated specific-film-former agents' sensitive to electrical field and pH encountered in the vicinity of cathodic areas.[14] Smart control may also incorporate chemical or nanostructures inhibitors into the protective coating[16] Corrosion reaction drives the release of these corrosion inhibitors, preventing the dissolution of the underlying metal. Nano technology is expected to have great possibilities in the O&G industry though the next step from research to concerted practical application is awaited.

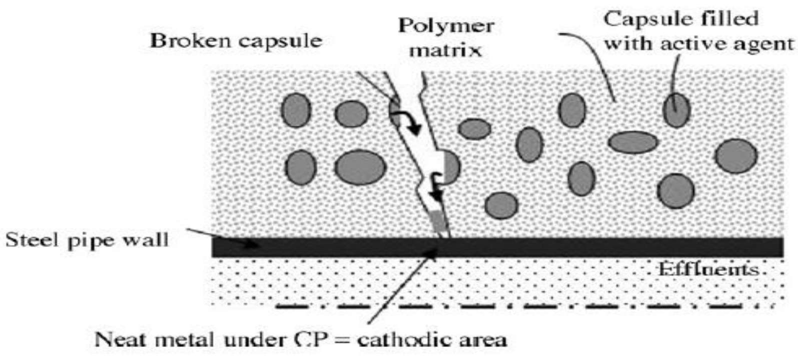

Figure 3: Schematic of an organic pipe coating

CORROSION INTEGRITY MANAGEMENT & HSEQ

Corrosion and integrity management (C&IM) are at the very heart of the risk assessment process. Our great leaders in this topic are the lessons of the past that we must continually pull forward and use as flags to wave before the industry to ensure the reminders of hard lessons of yesterday are an effective persuasion to keep such efforts upfront and not lost. And it is essential for such C&IM to be funded continuously as planned events; whether as regulatory requirement, by safety case, safety environment management systems (SEMS) typically based on the API SEMP 75, accepted industry or company standards, best practice or indeed company policy. Of major importance is to demonstrate knowledge of the cash flow sheet and the effect of safety on company's profitability. And to that effect multi-million dollar savings can be realized for large projects, via the application of occupational safety principles alone, often being very feasible even in a downturn when every aspect is heavily scrutinized for cost savings, safety in general, and especially when related to loss of containment. Nevertheless, it is prudent to continue the march on C&IM and safety to schedule, regulatory and policy. Best results are found in early design, verification, re-verification and operations phases, and during failure or incident investigations. Such early reconnaissance is suited to the PHAZOP (Preliminary) HAZOP.

Actions and Timing

Best results are noted to be just prior to the end of detailed design HAZOP or equivalent FMECA and still later operational and revalidations of same. Typically, the design HAZOPs support regulatory aspects such as the UK Safety Case in most parts of the world and also the Bureau of Safety & Environment Enforcement (BSEE), and other national bodies. The C&IM is considered part of regulatory systems world-wide and appears embedded in industry standards and company policy, although it is not always mandated with clarity. In the oil and gas industry the Piper Alpha[2] a point-in–time event, along with Bhopal, Chernobyl, Texas City and the catastrophic BP Macondo accident have produced a ground swell of demand for change including how risk, management of change, design and administrative procedures are applied; all of which have corrosion and integrity issues embedded.[2] Sadly there are indeed many onshore disasters too, though the focus here is for offshore and subsea. The commonality for all is the investigation or 'post mortem' still begging the questions; Why did we not have these "changes" already in place before these events took place? How can we be better? How could it have been better? What will take place now - and will it be good enough? Most of the time it's all about timing, see project progress Figure 4, below.

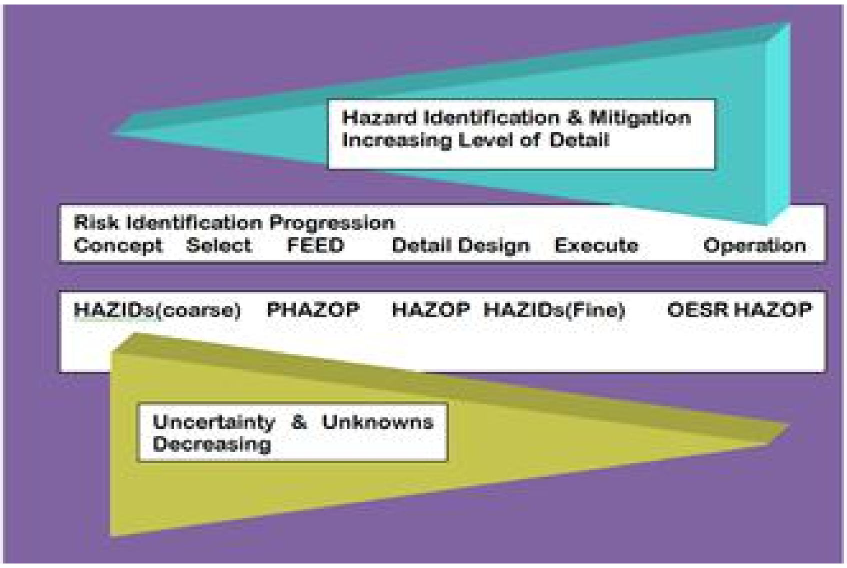

Figure 4: Desirable project Hazard Analysis.

HAZOP is a formal process embedded in risk management practices.[18] Typically, the client has established procedures, standards or policies which guide the planning process prior to the HAZOP, including the disciplines and reflected in the members of the study team, the methodology of investigation and the follow-on used to ensure findings are closed-out. Typically, companies have an internal roadmap specifying the point in the design process at which the HAZOP is applied. Experience has shown such HAZOP's conducted at the 70% to 90% design point or just before issuing P&IDs for construction.[17] Additionally, HAZOPs are done on vendor packages and during the operations stage as an operational, environmental and safety review (OESR) typically after one year of operation. Thus, the use of HAZOP earlier in the design order has considerable value and those clients already using such criteria clearly appreciate the points made. The PHAZOP is therefore an essential tool to finding C&IM threats and hazards sufficiently early, for appropriate changes to be made (MOC). Noting that the PHAZOP may be considered a 'pseudo baseliner' to the 70% and/or 90% design points mentioned earlier. In fact, HAZOP is often mandatory before any changes are implemented after construction and plant running.

The origins of the PHAZOP are be attributed to the safety author Trevor Kletz[12] who often opined that the one aspect he would do differently, if he could do it over, would be to conduct a HAZOP earlier in the design process; as this would provide the opportunity to identify and mitigate hazards when the opportunity to influence the design was greater. This is supported by the observation that changes are more problematic and costly when detected later in the design or indeed operational stages. in the words of one Tom Folk [22] 'the client may pay a little now or a lot more later'. Thus, we may construe the need to: 1) find the hazards as early as possible in the design process; 2) answer the following questions: when can the PHAZOP be effective as a process? How early is too early to get meaningful results? What kinds of design products are available at early stages for best utilization? Is the goal setting clear and evident to the participants? Do they have genuine buy-in and full commitment? These are only answered by experience such that we can generate a shared interest arriving at a common wisdom to eliminate C&IM issues [24] by 'engineering them out'.

CORROSION & AIM GAPS

PHAZOP as a process fits neatly into the existing risk assessment tools and it is desirable to have a comfortable familiarity with the approach and use of comprehensive teams to methodically assess the design. This should be done by people who have an area of knowledge management in which they can identify issues or gaps to lessen what is not known. Finding out what is known about the design is an exercise in tabulating which is known in a tangible, visual or conceptual form. This sum total of knowledge begs the questions: Do we know all that can be known and so have a complete list of hazards and full understanding of the risk? Can we know how much we don't know about a design and its hazards? Are we really certain of the full knowledge of the C&IM strategies, plans, execution and validation? For completeness teams must determine that all physical design and operational elements are included to realistically reduce risk to the ALARP condition. And importantly the SME's must resolve that no new hazards are created by any new substitutions or MOC's, and that lessons learned from the past are included and rolled forward to future design and C&IM campaigns. In practical terms, there were 106 recommendations from the Piper Alpha incident Cullen Report and very near the top of the list was the Safety Case which still has not been implemented as such in the USA. However, the BSEE (SEMS) regulations do carry related content based on performance standards interpreted as 'fit-for-purpose' has much merit compared to the pre-Macondo MMS prescriptive rulings. Unfortunately, the PHAZOP is not as well accepted as it should be, but if it were accepted in every corner of the world, with the appropriate leadership and SME's engaged then the ALARP function would be more highly effective.

MECHANICAL CHALLENGES AND ADVANCES

In the offshore and subsea sectors the greatest IM challenges from a mechanical perspective are typically related to:

- Dropped object damage
- Spanning integrity (accelerated by growth of corrosion defects)
- Riser mechanical integrity and fatigue life under extreme sea state loadings.

Mechanical forces and stresses can be critical with respect to the offshore steel catenary riser (SCR), touch down zone (TDZ) and stress joints (steel or titanium). This is especially dangerous at combination corrosion-erosion and fatigue sites (for internal pipe) and on seawater side, sensitivity both with and without cathodic protection (CP). Danger points can be loss of CP at shielded and unshielded areas, often requiring advanced measurements to quantify; typically via engineering criticality analyses (ECA), vibration assessment, and fitness for service (FFS) exercises. Here the links (positive and problematic) between HSE, quality and revenues; may be referred to as the acronym HSEQ$, and solving this paradigm is probably pivotal to best improvements.

Globally the topics most discussed[2,27] in the modern era appear to be mooring chain degradation and related loss of strength; tension leg platform (TLP) integrity issues, as well as corrosion under insulation (CUI) threats where a loss of hydrocarbon pressure containment would be catastrophic due to a major accident event (MAE), since there have been several near misses.

Invariably there are creative and pragmatic solutions available to address these threats and issues; most are unique and proprietary, often including a mixture of alleviating criteria defined as a result of private company joint ventures, or solution generating joint industry projects (JIP's).

LESSONS LEARNED

The best and most informative lessons learned are always those best understood; and for Corrosion and IM that must mean a full appreciation of the mechanism(s) and the main steps leading up to the accident or mishap event. If the critical step in the 'Swiss cheese' scenario is not trivial and would have stopped the event; then that step may be defined as the primary or on occasion the secondary root cause. For example, the Piper Alpha disaster of which much has been written and discussed, is widely accepted to have been primarily a failure of the permit to work (p.t.w.) system. However, a compelling argument can be made that due to the owners ignoring or delaying attention to the corrosion issues (The condensate systems were said to be 'plagued' with corrosion problems. Then it is reasonable to stipulate that if the corrosion issues had been addressed in an orderly, logical and timely manner, then the p.t.w. issue would not have occurred etc etc.) This will no doubt continue to be debated; but from an IM perspective; the simple act of regular HAZOP or FMECA workshops (say 3-5 yearly) on such projects would eliminate such corrosion and other integrity engineering issues. This can only be a recommendation, but the actual act of utilizing corrosion SME's at such workshops, might be the best enforcer. In the extreme case this may be more decisively mandated by Regulation; as has now effectively been done by the UK HSSE and the US BSEE authorities.

The operators should interpret the regulations, codes, standards and practices as to their intention and not as a minimum requirement. The objective is agreed by all, namely to eliminate major mechanical and structural integrity issues; by practicing a sound culture of safety. Within that the 'HSEQIM$' concept evolves as a sort of Venn diagram acronym. The corrosion scene in India is seemingly more sensitive and acute, so actually these ideas can be more meaningful in that region, provided the will is there to execute.

Pertinent Case Histories

Since C&IM traditionally relies on precedence and proof, three case histories are presented by way of typical examples are summarized below:

Case1 Marine integrated new inhibitor scheme to eliminate pitting and cavitation corrosion in ship cooling systems. The key differentiator was the use of delayed cyclic polarization curves with a relevant pre-corrosion and pre-filming parameters to simulate real world application conditions. The application proved successful in sea trials and thereafter. Life cycle management scopes were met by careful selection of SME's from client, design teams, and close workings with the supply vendors.

Case 2 The selection of a nickel alloy over a preferred copper alloy was sanctioned largely due to a better galvanic corrosion performance – contrary to expectations since the potential differences were unfavorable. However the critical differences demonstrated revolved around the exchange current densities of the two candidates observed and explained by the mixed potential theory. The new alloy has been successfully deployed for several years.

Case 3 The use of valuable third party reviews led to the re-appraisal and selection of more appropriate CRA's. Feedback was good; though the lesson learned has been to note that certain candidate alloys may have much lower friction factors (giving far smoother flows) making for very much high Reynolds numbers, albeit not near the erosion impingement ranges.

Modern day progress regarding new alloys, green inhibitors, best coatings, adaptive sensors, etc are likely to become more important in due course, especially as we plunge into more aggressive HP, HT, HV reservoirs in the future, and as existing assets turn ‘sour’.

Talking points

Regarding infrastructure integrity if the corrosion can be controlled then a major reduction of mechanical integrity threats can be realized, not necessary stopping but buying more time within the life cycle. The argument holds for old versus new steel, and it is interpreted that risk based determinations of localized corrosion can usefully quantify and address integrity issues for life cycle extension solutions, and this is valuable criteria for both new greenfield (GF) and old brownfield (BF) situation. The use of best working solutions to these challenges can be made by the adoption of modified existing technology such as sensors and adapted nano coatings for new or repaired old field segments. Thus, revised risk solutions for ageing pipe with retrofit sensors using appropriately pre-corroded spools of the field signature and ring pair variety as available on the market.

The result of such advanced techniques and modified monitoring can be successfully used with planned just-in-time (JIT) inspection whereupon intense, integrated monitoring and inspection are combined to give really good reliable data upon which decisive actions (such as part replacement, spool retrofit, etc, can be taken as failure. If relevant monitoring or inspection are not possible then modeling algorithms based on mixed potential theory and non-dimensional fluid analyses can be used to predict such imminent failure zones. This might usefully be based on the Chilton-Colburn[25] approach, with a modified form of the correlation given below.

Links Between Flow and Corrosion

By analyzing the flow, heat and, mass transfer correlations usually studied in the field of mechanical engineering, and relating to the mixed potential theory for corrosion mechanisms; it is possible to connect corrosion rates to flow regimes. The correlations obtained are empirical algorithms that can apply well on a case basis, provided the intermediate instrumented testing loops described earlier (items 4, and 6 in the 18 point listing) are used, and parameters kept within design envelopes.

Relationship between Heat and Mass;

$$J_M = \frac{f}{2} = \frac{Sh}{Re\, Sc^{\frac{1}{3}}} = J_H = \frac{f}{2} = \frac{Nu}{Re\, Pr^{\frac{1}{3}}}$$

Here the key parameters are the Reynolds number (Re), Schmidt number (Sc) and the Sherwood number (Sh) for the mass transfer side, and the equivalent Nusselt (Nu) and Prandtl (Pr) numbers on the heat transfer side of the J-factor analogy. The friction factor (f) from the Moody diagram can be examined closely with the wetting tendency at the wall, although the Nikuradse formula may be preferred for assessing f better in rougher surfaces akin to pipe internal surfaces under turbulent flow regimes.[26,27] It is clear that whilst a full understanding of corrosion mechanisms is preferred, since industry often moves faster than knowledge acquisition, the engineering method can often be used to supplement or override the scientific method on an empirical and risk basis, with fine tuning as theory and practice converge. The applied methods are often initiated in the laboratory but must be supplemented by field testing. The latter can be set up so that there is virtually nil impact on production activities, by the use of appropriate bypass loops with instrumented sections (using non-standard or modified sensors, probes, coupons and mapping spools) ideally with welded segments.

This approach is also safer and allows coupons and probes to be retrieved and examined off load rather than the dangerous on load techniques hitherto used. And once assessed the bypass loop can be re-introduced to the production fluids. The data accrued can be far more valuable than that achieved from single probes and coupons scattered around the system. For ageing plant the bypass loop can be constructed of pre-corroded sections for a likewise analyses; noting that the mixing of old and new steel should be carefully assessed especially at the interfacial and welded areas. Details of such examples and approaches are in the private domain but can be applied quite well on a case by case basis, via rigorous multiple disciplined engineering workshops akin to FMECA or HAZOP repeated (e.g. 1, 3, 5, 10 yearly) depending on risk tolerances per the client (operator), selected engineering companies, vendors and SME partners.

The success of this approach has been verified by historical examples per onshore (live MIC studies) for civil process plant, marine exposures for new inhibitor schemes, naval steam systems for new alloys, and aggressive ocean seawater salt spray exposures looking at multiple stressed and unstressed panels and bolting. In reality most such 'intermediate' testing tends to be retained for the asset life cycle since a constant appraisal of the materials performance is available as a bench marker or integrity verifier. And if the System PTV /stress regimes change the bypass loop allows for an experimental change (probe coupon design etc.) at relatively short notice and minimal cost with the confidence of relevance and reliability to the asset in question. One very valid way forward is the use of such pilot studies as proving grounds for full field surveillance, and to more reliably predict corrosion rates subsea say from the translation of topsides data accrued. There are indeed many engineering mishaps witnessed with cases of 'over conservatism' and 'under conservatism' with major ramifications and penalties for both extremes, but hopefully with continued iteration and knowledge sharing, C&IM related MAEs can be eliminated or significantly reduced.

CONCLUSIONS and RECOMMENDATIONS

It is concluded and recommended that risk oriented assessment of pertinent corrosion threats can address integrity matters and develop operationally acceptable ALARP solutions, with a decent ROI for both new and ageing assets. The findings emphasize the need for career lessons learned, to be taken seriously and applied; and an 18 point guidance has been presented.

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