BEST PRACTICE IN DESALINATION PRESSURE EQUIPMENT OPERATION AND MAINTENANCE

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Abstract

The purpose of the paper is to review problems and opportunities in desalination pressure equipment operation and maintenance (O&M) and to consider what constitutes best practice.

The paper:
- Explores existing O&M practices internationally
- Reviews existing codes, standards and regulatory requirements applicable to desalination
- Considers codes, standards and regulatory requirements not typically applied to desalination that could be adopted by or adapted to suit desalination plants
- Presents a view of best practice in Pressure Equipment O&M for consideration by desalination operators and maintainers.

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II. The Status Quo

2.1 Standards and Regulation

As noted by McCagh et al. [1] pressure equipment has historically been subject to regulation in most process industries but it is not typically the case in desalination operations, primarily due to relatively benign nature of the process fluid, and the relatively small volume of each individual vessel. The few O&M codes and standards that do exist were typically (although not always) developed without the specific equipment types and risks encountered in desalination in mind.

Take the Australian example. AS4343 Table B1 determines the classification of pressure equipment. An individual reverse osmosis vessel is typically then classified as hazard level E, due to it's 'non–harmful liquid', low temperature, and the product of the pressure and volume.

The code wasn't developed to take into account the harmful nature of projectile contents of the vessels, as a risk that comes with its liquid contents, nor the characteristic that means that high pressure pumps keep pumping high pressure fluid well after the failure, rather than ejecting a limited storage volume thereby quickly relieving pressure. If we take the view that the contents can be considered harmful (aside from the pressure and volume impacts), then that classification as an unfired pressure vessel could reach C or D. As pressure piping, that classification could reach B or C.

More compellingly, advice received from Australian pressure vessel experts indicates that the manifolded nature of an RO system means that the total system volume should be considered in classifying hazard level, rather than a single vessel, which would dictate classification of hazard level B.

So what? The implication of classification B, C or D rather than E is that AS3788 Pressure Equipment – In-service Inspection then dictates specific internal and external inspection requirements at commissioning and subsequent prescribed periods, typically 2 yearly external and 4 yearly internal inspections.

Interestingly, even for hazard level E, there is still a requirement that "in-service inspection of such equipment should follow the principles of this Standard, along with good engineering practice". The onus being then on determining your own justification for not carrying out similarly structured inspections.

Corresponding regulations (e.g. Queensland Work Health and Safety Regulation Chapter 5 Plant and structure) are less prescriptive but require pressure equipment maintenance, inspection and testing (section 213 and 224)

- on a regular basis by competent persons
- in accordance with the manufacturer's recommendations or those of a competent person, or annually

Also for items of plant requiring registration under the regulations, pressure vessels hazard level A, B, C but not for serially produced vessels (section 237), records must be kept of all tests, inspections, maintenance, commissioning, decommissioning, dismantling and alterations of the plant.
The regulations then call up a Code of Practice that in turn references the Australian Standards 4343, 3788, and 3873 amongst others.

In summary, taking the Australian example,

- law does not explicitly require adherence to mandated inspection timeframes but do require inspections by a competent person according to expert advice
- Australian Standard 3788 requires that even when hazard levels are low (E), the principles of the standard should still govern in-service inspection, so there is a strong argument to adopt the guidance of the standard.

2.2 Supplier Advice

Guidance on how to ensure equipment reliability and safety tends to be insufficiently detailed regarding O&M practice. A typical example is vessel supplier advice on leak management, that leaks must be addressed. For operators and maintainers, this advice presents significant problems.
Of course it is completely appropriate to highlight the hazards associated with leaks. However the information that is not provided is:

- What types of leaks can be expected?
- What is the consequence of each type of leak?
- Are some leaks more important than others?
- For each type of leak, what is the failure mode if these leaks are allowed to persist?
- For each type of leak, how long will it take for a leak to reach the point where a catastrophic failure is possible?

Broadly, it is clear based on reasonable logic and experience that permeate port leaks may not be as critical as side port leaks however to date it has been up to operators and maintainers to develop their own standards regarding the response times for each type of leak. Despite there being only a small number of common manufacturers of RO vessels, each model may be designed quite differently, particularly end closure and side port arrangements so there is no single answer for all O&M practitioners.

Leaks do occur, and they cannot be resolved instantaneously, and practical advice is required as to how to manage leaks in a production critical environment so this is a perfect example of the type of gaps that can be seen in supplier advice.

2.3 Aging Plant and Equipment

As the installed capacity of desalination continues to grow, so too does the problem of maintaining aging plant. With this growth, the overall risk of age related equipment unreliability and safety incidents increases.

As a bulk water supply technology, SWRO arguably only now has begun to mature as the transition from thermal has come since 2005, with the operation of the early mega plant Ashkelon and the explosion in capacity in the following years throughout the Middle East, Spain, and Australia.

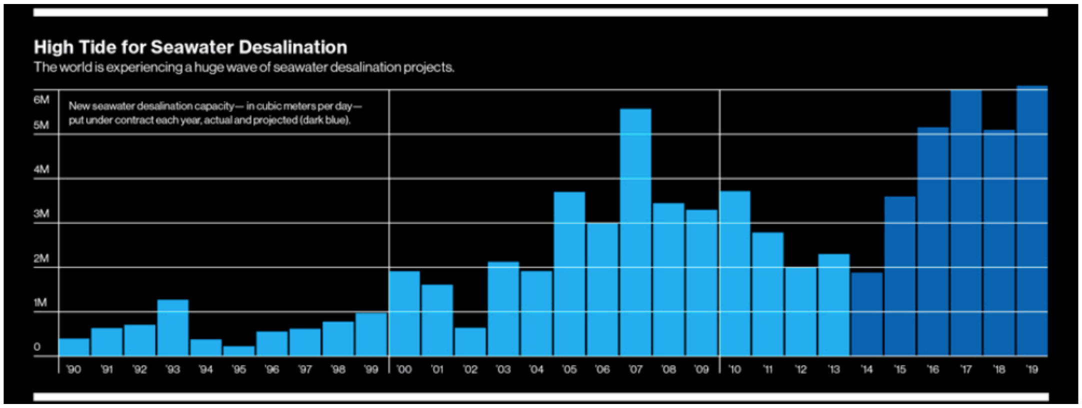

Figure 1. Installed capacity by year (Talbot) [2]

Figure 1 illustrates the peak of desalination plant construction from 2005 to 2010 during which >3000ML/d were installed each year. The plants installed during that era, clearly the vast majority of installed capacity in existence are now collectively approaching 'middle age'.

With age related failures more likely, the industry faces the challenge of living up to it's existing record of reliability and safety, despite this increased risk.

2.4 Partial Adoption of Standards

The risk inherent in partial adoption of standards is raised with the example previously presented by Eisberg [3]. Section X of the ASME X Boiler and Pressure Vessel Code (ASME BPVC.X-2015) presents design and construction specifications widely accepted as the industry standard for RO Pressure Vessels, but often procurers choose not to have vessels stamped with the Certification Mark in order to make a purchase cost saving. This results in the potential for compromises in quality relative to the intent of the code.

On the other hand, partial adoption of standards can be an opportunity. Where standards not specifically developed with desalination in mind have certain relevant aspects, the opportunity exists to adopt/ utilize the beneficial parts of standards.

2.5 Operators Concerns

Operations Managers from leading service providers were consulted during preparation of this paper as to how they perceive pressure equipment management challenges.

The key outcomes from this consultation included:

- Safety and corrosion ranked above reliability in importance
- Each of the pressure equipment components were of some concern, rather than there being just a single challenging issue
- A wide variety of approaches to management of pressure equipment inspection frequencies and response times

2.6 Need for Guidance on O&M Practices

Given the growth in mature installed capacity, the value and importance to the industry of definition of appropriate practices to optimize outcomes for owners, operators and end users is also reaching new levels.

In doing all things reasonably practicable to prevent unreliability and safety incidents, operations managers and teams need to demonstrate knowledge of best practice in implementing their own strategies, plans and procedures. The difficulty is that no clear best practice guide applicable to the industry exists.

Consultation mentioned previously has confirmed that there is some appetite for the development of a standard of practice for pressure equipment operation within the industry. However, any best practice guide must allow the flexibility for individual facilities to make decisions regarding appropriate practices given their own context, including factors such as:

- Production demand
- Safety risk tolerance and availability of funds to eliminate risk or develop extra precautions

III. What are the Key Objectives of Pressure Equipment O&M

Pressure equipment operations and maintenance is important only because of the consequence of failure. Clearly it is a risk that sits alongside other significant operational risks, however in many cases, as outlined earlier, it is a relatively unregulated risk e.g. compared to high voltage electrical safety. Safety aside, failures can become very expensive in terms of lost production, public health risk and economic losses associated with loss of supply and asset repair/ replacement costs.

Pressure equipment operations and maintenance broadly consists of the following key objectives:

- Reliability/ Availability – the ability to consistently achieve plant productivity targets
- Safety – keeping safety risk to the minimum practicable level
- Cost – ensuring cost effectiveness
- Regulatory Compliance – irrespective of whether RO vessels maintenance is considered a specifically regulated activity, there are overarching, safety related obligations in every major jurisdiction

Achieving the optimum balance is challenging as the short term cost increases and loss of availability required to achieve improvements in reliability are more easily measurable than the corresponding future savings or reduced safety risk achieved due to that improved reliability. So the availability of tools to help resolve these conflicts is paramount.

IV. What Tools Are Available to Achieve these Key Objectives Including Identification of Critical Aspects

4.1 Maintenance Focused Tools

Owens [4] describes steps to ‘production maintenance best practices’, of which the most relevant can be summarized as:

- Improve failure data collection – e.g. time between failures, downtime, repair replace and part costs, causes
- Using the information from this data collection, determine the corresponding value of uptime or improved availability
- Determine what changes could improve uptime
- Invest in technology to assist improvement process e.g. computerized maintenance monitoring system
- Schedule preventative maintenance, and allocate a human resource for planning
- Introduce predictive tools e.g. visual inspections, vibration monitoring, thermography
- Move toward Total Productive Maintenance (comprising elements of all other points)
- Implement Reliability Centred Maintenance (also comprising elements of all other points)

While many of these steps would typically be in place in modern desalination faciliites, the last couple of points deserve specific discussion.

Total Productive Maintenance evolved in Japan from 1971 in response to cost, quality and production versatility pressures resulting in a programme designed to dramatically improve profitability, prevent failures and quality breaches, promote team participation in improvements, create clean, well organized workplaces and foster organizational expertise (Nakajima [5]). While this is of interest in relation to maintenance best practice, it is only relevant here to the extent that it may provide an overarching framework within which to examine the specific part that pressure equipment plays in unreliability.

Reliability Centred Maintenance (RCM) similarly is applied to plant as a whole, but is more directly relevant as a “systematic approach to defining a routine maintenance programme composed of cost effective tasks that preserve important functions”. Failure Mode Effects and Criticality Analysis (FMECA) is one of the cornerstones of this approach as described by Aritio et al. [6]. By determining how plant is likely to fail, and the consequences of the failure, a far more precise suite of preventative and condition based tasks is able to be identified and assessed for cost effectiveness.

Inspection (RBI) is “a process that involves the planning of an inspection on the basis of the information obtained from a risk analysis of the equipment”. On that basis RBI is a tool that fits neatly within the suite of possible actions from FMECA, that in turn is a key part of RCM.

4.2 Safety Focused Tools

While FMECA provides an effective means of managing safety risk due to equipment failure in most cases, it is not absolutely effective in managing low probability high consequence events where it is typically implemented in conjunction with the concept of tolerable risk.

In particular the failure to put in place a precautions could be seen as negligent where an event is foreseeable and where that precaution is considered reasonably practicable to implement, regardless of the perceived tolerability of the risk. This problem is innovatively resolved using the process described by Robinson et al [7] whereby all reasonably practicable precautions are put in place for high consequence risks. Reasonable practicability takes into account factors including likelihood and consequence, the cost of implementing the precaution, inconvenience, and impacts on service provision (termed 'utility of conduct' by Robinson et al.) . To follow this process is considered as the best practice demonstration of safety due diligence.

Learnings from Artal et al. [8] could be incorporated in any risk assessment, ensuring involvement of the team in definition of the numerical value of consequence of various types of safety incident, and incorporating a novel and reasonable approach to likelihood classification/ quantification based on industry benchmark fatality rate. Some analysis of the data behind this fatality rate could provide value in defining likelihoods for individual risks.

V. How Are These Critical Aspects Addressed?

5.1 Codes and Standards and Regulatory Requirements

The section summarizes existing codes, standards and regulatory requirements applicable to desalination pressure equipment and particularly fiberglass pressure vessels, grooved couplings, flanged joints, and compression fittings, including the following jurisdictions and publishers:

- United States/ American Society of Mechanical Enginers (ASME)/American Society for Testing and Materials (ASTM)/the National Board of Boiler and Pressure Vessel Inspectors
- European/ UK Health and Safety Executive (UKHSE)
- Australian/ NZ

5.1.1 US including ASME/ ASTM/ National Board Inspection Code (NBIC)

The US has by far the most comprehensive and widely accepted standards for application to pressure equipment management through the ASME, ASTM and NBIC.

ASME Boiler and Pressure Vessel Code Section X

ASME BPV Code Section X (ASME BPVC.X-2015) Class 1 is the clear industry standard in RO pressure vessel design and manufacturing as documented by Eisberg [2]. Eisberg described the risks of not fully implementing the intent of the standard, through the process of 'code stamping' including third party inspection and certification of the vessel by an (ASME) Authorized Inspector (AI).

The typical activities carried out by an AI would be

- Verify the qualification of the filament-winding procedure under the Code including checks and cyclic pressure and hydrostatic qualification pressure test
- Witness the hydrostatic leakage test of each vessel

- Verification of the fiber weight of the combined fiber filaments and resin
- Fiber, resin and curing agent are according to the Procedure
- Verify speed of winding, uniformity of tension and adherence to patterns
- Check curing by verification of post cure time and temperature, hardness tests
- Examination for defects

With cost being an obvious factor in the industry's tendency not to order 'code stamped' vessels, there is the opportunity to significantly reduce the costs of this quality assurance for large orders. Note that ASME BPVC.X-2015 allows for alternative inspection and quality control where it is not practical to personally perform each required inspection in the case of multiple duplicate vessels, as is typically the case for bulk supply scale desalination. This does require this alternative procedure to be agreed by the Authorised Inspection Agency, the local jurisdiction, and the ASME Designee.

One of the cornerstones of the Code is Table 6-100.1 which sets out acceptance criteria for visual inspections. While the acceptance criteria are specified for the purpose of pre-delivery, some aspects of the table form a useful reference for in service inspections, and the table has been adapted for the operation phase inspections by some plants.

ASME PCC-1-2000 Guidelines for Pressure Boundary Bolted Flange Joint Assembly

This ASME standard is considered relevant due to the frequency of maintenance requiring joint dis-assembly and assembly in most plants. The standard provides a range of guidelines including alignment, gasket installation, lubrication, tightening methods, target torques, sealing surface defect allowances and training and qualification of personnel. Application of the standard should provide effective protection against joint failure.

NBIC Part 2 National Board Inspection Code NBIC Part 2

The National Board Inspection Code NBIC Part 2 – Inspection provides guidelines for internal and external inspection of piping and piping systems including:

- A method for estimating remaining service life
- A method for estimating inspection intervals including for pressure retaining items subject to erosion or corrosion
- Pressure vessel inspection report form (Form NB-7)
- Fitness for service assessment report form (NB-403)
- Provisions for Fiber Reinforced Thermosetting Plastic Pressure Equipment including
    - Specific inspection intervals, (nominally externally every 2-3 years, internally 1 year after being placed in service, and thereafter at a frequency developed in consideration of the results of that first inspection)
    - scope/ defect list (almost identical to ASME Table 6-100.1), and photographs of 'typical conditions' as a reference for inspectors

Other Design & Manufacture Standards

Various US based standards govern other system components, but at this time these are only relevant for the procurement of replacement parts and knowledge of QA requirements, rather than providing specific guidance regarding O&M. Some of the more important of these include:

- ASTM F1476 Standard Specification for Performance of Gasketed Mechanical Couplings for Use in Piping Applications – covers grooved couplings (e.g. Victaulic/ Piedmont)
- ASTM A781 Standard Specification for Castings, Steel and Alloy, Common Requirements, for General Industrial Use – includes for evaluation of conformance to chemical composition, mechanical and surface discontinuity requirements
- ASTM A890 Castings, Iron-Chromium-Nickel-Molybdenum Corrosion-Resistant, Duplex (Austenitic/Ferritic) for General Application
- ASTM A380 and A967 relating to passivation
- ANSI/ MSS SP-55-2011 Quality Standard for Steel Castings for Valves, Flanges and Fittings and Other Piping Components - Visual Method for Evaluation of Surface Irregularities – includes reference photographs

Regulations

The National Board Synopsis of Boiler and Pressure Vessel Laws, Rules and Regulations [9] provides a useful snapshot of ASME/ NBIC related aspects by jurisdiction.

While all 50 states recognize the ASME Boiler and Pressure Vessel Code by law , the degree to which it is adopted varies significantly across the states. For example California and Illnois adopts Section X, while Florida, New York and Texas do not, while of these states only Illnois mandates in service inspection of pressure vessels according to the Synopsis.

Regardless of this, there are some general requirements to ensure safety, that would require some logical basis for action other than the NBIC specification. For example in California State Subchapter 1. Unfired Pressure Vessel Safety Orders Article 4.:

"§467(b) The owner or user of any pressure vessel not specifically covered or exempted elsewhere in these Orders shall provide such inspection and maintenance as is necessary to insure safe operation of the pressure vessel."

And again in California under the same Article, as would be expected in most modern jurisdictions there exists a requirement to do what is reasonable:

"§560. Safe Practices…(a) No person shall………fail or neglect to do every other thing reasonably necessary to protect the life and safety of employees."

This requirement again justifies the use of Robinson et al. model to solve the problem of high consequence, low probability safety risks. Once again, tolerable risk would seem unlikely a suitable defense if something simple could have been implemented to save a life, and wasn't because the risk was deemed tolerable due to it's unlikelihood.

5.1.2 European

The Pressure Equipment Directive (PED) 2014/68/EU is equivalent to the ASME BPVC in that it provides requirements for pressure equipment, but is law in the European Union. They are accompanied by PED Guidelines that are not legally binding but as is usually the case, would require a substantial argument to vary from them.

The PED is focused on the obligations of a manufacturer (e.g. design and quality assurance), rather than on an operator and maintainer, so is of limited relevance here given the subject of management of pressure equipment. However it does specify in Annexure I the supply of "all necessary safety information relating to… maintenance including checks by the user". So it does provide a reasonable basis to expect necessary detail from supplier regarding what in service inspections or other maintenance is required.

Guideline H-03 related to Annex I section 3.3 and 3.4 requires advice of "residual hazards…that might arise from foreseeable misuse".

Council Directive 89/391/EEC on the Introduction of Measures to Encourage Improvements in the Safety and Health of Workers at Work recognizing:

"national provisions on the subject, which often include technical specifications and/or self-regulatory standards, may result in different levels of safety and health protection and allow competition at the expense of safety and health"

This reflects the concern raised in the survey conducted for the purpose of this paper, that compromising safety can result in a competitive (cost) advantage, and that this is not a positive thing for the industry.

Article 6 of Council Directive 89/391/EEC provides general principles of prevention, including that the employer must take necessary measures for prevention of risks, by avoiding risk or evaluating and combating risks at the source amongst other considerations.

EN13445 – Unfired Pressure Vessels is the European standard for design and fabrication, similar to ASME BPVC, but does not appear to have significant requirements for O&M.

5.1.3 UK

Aside from the Pressure Equipment (Safety) Regulations 2016 that effectively enact the PED in the UK, the key legislation is the Pressure Systems Safety Regulations 2000. The UK Government body, Health and Safety Executive (HSE) publish a number of documents relating to management of pressure equipment including the accompaniment to that legislation, "L122 Safety of Pressure Systems Pressure Systems Safety Regulations 2000 Code of Practice and guidance"

The regulations require "a written scheme for the periodic examination" of pressure equipment "in which a defect may give rise to danger". The guidance provided is that the user/ owner ensures the scheme is appropriate and that a competent person specifies the nature and frequency of examinations/inspections.

Based on the volume and pressure of the system, RO systems are likely to be categorized as Intermediate or Major under the Code of Practice clause 98. This in turn requires, in relation to that competent person:

- Staff -"at least one senior member of staff of chartered engineer or equivalent status…supported by technically qualified and experienced staff with knowledge of law, codes of practice,

examination and inspection techniques and understanding of the effects of operation for the system concerned"
- Specialist services – "in-house or clearly established access to design and plant operation advice, materials engineering and NDT".

Clause 103 scope includes not only pressure vessels themselves, but "pipes, valves, pumps, compressors, hoses, bellows and other pressure-containing components" where "Mechanical integrity is liable to be significantly reduced by corrosion, erosion, fatigue or any other factors, and failure….would give rise to danger".

The implication here then is that the entire pressurized RO system is subject to such a written scheme, with clearly defined inspection intervals.

Provision and Use of Work Equipment Regulations 1998 also contains some similar requirements to maintain and inspect and the Management of Health and Safety at Work Regulations 1999 include the above mentioned aspects from Council Directive 89/391/EEC.

There are also a range of design and construct related British Standards too numerous to cover here.

5.1.3 Australian/ New Zealand

Australian Standards

Australia Standards produces the following pressure equipment documents:
- AS1210 Pressure vessels
- AS4343 Hazard levels
- AS3788 Pressure equipment – in-service inspection
- AS3873 Pressure equipment – Operation and maintenance

AS1210 is the design and fabrication standard equivalent to ASME BPVC/ EN 13445. As discussed in section 2 of this paper, AS4343 allows for classification of hazard level, with implications under AS3788 including inspection requirements and intervals. AS3873 is intended to provide clear minimum requirements to ensure "safe, economic performance and protection of persons, equipment and the environment." Its provisions are quite far reaching and cover:

- a safety management system and procedures to manage the use of pressure equipment and ensure safety of personnel
- commissioning
- risk management and risk assessment methodology including reference to FMEA and hazard and operability study and methods for controlling risks
- training and assessment of personnel competency
- management of change
- operational surveillance, and it's role in assuring the quality of the system when combined with periodic in-service inspection
- safe isolation
- documentation and records depending on hazard level

The requirement for operational surveillance as a key driver for positive plant outcomes including risk mitigation is important to note, given that the act of physical surveillance includes exposure to risk. It is logical, and supported by this standard that this surveillance is required, with the obvious caveat that risk must be minimized to the extent reasonably practicable.

Regulations

The previously mentioned Queensland Work Health and Safety legislation is an adoption of the national 'harmonised' safety legislation effective through most of Australia. Aside from that referenced in section 2.1 of this paper, McCagh et al. referenced the concept of reasonable practicability written into law as that which is:

"reasonably able to be done….taking into account and weighing up all relevant matters including…likelihood..degree of harm..what the person …ought reasonably to know about..ways of eliminating or minimizing the risk….availability and suitability of ways to eliminate the risk….the cost associated with available ways of minimizing the risk, including whether the cost is grossly disproportionate to the risk".

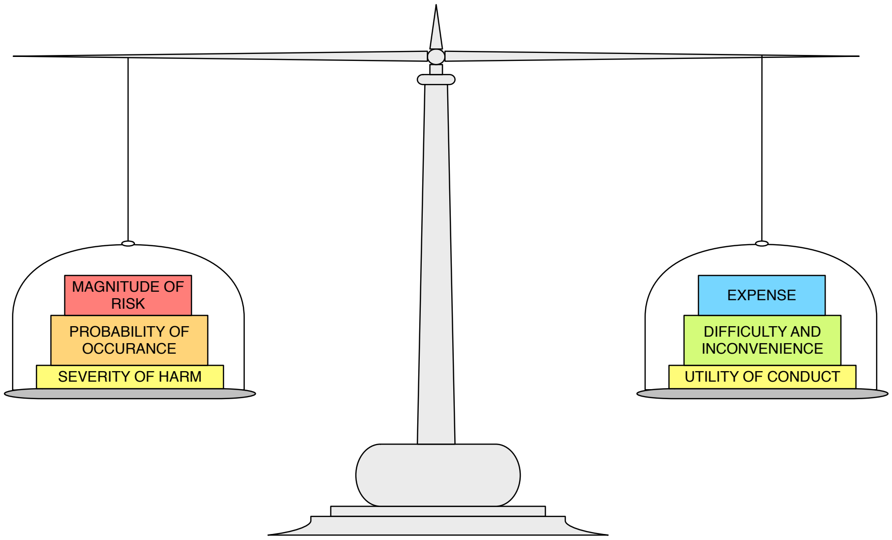

Figure 2: Risk balance diagram (courtesy R2A)

5.2 Options for Adoption/ Adaptation of Codes and Standards

Aspects of codes, standards and regulatory requirements that may not be typically applied to desalination that could be adopted by or adapted to suit desalination operations include:

- For RO pressure vessels, ASME X Table 6 and NBIC/ AS recommendations re inspection intervals can be adopted as a reasonable, defensible minimum standard (including the allowance to vary those based on evidence / competent person's advice)

- Use ASME X as basis for own QA (spend a proportion of savings carrying out a similar programme) if believe value is not in stamping process (theoretically the same outcome could be achieved through simply adapting, but would require ASME approval of specific programme)
- Adopt the ASME PCC-1-2000 Guidelines for Pressure Boundary Bolted Flange Joint Assembly approach and apply any relevant parts to equivalent processes for other safety critical equipment that make up the pressure system e.g. grooved couplings and compression fittings

5.3 Other Options for Addressing Key Objectives

So what are the options for addressing aspects through means other than the previously described tools, regulations and standards, including practices already in place at desalination facilities? Some are discussed here.

Use the best quality suppliers information. For example Victaulic I-100 Field Installation Handbook provides an installation inspection guide that could form the basis of in-service inspections, with some modifications to cover operational phase aspects including corrosion. Where more detailed information is required, lobby as an industry to have critical information included in supplier guides.

Adopt expert advice. Corrosion management failure mode knowledge has benefited from previous papers including the 2011 paper by Heiner and Parravicini [10]. Consolidation of the industry body of knowledge on the subject to assist in the implementation of corrosion mitigating precautions will improve the overall efficiency of the industry.

Doug Eisberg has provided strong leadership in the area of pressure vessel quality and has shared advice on managing risks including figure below providing guidance on probable areas of cracking around pressure vessel side ports.

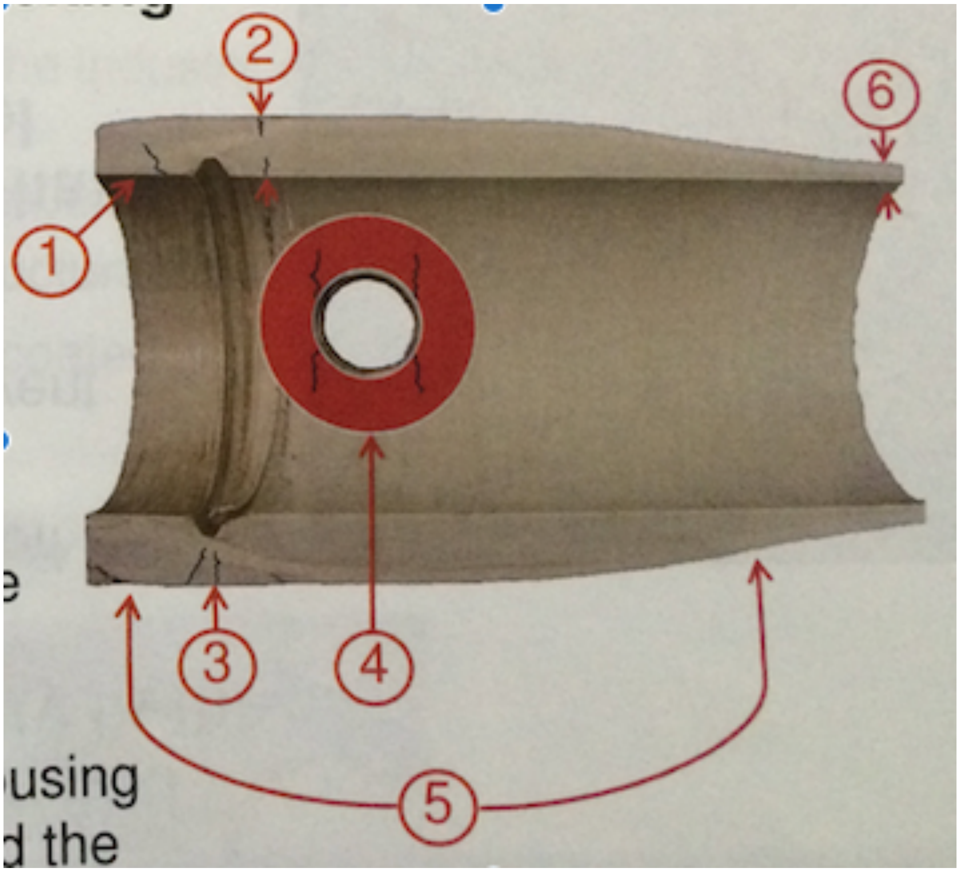

Figure 3. Tell tale crack locations in RO pressure vessels (courtesy Eisberg)

VI. Conclusions: What is the Best Practice Solution?

While strong frameworks for pressure equipment management are in place in major process industries, the desalination industry has avoided regulation, given it's lower risk profile relative to other process industries. The key opportunity then is to adopt aspects of available standards and guidance documents, taking into account this lower risk profile.

In addition, where existing guidance presents challenges in terms of cost effectiveness, alternative approaches may be valid. The problem of achieving a balance between cost and quality/ reliability/ safety in pressure vessel procurement is one example where options for addressing quality risk in the absence of the ASME BPVC Section X specified inspection processes seems a logical way forward.

Best practice in pressure equipment management would appear to include elements of:

- RCM and particularly FMEA/ FMECA leveraging the body of knowledge developed by the industry as a whole, rather than within the limits of isolated experience
- Disciplined collection of site failure data and root cause analysis to feed into FMEA/ FMECA and precaution development
- Risk assessment, recognizing the innovation by Robinson et al. addressing the shortcoming of tolerable risk approach for high consequence, rare likelihood failures

- Risk based inspection, as part of the suite of precautions informed by FMECA, on frequencies and to standards adapted from available published standards e.g. NBIC or AS3788 (maintain equipment as if it is regulated risk level, even if technically not)
- Decision making in accordance with advice by Robinson et al. determining whether any precaution is reasonably practicable to implement, particularly for high consequence, rare likelihood failures
- For RO pressure vessels, adapt ASME BPVC Section X Table 6-100.1 for the purpose of in-service inspections and adopt the advice of Eisberg regarding 'tell-tale' crack locations
- For other equipment types, adopt the best available supplier information (e.g. Victaulic Installation Inspection section of I-100 Field Installation Handbook) as a starting point for inspection criteria
- Where supplier information has not been sufficient to date, leverage industry critical mass to lobby for improved quality of advice regarding failure modes and precautions (broadly required by law)
- For asset replacement purchases, allow for the industry learnings regarding
    - RO pressure vessel QA and the need to weigh up the cost of the assurance historically provided by the requirements of ASME BPVC Section X inspections, against the cost of alternative assurance methodologies, including a sub-set of the Section X prescribed inspections
    - Corrosion mitigating precautions including casting quality assurance according to ASTM and ANSI/MSS standards, and avoidance of crevice corrosion sites and other aspects identified by Heiner et al.
- For asset replacement activities, adopt a rigorous approach to assembly equivalent to the ASME PCC-1 (i.e. creation of an equivalent guide for other key components including grooved couplings, compression fittings)

A guide/ code of practice could be developed with cooperation of the industry, incorporating the above aspects, somewhat simplifying what is an extremely complex area to manage effectively as demonstrated by this review.

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