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PNEUMATIC TESTING OF PIPING MANAGING THE HAZARDS FOR HIGH ENERGY TESTS

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ABSTRACT

Pneumatic pressure testing is used extensively during construction of LNG plants to avoid the problems that can be caused by water that may be left in a piping system (particularly in valves) if hydrotesting was performed. Due to the much greater compressibility of gas, there is significantly more energy (and thus risk) associated with a pneumatic test than with a hydrostatic test.

A major gas project safely conducted numerous pneumatic tests with stored energies of up to 6,675 MJ. Observing a commonly used limit of 270 MJ would have resulted in hundreds of additional closure welds.

This paper discusses practical aspects of performing pneumatic testing, the risk mitigations put in place and present two calculation methods that can be used to check whether exclusion zones for blast wave pressure are adequate for fragment throw.

INTRODUCTION

A commonly used piping design code, ASME B31.3 *Process Piping* [1] requires that all piping be subjected to a hydrostatic leak test, but recognizes that hydrostatic testing may be impractical in some special circumstances and allows pneumatic testing as an alternative. The very low temperatures associated with cryogenic piping in LNG plants mean that even tiny amounts of residual water that may remain after hydrostatic testing cannot be tolerated. Furthermore, some systems (e.g. flare lines) are unable to handle the weight of water associated with hydrotesting. Thus, pneumatic testing is commonly used in the construction of LNG plants.

Pneumatic testing is performed at a lower pressure (1.1 x design) than a hydrostatic test (1.5 x design x temperature factor). Two main dangers are associated with explosive failure during a pneumatic test: blast wave and fragment throw. The two relevant safety standards, ASME PCC-2 *Repair of Pressure Equipment and Piping* [2] and AS 3788 *Pressure Equipment-In-Service Inspection* [3] only provide calculation methods for protection against blast wave pressure. However, no method is provided to quantify a suitable exclusion zone to guard against fragment throw. Note that the 2015 edition of ASME PCC-2 added Minimum Distances for Fragment Throw Considerations in Table III-2. A lesson from a fatal industry incident during a failed pneumatic test was that setting exclusion zones only based on blast wave pressure or on total stored energy can be non-conservative.

A major gas project safely conducted numerous pneumatic tests with stored energies as high as 6,675 MJ. Both AS 3788 and ASME PCC-2 recommend limiting stored energy to 270 MJ (271 MJ in ASME PCC-2), but do not prohibit exceeding it. This limit of of 270 MJ is impractical for many of the piping systems tested due to both test pressure (up to 170 bar) and line size (up to DN1800) and would have resulted in hundreds of additional closure welds.

CODES AND STANDARDS REQUIREMENTS

ASME B31.3 cautions against pneumatic testing due to the hazard of released energy stored in compressed gas. Appendix F directs the user to ASME PCC-2, *Repair of Pressure Equipment and Piping*, Article 5.1, for equations and considerations to safely test pneumatically. Local Australian (AS) regulations also need to be complied to. AS 3788 Pressure Equipment – In-service inspection, Appendix D16, provides the minimum requirements for pneumatic pressure testing.

Both ASME PCC-2 and AS 3788 provide minimum exclusion zones based on the damage that could be caused by a blast wave resulting from the instantaneous release of all the stored energy of the test media. In AS 3788 the exclusion zones are fixed for given stored energy brackets. ASME PCC-2 allows the user to set the exclusion zone based on the level of risk that an Owner is prepared to take. ASME PCC-2 Article 5.1 §6.2 (f)(7) lists size and travel distance of fragments as a factor to consider as part of a hazard analysis, but no further details are provided as to how to perform this. The 2015 edition introduced Table III-2 but (as will be explained later) this table has limitations.

Note that both ASME PCC-2 and AS 3788 do not distinguish between piping and pressure vessels. The theory behind the (blast wave) exclusion zones is more applicable to pressure vessels as the energy is concentrated densely in one packed volume. With piping systems, the energy is usually distributed over a large area. In the event of a dramatic pipe rupture, it is not possible for all the energy to be released at once since most of the energy will be some distance from the opening and will need time to travel to the ruptured area. This is true for ductile materials. For a brittle material, a lot more energy could be released as the material does not first yield but suddenly fails. To avoid brittle failure, limits are set on the minimum testing temperature.

Figure 1 graphically illustrates exclusion zones as a function of stored energy for various standards. The project defined a High Stored Energy test (requiring owner review) as one exceeding 270 MJ. For blast protection, AS 3788 is more conservative than ASME PCC-2. At energies of less than 270 MJ and greater than 800 MJ the fragment throw exclusion zone of PCC-2 (2015) results in a greater exclusion zone than AS 3788. Contractually, the 2015 edition was not in place and the project used a standard 200 m exclusion zone for tests above

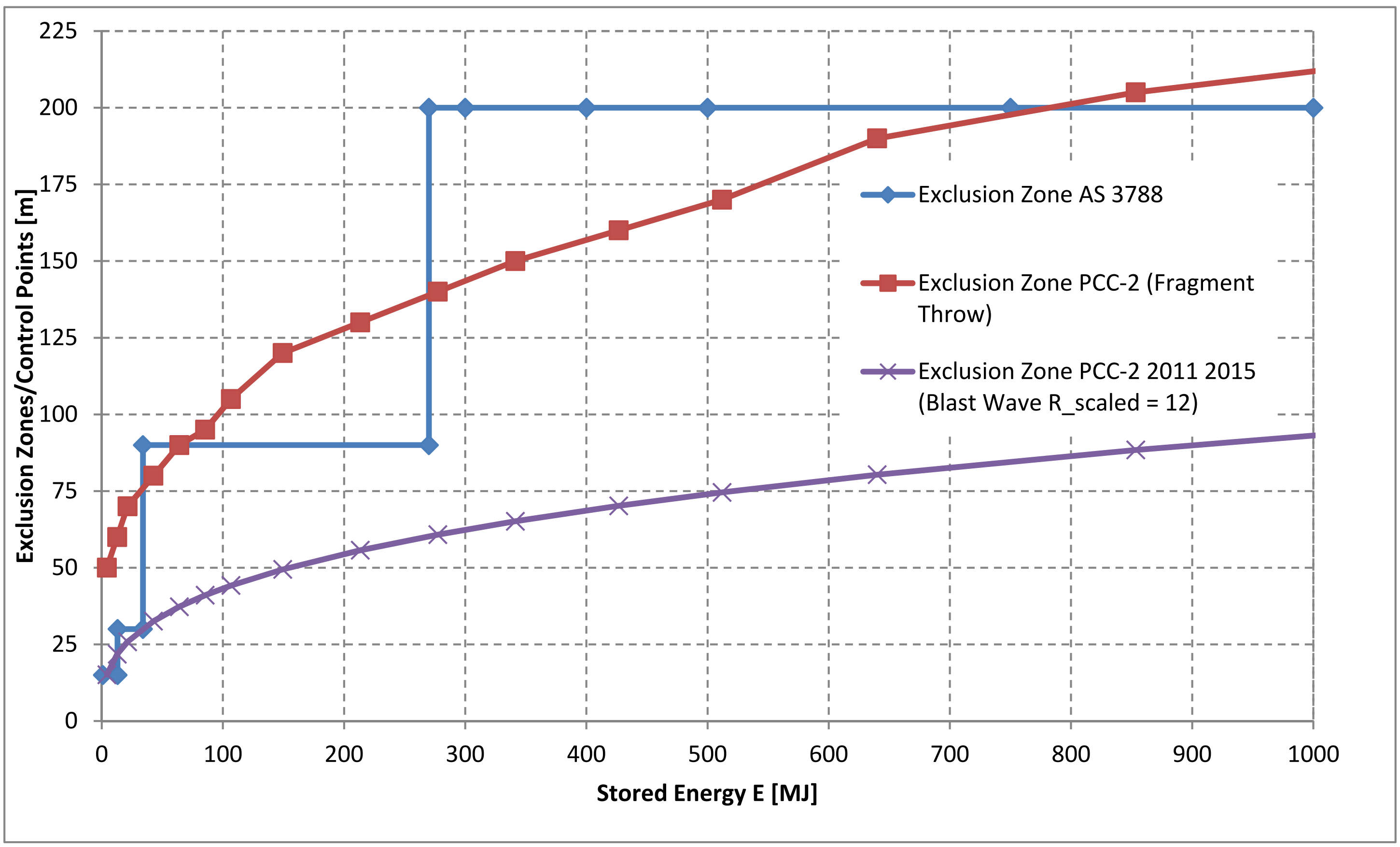

Figure 1: Exclusion zones for AS 3788 and ASME PCC-2

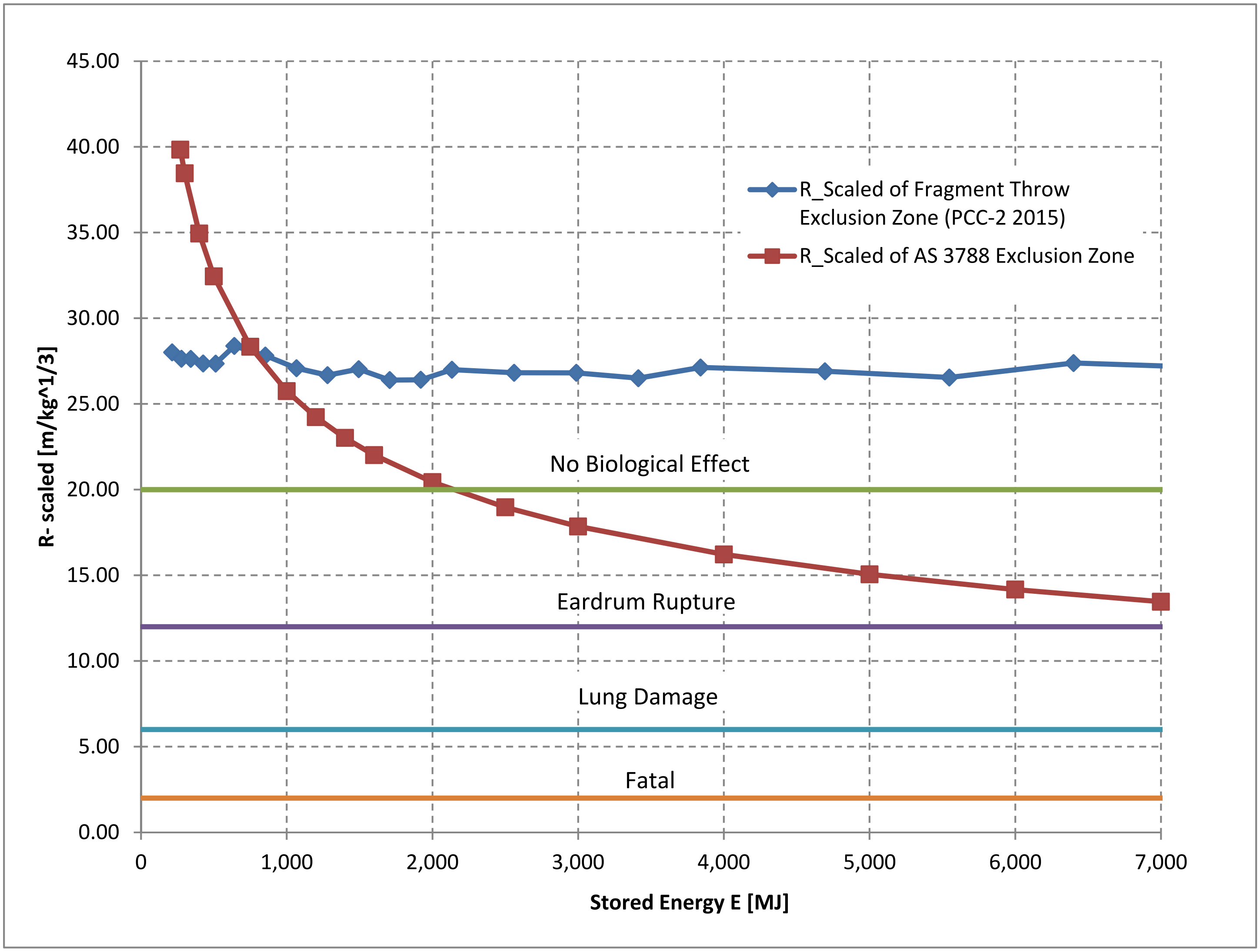

Figure 2: R_{scaled} values against stored energy

270 MJ. It should be noted that Australian Standards and the corporate piping standard require 100% RT/UT on all butt welds prior to pneumatic testing, exceeding the requirements in ASME PCC-2. The Australian Standards allow relaxation of this requirement subject to owner's approval and a critical engineering assessment. Fragment throw would presumably be one of the issues addressed by a critical engineering assessment.

The project evaluated fragment throw using methods available in the public domain which will be discussed later – in some cases these did result in larger exclusion zones. While not shown, it should be noted that at 20,000 MJ (about 3 times the largest project test) the PCC-2 blast wave exclusion zone (for R_{scaled} = 12) reaches 200 m. R-scaled is a consequence factor [2]. A value of 2 m / ($kg^{1/3}$) or less would be fatal while a value of 20 or greater would have no biological effect.

Figure 2 illustrates equivalent R_{scaled} values PCC-2 (2015) Table III-2 and the AS 3788 standard 200 m exclusion zone for tests above 270 MJ against stored energy. The various PCC-2 blast wave R_{scaled} values are included. The relatively constant R_{scaled} value of the PCC-2 fragment throw table suggests that the underlying theory behind this table is similar to the PCC-2 blast protection methods. By using a R_{scaled} value of 27 in PCC-2 equation III-1, a user would obtain very similar exclusion zones to PCC-2 (2015) Table III-2.

INDUSTRY INCIDENT

In 2009, an explosion happened at the Deep-Water Port construction site in Shanghai [4]. The explosion occurred during a pneumatic test of 600 m of DN900 pipe. The testing pressure of this system was 15.6 MPa however the explosion occurred at 12.3MPa.

The explosion resulted in 1 fatality and 15 injuries which were caused by the fragments of the exploded piping system. The worker who was fatally injured was 350 m away when he was hit by a scaffolding rod. The remaining injured workers were performing insulation works 100 m away from the explosion location.

The exclusion zones are shown in Table 1 below. The killed worker was 350 m away, substantially more than the minimum safe distance. This unfortunate incident indicates that while the (pre-2015) exclusion zones will protect personnel from a blast wave they do not guarantee safety against fragment throw.

Table 1: Exclusion zones in meters from different standards for a 15.6 MPa (est. 9 544 MJ) pneumatic test

	ASME PCC-2 (2011)(1)	AS 3378	ASME PCC-2 (2015)(2)
Exclusion zone	198	200	420

(1) This is the exclusion zone for blast wave per PCC-2 using R_{scaled} = 12 (ear drum rupture). Using a R_{scaled} = 2 (fatality) would require an exclusion zone of only 33 m.

(2) The 2015 edition of ASME PCC-2 introduced Table III-2 (fragment throw).

FRAGMENT THROW

ASME PCC-2 (2015) requires minimum distances per Table III-2 when fragments are at risk of being created. If these distances are not achievable, the distance may be evaluated using methods available in the public domain. Two such methods are presented here, F3D Method and Baum's Method. These methods are for specific piping components only – they do not consider other items in the vicinity (e.g. scaffolding or tools). Both methods are independent of the total stored energy.

Symbols used:

V – velocity [m/s]
P – test pressure [Pa]
A – inside area of fragment on which pressure acts [m^2]
D – Inside diameter of fragment [m]
R – end cap inner radius [m]
m – Mass of fragment [kg]
F – dimensionless initial acceleration [·]
a – speed of sound in test medium [m/s]

F3D METHOD

This method is suited for analyzing small items on branch connections that could become projectiles if a weld was to fail or a threaded connection suddenly disengage. The projectile is launched by the pressure acting on it. The method assumes that the pressure force acts on the projectile for a length equal to 3 diameters of the projectile. This is the work done on the projectile and it is all assumed to be converted to kinetic energy. With the energy and mass known, the velocity can be calculated. Simple projectile motion formulas are used to calculate horizontal travel distance. The volume of the major header is deemed so large that there is negligible loss of pressure as the fragment is launched.

The choice of the factor 3 was selected to remain consistent with the factor used by a 3rd party consultancy who performed a study for exclusion zones in the module yards for the project. The literature upon which this method is based [6, 7] stated that a value of 2 was more accurate. Thus, the factor of 3 provides a design margin. The initial velocity is:

$$V = \sqrt{\frac{6 \cdot P \cdot A \cdot D}{m}}$$

BAUM'S METHOD FOR END CAPS

The F3D Method is unsuitable when the fragment is the same size as the main header – for example if a the buttweld on an end cap or blind flange was suddenly to fail. The Baum methods [8] calculate realistic upper limit values derived from experimental test data.

A dimensionless initial acceleration F (independent of fragment type) is calculated:

$$F = \frac{P \cdot A \cdot R}{m \cdot a^2}$$

Different equations are used, depending on the fragment type, to calculate an upper limit velocity. For the fragment type "end cap" the velocity is:

$$V = 2a\sqrt{F}$$

Substituting for F, the initial velocity is:

$$V = \sqrt{\frac{2 \cdot P \cdot A \cdot D}{m}}$$

The Baum end cap method is identical in form to the F3D method, except that the Baum method will result in a velocity of $\sqrt{3}$ less than the F3D Method. It could be said that the Baum end cap method is the F3D method using a factor of 1, or perhaps the FD method. Standard tables (Table 2) were developed.

Table 2: Exclusion zones in meters for blind flanges using Baum end cap equations

	Test Pressure [barg]				
	10	**21**	**10**	**30**	**60**
DN100	19	32	13	29	50
DN300	65	123	40	100	188
DN500	101	194	59	151	288
DN600	122	235	67	173	332
DN900(A)	131	252	74	194	373
DN1200(A)	148	287	126	339	657
	CL-150 Flanges		**CL-300 Flanges**		

Table 2 can be used to obtain information about whether a system may have components at risk of exceeding the exclusion zone in place for fragment throw. For example in a Cl150 system being tested at 21 bar with a 200 m exclusion zone already in place, only components larger than DN500 require investigation. This could be a variety of options: performing full RT/UT on the at-risk components, locally increasing the exclusion zone or considering how well restrained the component is, i.e. the Baum method assumes an unrestrained flange at the end of a line, but a flange pair within a line would pose a much lower risk.

Table Notes:

- Yellow indicates that further investigation is required; 200 m exclusion zone assumed to already be in place.
- Total failure of butt weld on weld neck flange
- Weld neck flange with blind, nuts and bolts ejected as a unit
- Launch parameters 45° from 10m
- Baum equations (end cap method) used

TEST MEDIUM

Air was used for pneumatic testing at the project. The quality of air is an important consideration. The project specification specified “dry clean oil-free air” and that “oil lubricated compressors shall not be used”. This was realized to be an unreasonable requirement – high volume, high pressure compressors that are not oil lubricated are extremely difficult (if not impossible) to obtain. The strict definition of dry and oil-free would mean zero oil or water in the air. However, to achieve absolute zero would be impossible.

The corporate piping standard and ASME PCC-2 provide a more reasonable approach by specifying that the air conform to Class 1, 2 or 3 per ISO 8573-1. This allows the user to select the appropriate level of air quality for a tested system. This was the approach ultimately used by the project. Oil lubricated compressors were used, but the air was run through a filter system to achieve Class 0 or Class 1. The major drawback is that there is no practical way to verify air quality at site. The filter vendors provide laboratory reports and certification showing that a filter system met a specified standard, but there is no practical satisfactory way to quantify this at a remote construction site. ASTM D4285 does provide a practical, qualitative method to check for oil in compressed air but is not a very scientific method and is open to interpretation. This presents an opportunity for future revisions of corporate and industry standards.

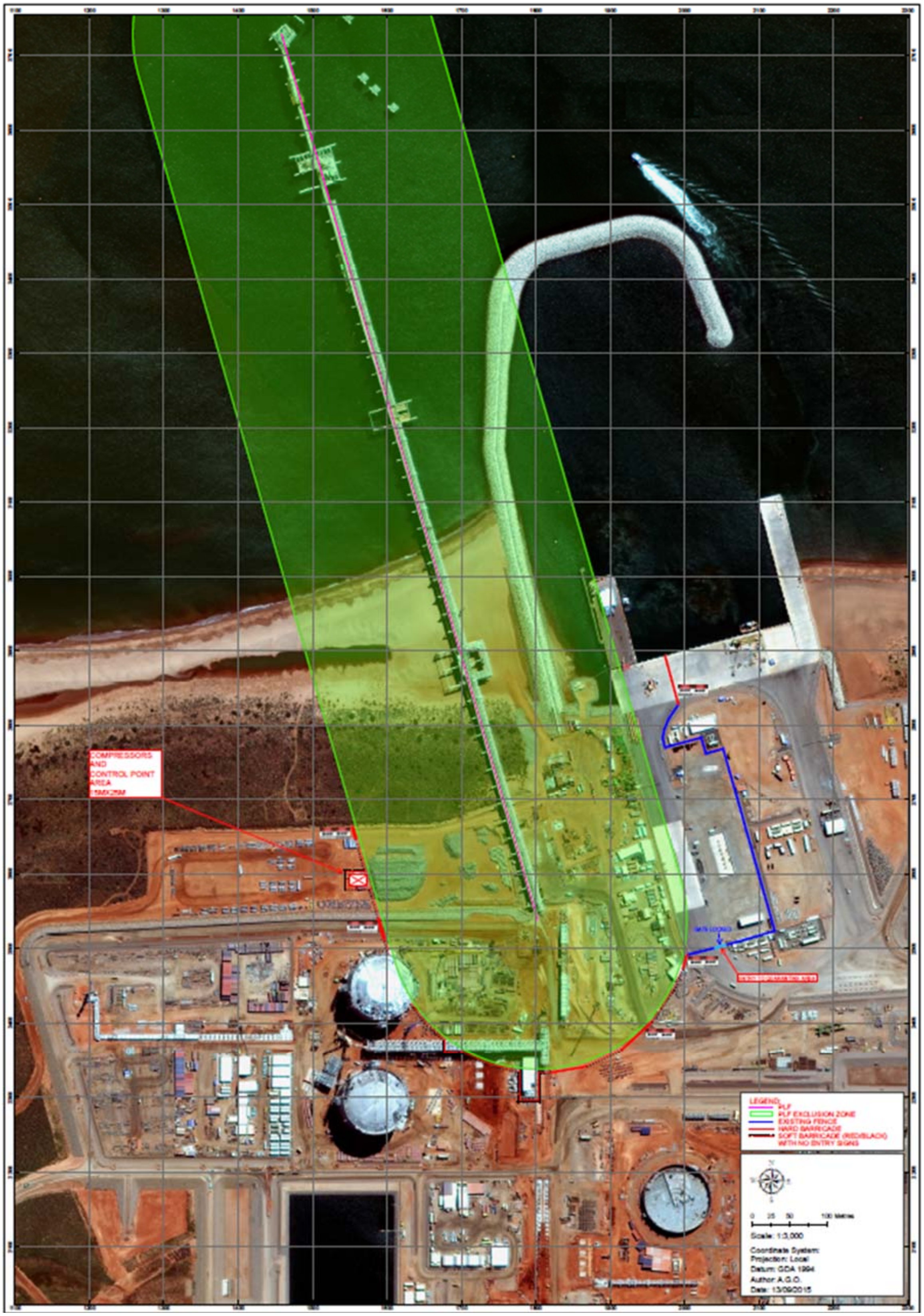

Figure 3: Loading lines on jetty (in red) and 200 m exclusion zone for 6,675 MJ pneumatic test

EXAMPLE OF A HIGH STORED ENERGY TEST

The pneumatic test with the largest stored energy performed at the project was two 1.4 km long DN750 loading linepipes tested at 34 bar (stored energy 6,675 MJ; 200 m exclusion zone per AS 3788) – see Figure 3. The air was run through a filtration system to give Class 1 per ISO 8573 Part 1. A check per ASTM D4285 was performed prior to testing. This test was 25 times the recommended maximum stored energy limit of 270 MJ – observing this limit would have required at least 25 closure welds. Additional factors taken into consideration:

- Piping material was stainless steel 304L, a highly ductile material.
- The warm ambient conditions (local night time temperatures are above 15°C) reduced the probably of brittle failure.
- The lines had been hydrostatically tested in module yards at 48 bar (typically in approximately 50 m sections).
- All site hook-up circumferential butt welds received 100% RT/UT per line class requirements.
- The energy was distributed over a large area.
- Location of the line on a jetty provided a natural exclusion zone and there is only one access point to the jetty.
- The R_{scaled} value associated with this test was above 12 – i.e. no biological effect risk.

ASME PCC-2 Article 5.1 § 5.2 mentions relevant factors to consider when performing a detailed hazard analysis – many were applicable to this test. Taking these into account, the risk was deemed to be relatively low despite the high stored energy. Due to the fact that all hook up-welds had received 100% RT/UT and all lines had been tested at 48 bar in sections previously, fragment throw was not deemed a credible scenario. However, if fragment throw was a concern, Table 2 could have been used with linear interpolation (not strictly speaking correct, but acceptable as a first pass estimate) to obtain an estimate for the exclusion zone required for DN750 Cl300 flange assembly at 34 bar: 206 m. This would indicate that further investigation is required.

CONCLUSION

A major gas project used a risk based approach supported by additional engineering and hazard analysis to conduct high stored energy pneumatic tests up to 6,675 MJ. Methods to estimate fragment throw for specific components were developed based on available literature. These revealed that basing exclusion zones solely on total stored energy can be inadequate.

These are the key lessons learned from this effort:

- Attempting to observe a 270 MJ limit will result in an undesirably high number of closure welds.
- Avoid unnecessarily tight specifications for purity of test medium – a fit for purpose approach is recommended (e.g. a flare line versus piping going to a cryogenic heat exchanger).
- The authors are not aware of any method to quantify air quality from a compressor.
- Extra precautions should be taken to ensure all threaded plugs are properly engaged – the exclusion zones required to guard against fragment throw are impractically large.
- For any pneumatic test always consider fragment throw as well as the blast wave exclusion zones – it may be necessary to perform additional NDE or increase exclusion zones.
- Accounting for mitigating factors in a hazard analysis may support a high stored energy pneumatic test as an acceptable option.

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