Managing Australia's Thin Wall High Strength Pipelines

Australian Pipeline Research

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Technical Scope and Key Words: Australia, research, thin wall, pipe

ABSTRACT

Australia's gas and liquid petroleum pipelines are characterised by being long distance, made from small diameter, thin wall, high strength pipe, and serving relatively small loads (See Figure 1). As a result, all aspects of design, construction and operation must be driven by lowering costs and improving efficiencies, yet meet some of the world's most demanding standards for safety and integrity. Since the early 1980s, the fledgling Australian pipeline industry has carried out ad hoc research directed at solving the particular problems that confront the use of thin wall high strength pipe. In 1996, the industry initiated a more wide ranging and better organised co-operative research program, but with the same emphasis. This research program has been most successful, and has tackled, among other things, weld defect assessment, hydrostatic testing for 80% SMYS pipelines, damage assessment and risk, corrosion, adhesion of polyethylene shrink sleeves, in-service welding, cold and hot cracking of weld metal – all directed to the use of thin wall pipe, improving safety and integrity, and extending the work done by EPRG and PRC-I on thicker wall, lower grade pipe.

This paper will provide a summary of the results and experience from the 7 year old Australian Pipeline Research Program, with particular emphasis on the Australian environment and the ways in which our research has been translated into the Australian Standard for gas and liquid petroleum pipelines.

INTRODUCTION

Since 1996, the Australian pipeline industry, represented by members of the Australian Pipeline Industry Association (APIA), has contributed $2,150,000 in cash and $3,800,000 of in-kind to an industry-wide research program that has addressed almost every facet of the life cycle of high pressure gas and liquid petroleum pipelines. The value of the research program to the Australian industry has been estimated to be in excess of $200 million in savings in capital costs and improved efficiencies in design, construction and operation of Australia's long distance pipelines. The quality of the Australian Pipeline Research Program has been recognised by the inclusion of APIA in a co-operative program with the US-based Pipeline Research Council – International and the European Pipeline Research Group.

The research program has assisted in the development of the Australian pipeline standard, AS2885. It has been objectively argued on the basis of a bench marking study [1] that AS2885 is superior in many ways to comparable international standards.

[1] Fletcher L., Venton P., Kimber M., Haddow I., Bilston K., Australian Standard AS2885: A modern Standard for design, construction, welding, operation and maintenance of high integrity petroleum pipelines, International Conference on the Application and Evaluation of High-Grade Pipelines in Hostile Environments Hotel Pacifico, Yokohama, Japan November 7-8, 2002 [also presented to the Joint Technical Meeting in Berlin 20-22 May 2003]

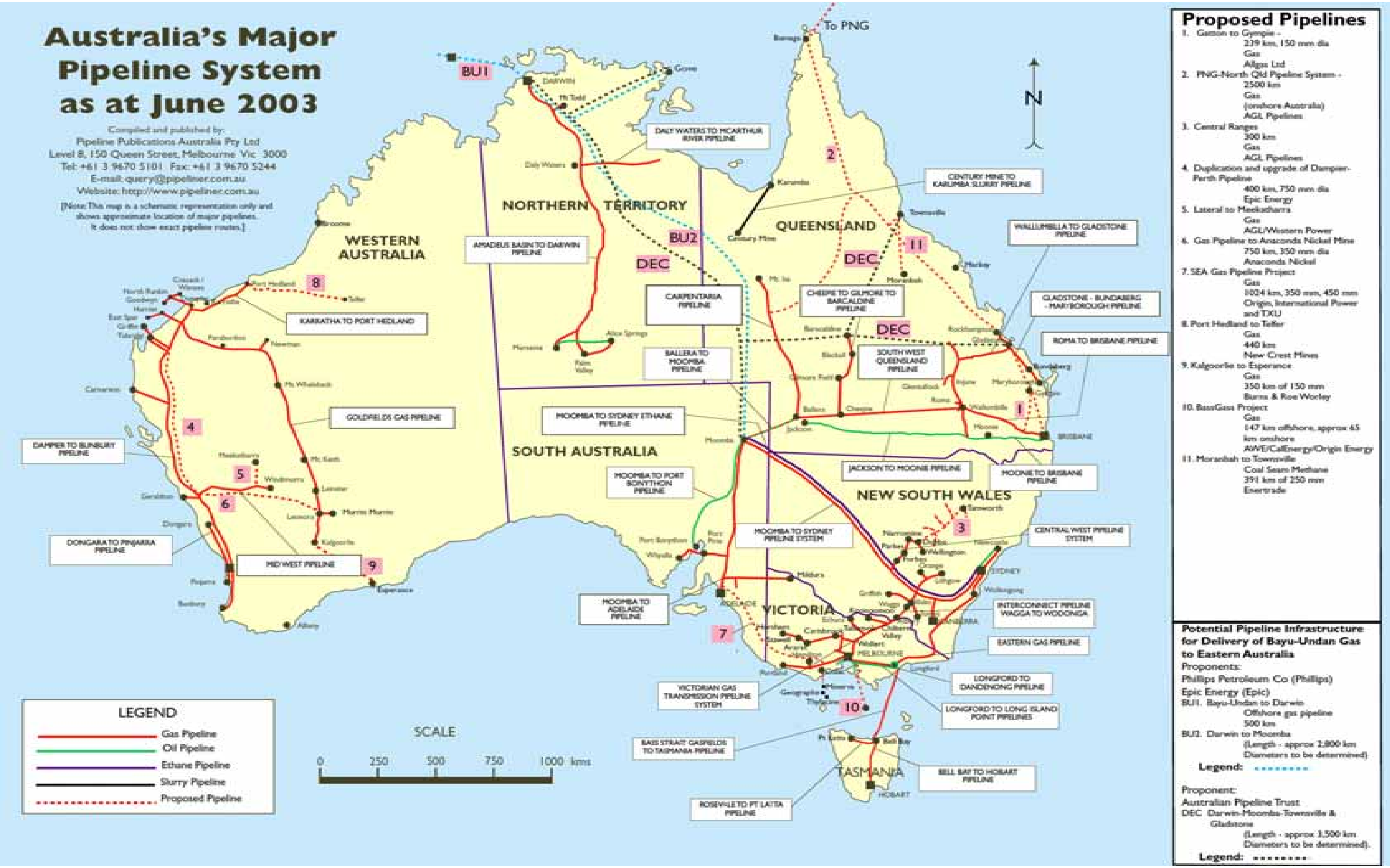

Figure 1: Petroleum (gas & liquid) Pipelines in Australia (Note relatively small diameter of proposed pipelines)
(Map Source: NEMMCO Statement of Opportunities and Pipeline Publications)

HISTORY

Since the Australian natural gas pipeline industry began in 1969, its participants have been committed to good, high quality pipeline design, construction and operation. During the first few years after 1969, the pipeline industry relied primarily upon the United States for its design, construction and operational standards for petroleum pipelines in the form of ASME B31.4 and B31.8. Between 1969 and 1972, pipeline engineers developed an Australian Standard – CB28 – 1972 – for gas pipelines, which was, to all intents and purposes, a copy of the relevant US standards, and did not reflect Australian conditions.

By 1980, some sections of the pipeline industry began to undertake research into improvements to pipeline technology, including the results of lessons learned from significant welding and coating problems encountered during the construction of the Moomba to Sydney and Wilton to Wollongong pipelines. Ongoing links with British Gas between some members of the Australian pipeline industry, including the Pipeline Authority and Gas & Fuel Corporation, provided access to its comprehensive research program. BHP Steel and Tubemakers were also engaged in pipeline steel research which was shared among industry participants. In 1981, one of the authors (Kimber) received strong encouragement from the US-based Pipeline Research Committee for the Pipeline Authority to join the PRC as the first non-North American member, but the Pipeline Authority saw fit not to accept the invitation. It was not until the Pipeline Authority suffered a major pipeline failure due to stress corrosion cracking in July 1982, that the Authority saw value in membership of an international pipeline research group. The Pipelines Authority of South Australia also joined PRC shortly after that.

During the early years of the 1980s, the next edition of the Australian Pipeline Standard was completed – AS1697–1981. While this new standard better reflected Australian conditions, it still bore a strong resemblance to the US standard. Local research into pipeline technology continued to be a low priority for the Australian pipeline industry. It was prepared to be a follower, rather than a leader.

A change in attitude to research began to appear in the mid to late 1980s. Membership of the PRC by both the Pipeline Authority and the Pipelines Authority of South Australia encouraged both organisations to send their pipeline engineers to meetings in the US, Canada and Europe. These engineers began to compare the overseas research programs with Australian needs and to redirect that research to better suit the local environment. In addition, contacts with their peers in other countries taught the Australian engineers new skills, which they applied to Australian pipelines. In association with steel, pipe and coating manufacturers, the better educated pipeline engineers were encouraged to use new materials and techniques. Perhaps the most significant aspect of this improved perspective was a clear intention by a small number of pipeline engineers to develop the Australian pipeline standards according to the “laws of nature” rather than the earlier paradigm of “laws of man”. That is, to apply the outcomes of research and intelligent application of science and mathematics to setting standards, rather than relying upon empiricism and rules of thumb. This new approach was first implemented through AS2885-1987.

But the new approach came at a price. The Australian pipeline standard became less of a recipe book and more of a standard that set down principles and processes that relied upon the skills and experience of pipeline engineers and technicians to implement them in design, construction and operation of pipelines. The latest version of the Australian Standard AS2885 is considered to be at least equal to, or in some aspects better than other internationally recognised pipeline standards.

Why is this so? The reasons were encapsulated in an Australian paper presented to a conference in Yokohama and also the Joint Technical Meeting in Berlin[2].

From 1987 onwards, the Australian pipeline industry placed more and more emphasis on research and its translation into the Australian Standard. Membership of the Pipeline Research Committee was continued by several companies until the mid-1990s, but ultimately the new owners of the pipelines decided that economies could be made by discontinuing membership. Many firms thought that their US or Canadian part-owners would bring the results of research with them, and that those results could be applied here. Unfortunately for the Australian pipeline industry, the overseas owners often forced a regressive approach – that is, back to the recipe book. Further, the intellectual stimulation for our Australian pipeline engineers provided by membership of international research organisations was stopped. We became a branch office, subject to the dictates of overseas principals. But for the APIA's Pipeline Research Program, and the dedication of a very small and diminishing band of pipeline engineers, that is where we would still be today.

THE AUSTRALIAN RESEARCH PROGRAM

During the late 1980s and early 1990s, a number of Australian co-operative research programs were started. Subjects that were studied included:

- pipeline coatings for station pipework
- standardised testing procedures for fusion bonded epoxy and extruded polyethylene coatings
- threshold stress for stress corrosion cracking
- the science of cold field bending
- engineering critical assessment of pipeline girth welds
- effect of telluric currents on corrosion
- the science of holiday detection for various types of coatings
- in-service welding techniques
- pipeline damage due to third party activities

Co-operative research into pipeline coatings and cathodic protection was undertaken by engineers from pipeline owners and coating companies from the early 1980s. Testing methods and ranking studies for coatings were done in the owners' and coating companies' laboratories which greatly benefited pipeline industry's corrosion mitigation and protection programs and procedures.

The Welding Technology Institute of Australia (WTIA) through its Panel 7 – Pipelines Group also contributed a great deal to research in the 1980s and into the 1990s. Panel 7 was made up of members of the pipeline, steel and pipe manufacturing industry. Panel 7's research was primarily directed to welding and NDT processes for pipelines. However, it also addressed fracture control and steel metallurgy. The work of Panel 7 made a significant contribution to the development of the welding section of AS2885 and its predecessors.

The results of these, and other research projects, found their way into the various Australian standards that are still in use today. The approach of applying the laws of nature was increasingly implemented, and the resulting Standards were more practical and led to a lowering of costs of pipeline ownership.

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[2] Fletcher L., Venton P., Kimber M., Haddow I., Bilston K., Australian Standard AS2885: *A modern Standard for design, construction, welding, operation and maintenance of high integrity petroleum pipelines*, International Conference on the Application and Evaluation of High-Grade Pipelines in Hostile Environments Hotel Pacifico, Yokohama, JAPAN November 7-8, 2002 [also presented to the Joint Technical Meeting in Berlin 20-22 May 2003]

In 1996, one of the authors (Fletcher) took over the role of Executive Director of the Co-operative Research Centre for Welding and Joining (now CRC for Welded Structures). Mr Fletcher had previously been head of Tubemakers' Pipeline Research Laboratory, and an eager participant in the co-operative research referred to above. Mr Fletcher assembled a group of like-minded individuals, including the other authors, to develop a research program specifically directed to petroleum pipelines and to sell it to the industry. The research program was overseen by WTIA's Panel 7 and administered by a Program Management Committee chaired by Mr Kimber.

In November 1998, Mr Kimber, who was the Chairman of the APIA Research and Standards Committee, in association the other authors, proposed that the APIA should take a role in managing pipeline research.

The first APIA administered Australian Pipeline Research Program 1998-2000 included:

- Finite element analysis of welding on in-service pipelines
- Evaluation of the use of ultrasonic testing of girth welds in thin wall pipe
- Further work on girth welding equipment for small diameter pipe
- Cracking in high strength cellulosic welds
- Girth weld defect acceptance criteria
- Fracture risk in thin wall high strength pipelines
- Development of heat flow modelling for application to hydrostatic testing
- Resistance to external interference (Part 1)
- Development of a realistic specification for pipeline backfill
- Pipeline awareness – development of improved methods of protecting pipelines from third party damage
- Development of standard approaches to technical audits by regulators

In 2000 to 2002, the Australian Pipeline Research Program included:

- Mechanised in-service welding (continued)
- Development of a knowledge base for mechanised girth welding
- Development of on-line monitoring for welding
- Hot cracking of weld metal in girth welds (continued)
- Defect acceptance levels and fracture risk in pipeline girth welds (continued)
- Pipeline hydrostatic test behaviour to accommodate 80% SMYS operating stress levels
- Investigation into the causes of the precipitation of elemental sulphur in transmission pipelines
- Pipeline awareness (continued)
- Adhesion of field joint coatings to extruded polyethylene[3]

In 2003 the Australian Pipeline Research Program included:

- Hydrogen assisted cold cracking in in-service welds (joint project with PRC-I)
- Development of fracture propagation prevention design tools for Australian pipelines

[3] Results confidential to APIA Australian Pipeline Research Program

- Field testing hydrostatic testing software
- Yield to tensile strength assessment for pipeline steels and the influence of coating application
- Adhesion of field joint coatings to extruded polyethylene (continued)
- Sulphur deposition (continued)

In 2004 the Australian Pipeline Research Program has commenced and includes:

- Pipeline resistance to external interference - Phase III
- Hydrogen assisted cold cracking in in-service welds (continued)
- Effect of transient loss of cathodic protection
- Environmental aspects of disposal of water used for hydrostatic testing of oil/gas pipelines
- Statistical analysis of pipeline incident data base
- Field applied coatings to cold damp pipework
- Fracture control and its application to Australia's thin wall high-grade Class 900 pipelines
- High Y/T ratio and low strain to failure effects in coated high strength pipe[4]

We are also considering proceeding with research on:

- Adhesion of repair coatings on extruded polyethylene
- Development of an alternative to the Notched Tensile Test
- Strain based design for management of land movement (mining subsidence, earthquakes, land-slip)

SOME OUTCOMES FROM THE AUSTRALIAN PIPELINE RESEARCH PROGRAM

The following is a brief description of the outcomes of the various research projects carried out under the auspices of the Australian Pipeline Research Program[5].

Project Title: External Interference to Pipelines Phase II

This project was initiated in response to the release of AS2885 (1997), in which pipeline designers were required to use penetration resistance as a physical measure against puncture. While the Standard allows use of penetration resistance, it gives no guidance on how to quantify this resistance and incorporate it into design. Phase I of this project in 2000 consisted of a comprehensive review of the worldwide literature on the topic, and also collated a database of damage sources and pipeline characteristics applicable in Australia. This phase extended the research through numerical analysis of the external interference problem. It consisted of:

- Experimental work, conducted on an in-situ pipeline using a variety of different types of equipment.
- Development and validation of a material failure model for use in finite element (FE) modelling of pipeline puncture.
- A parametric study on pipeline puncture under excavator loading, conducted using this material failure model.

[4] The authors invite participation from international pipeline research organisations and individuals in this project
[5] Members of EPRG and PRCI may wish to seek further information on any of the research projects

- A parametric and analytical study on pipeline denting under excavator loading.

The conclusions in this report, particularly those regarding puncture assessment, are invaluable in the design of pipelines in Australia. The studies carried out in this project have revealed results consistent with other studies, but offer several additional results that have not been previously addressed, such as:

- Experimental results for the damage to pipelines caused by drilling equipment;
- The investigation of the influence of tooth angle and position on the puncture load under excavator loading; and
- Presentation of denting and puncture analysis methods that are specifically tailored to the range of pipeline geometries present in Australia

Using the material failure model that was developed, a parametric study was conducted on puncture of pipelines under excavator tooth loading. This study showed that:

- The puncture load is not sensitive to pipe diameter, internal pressure or the angle of the tooth with respect to the axis of the pipe.
- The puncture load is strongly dependent on tooth size, pipe wall thickness, material grade and the position of contact.
- Simple analyses based on punching shear or membrane stresses tend to over-predict puncture loads for small or sharp teeth.

The tests showed that drilling equipment of all sorts is capable of puncturing pipelines if the drill head provides cutting action. Because operators may continue drilling operations well after initial contact, even thick walled pipelines are vulnerable to drills. For this reason, procedural measures rather than physical measures are recommended for these threats.

Based on the numerical results, a set of risk assessment tables was produced for quantifying the likelihood of puncture for a range of different excavator sizes and pipeline characteristics. Some conclusions drawn from these tables are:

Pipelines with wall thicknesses of 6.4mm and above typically have good protection against penetration from excavators of operating weights of up to 20 tonne when they are fitted with unworn, general purpose (blunt) teeth.

Pipelines of wall thickness of 4.8mm provide similar protection against general purpose teeth for excavators up to 15 tonne.

Pipelines of all sizes are vulnerable to penetration from even light excavators when highly worn or penetration type teeth (i.e. small, sharp teeth) are used.

Comparisons have been made with three tests conducted by the European Pipeline Research Group (EPRG). A peer review of this phase of the project by EPRG researchers is being undertaken.

Our work showed that the finite element modelling replicated the experimental results reasonably accurately, both in terms of the puncture loads and the deformation of the piping under load.

Project Title: Pipeline Awareness

This study has confirmed the widely held belief that excavation, and similar activities, are the leading causes of pipeline incidents and accidents, and that incidents involving third parties constitute the largest subset of this group. The research also shows that Australian high pressure pipelines are somewhat less vulnerable to damage from third parties that those in the USA and Canada. The researcher ascribes this to lower population densities, rather than any superior form of pipeline protection procedures.

APIA, with the assistance of its Pipeline Operators' Group committee administers a database of all transmission pipeline incidents. The 2004 research program includes statistical analysis of the incidents contained in the database.

Although there have been no fatal accidents recorded in Australia as a result of the failure of an operating transmission pipeline, the Australian pipeline industry should not be complacent. When the US gas pipeline incident and fatality frequencies are applied to the Australia pipeline system, about seven serious incidents per year, and one fatality every six years would be expected. On this basis, a single major accident, involving a small number of fatalities, would be sufficient to take the fatality frequency up to a level equal to or greater than that of the USA.

Although numerous suggestions are made for the improvement of pipeline awareness procedures, and on the relative merits of the various alternative methods, the report finds that the systems currently in use are already working quite well.

The greatest opportunity for improving the pipeline awareness systems is in the particular area of third party liaison. This is not a result of this area having been neglected, but because of its complexity.

An unexpected finding was that most third party interference incidents occur despite the awareness systems having done their job, and are a result of failures in the procedures for safely carrying out excavation in the vicinity of a pipeline. The people were well and truly aware of the pipeline, but they still managed to damage it. The report contains a number of suggestions for changes to AS2885, the Australian Standard covering the design, construction, and operation of gas and liquid petroleum pipelines.

- AS2885.1 needs an additional criterion for patrols to be considered "effective". To be considered "effective" the frequency of a patrol, and the methods of surveillance used, must be such that they have a high probability of detecting the design external interference event before the pipeline can be damaged.

- The criteria of effectiveness of one-call systems, in AS2885, should be strengthened. To be considered effective a one-call system should achieve the following:

  - The interference event, against which the system is intended to protect, must be within the area covered by the one-call service.
  - Systems must be in place to allow an accurate and timely response to a one-call inquiry.
  - The pipeline operator must have suitably qualified staff available to provide assistance to excavators who need to work near their pipelines.

Project Title: Mechanised In-service Welding & Software Development

Two factors make it difficult to weld onto a live pipeline that is carrying high pressure petroleum fluid:

- the flowing gas creates a large heat loss through the wall of the pipe, giving accelerated cooling of the weld. High carbon-equivalent steels are sensitive to such rapid cooling rates, which increase hardness, and increase the possibility of heat affected zone (HAZ) cracking.

- the local reduction in pipe wall strength during the welding process may allow the pipe wall to burst under the pipe's internal pressure. This hazardous event is termed 'burn-through'.

A third factor, that receives too little attention, is the inability of manual metal arc welding processes to achieve consistency of heat input. This variability is especially important in thin pipe because the inherent lack of control can be enough to cause the welding conditions to fall outside the safe welding envelope for burn-through or excessive hardening. The safe welding envelope is much larger in thick pipe. Most pipeline operators tend to err on the conservative side in respect of flow rates, cooling rates and weld quality, and hence have been forced to take pipelines out of service, or reduce pressures considerably, with consequent loss of revenue and greater cost. The aim of this project was to develop a methodology that would avoid, or at least limit, these circumstances.

This project had two deliverables:

- to develop software, based on earlier experiments done under this APIA Pipeline Research Program, to provide guidance to pipeline operators in the management of all the parameters that affect safety and weld quality during in-service welding; and
- to investigate the feasibility of using robotics to remove risk to welders and operating staff and to improve weld quality and consistency

The software that was developed allows the user to specify a set of pipe conditions (gas flow pressure etc) and estimate the safe welding conditions, by

- seeing an indication of the upper (burn-through) and lower (hardness) limits of heat input
- determining the HAZ hardness that will result for a given heat input weld
- determining the heat input that would create a burn-through risk.

It was demonstrated that a robotic system capable of in-service welding could be constructed using mini welding robots. Specifically, for circumferential welds a mechanised system such as that developed at the University of Wollongong produced effective in-service welds at controllable low heat input. Its restricted application to circumferential sleeves may not be a significant constraint since it is expected that most hot-tapping on thin wall pipelines would require the installation of a full encirclement fitting and therefore require a circumferential fillet weld.

Project Title: Mechanised Girth Welding Systems For Land Based Pipeline Construction in Australia

The original objective of this work was to evaluate alternative options for mechanised girth welding of land based pipelines in Australia. The feasibility study was followed by construction of a prototype girth welding system and practical evaluation of gas metal arc welding (GMAW) procedures. Commercial systems were evaluated against the requirements established in the foregoing studies. The focus of the work was on X80 pipe material and pipe diameters in the 400 to 500 mm range.

The principal outcomes of the work include:

- The development of welding procedures which provide adequate weld integrity and mechanical properties for X80 pipe without the need for internal root runs or copper backing rings.
- The development of additional tools to improve the reliability of the process in the field – including automated pipe ovality correction, on line weld integrity monitoring and weld data tracking.
- The development and construction of a unique ‘clam shell’ welding head to enable the critical system requirements for commercial systems to be identified.
- A review of currently available commercial systems and recommendations on their suitability for Australian conditions.
- A review of process enhancements which indicates that further consideration of multi-wire and flux core arc welding (FCAW) fill techniques may be justified if it is required to further minimize construction times.

A parallel project has resulted in the development for high speed root bead welding technique (‘Synchrowire’) which offers the opportunity for greatly improved lay rates and could offer substantial economies.

Project Title: Hot Cracking in Cellulosic Pipeline Girth Welds

Hot cracks in weld metal pose a significant threat to the integrity of pipeline girth welds due to their stress concentrating effect and the attendant risk of extension by cold cracking at lower temperature. This effect is particularly relevant in the case of high strength cellulosic weld metals where the extremely high levels of diffusible hydrogen increase the risk of hydrogen-assisted cold cracking, thereby posing a serious systemic threat to the construction and operation of pipelines.

Solidification cracking (SC), a particular form of hot cracking, has been known to occur in cellulosic weld metals under experimental conditions and there is anecdotal evidence of occurrences in Australian oil and gas pipeline construction. Furthermore, the root pass of pipeline girth welds deposited with cellulosic consumables seems to be more sensitive to the development of solidification cracking. It is likely that the specific attributes of the cellulosic consumables (high arc force, full penetration welding and high welding speeds) and the geometry of the weld configuration provide more favourable conditions for the development of solidification cracking than for other manual metal arc welding (MMAW) processes and conditions.

The current project work was designed to investigate the effect of welding parameters, such as welding speed and weld metal chemistry, on susceptibility to solidification cracking in root pass girth welds. A secondary aim of the work was to investigate the high temperature mechanical properties of cellulosic weld metals under tensile strains similar to those imposed on a root pass weld bead during the lifting and lowering cycle of a field construction procedure.

Solidification cracking in the pipe girth welds occurred predominantly in the low strength (E6010) weld metals, although evidence of Hydrogen-Assisted Cold Cracking (HACC) at weld defects and end craters was noted with the higher strength weld metals. SC was observed at the lower welding speed of 300mm/min, but susceptibility was enhanced by an increase in welding speed to 500mm/min. Welding at the higher speed required current levels near and above the top of the range recommended for a given consumable, and this is thought to be a major factor in increasing the risk of solidification cracking.

There was no significant correlation between solidification cracking and composition for the range of weld metal compositions studied. It was proposed that the observed cracking was more likely to be related to the welding conditions and the associated geometric and/or thermal effects.

Although the research project established that solidification cracking can occur in the root pass weld, evidence of hot cracking defects in completed production girth welds is relatively scarce. The relative absence of solidification cracking in completed production girth welds is considered to be due to dressing and hot pass welding subsequent to completion of the root pass. However, rather than relying on post-root pass weld procedures to eliminate any hot cracking that may occur, greater security would be found by observing procedures that minimize the probability of solidification cracking occurring in the root pass. The basis of this argument is that a small, but significant, risk resides in dependence on grinding and the hot pass to remove hot cracks. If the crack is too deep, its complete elimination may not occur, leaving a residual defect that can act as a powerful stress concentrator for subsequent cold cracking.

Experimental data obtained from the current work using 4.0mm diameter E6010 and E9010 electrodes indicate that the probability of root pass solidification cracking is minimized by:

- Careful alignment and fit-up of the pipe ends;
- Welding at speeds of less than 500mm/minute;
- Welding at currents below 160 Amps; and

- A delay of at least 10 seconds before lifting, following welding through the 6 o'clock position and 50-70% completion of the root pass.

It is recognised that current field practices normally exceed these recommended values for speed and current, and lifting is likely to take place during completion of the root pass as soon as it is 50% complete. Although the industry appears to be comfortable with these procedures, it should be aware that there is an attendant increased risk of solidification cracking.

Project Title: Defect Acceptance Levels & Fracture Risk in Pipeline Girth Welds

The Australian pipeline industry has adopted a 3 tier approach to assessment of girth weld defects. Tier 1 is a workmanship level which (depending on pipe diameter & wall thickness) contains considerable conservatism. Tier 2 is a generalised fitness for purpose (FFP) based level, and Tier 3 allows for an Engineering Critical Assessment (ECA). The approach, which is heavily based on the European Pipeline Research Group (EPRG) guidelines, has serious limitations in terms of wall thickness range (7 - 25 mm) and pipe grade (≤ X65 for Tier 2).

This project was conceived as a means of extending work done by the EPRG on assessment of weld defects to encompass the range of wall thicknesses and grades that are used on typical Australian pipelines – namely, ≥ 4.8 mm and grades X70 to X80. Weld repairs that result from the discovery of defects by radiography are expensive and if the criteria for defining defects is under- or over-conservative, then repair strategies and consequent costs are unacceptable. This research has assisted in the re-definition of weld defects for the Australian Standard AS2885.2 and will ensure the validity of current workmanship standards. It will also permit the implementation of newer and more effective ultrasonic methods of weld inspection.

The research project has shown that some welding consumables in common use undermatched the strength of the pipe and that currently permitted embedded defects limits for a pipe wall thickness of 5mm, in AS2885.2, would not ensure pipeline integrity under adverse loading. It was also shown by assessment of fracture mode that the required level of weld metal toughness in high strength pipe girth welds needs to be somewhat higher than that currently specified in AS2885.2 where yield strength undermatching is encountered.

In short, the outcomes from this project indicate that:

- some previously accepted welding procedures should be re-visited;
- it will provide pipeline contractors and owners with more cost effective tools to reduce the incidence of "false positives" in weld defect assessment;
- it will also improve pipeline construction rates because inspections can be properly targeted and fewer welds will need to be repaired; and
- it will give owners and designers more confidence in using higher grades of pipe.

Project Title: Pipeline Hydrostatic Strength Behaviour

This project was initiated as a response to a request from major pipeline owners to allow pipelines in Australia to be operated at stress levels above the current level of 72% of the specified minimum yield stress of the steel pipe material(SMYS). It is one of the many steps necessary to provide the intellectual basis for amending the Australian pipeline standard, AS2885, to allow operating stress levels of up to 80% of SMYS.

The aim of this project was to provide an ability to predict the behaviour of a pipeline section during hydrostatic pressure strength testing and to predict the hoop strains (elastic and plastic) in each pipe making up the section of pipeline, which could be many kilometres long. The need for the research has arisen because of the desire to increase the design factor for determining the maximum allowable operating pressure (MAOP) from 72% to perhaps 80% SMYS without at the same time reducing the hydrostatic test factor of 1.25. An increase in the hydrostatic test pressure without more effective control of the hoop strains experienced by the pipes making up the test section leads to a greater risk that the reserve ability of the pipe to undergo deformations in service may be prejudiced. This is especially the case with high strength pipe because, generally speaking, as the yield strength increases, the yield to tensile ratio increases and the strain to failure decreases.

Because hydrostatic test sections are never perfectly flat, and because the minimum test pressure must be achieved at the high point of the test section, much of the pipe in the test section will be tested to above the minimum test pressure. However, before this project was completed, there was no method of predicting with sufficient accuracy what plastic strains could occur in individual pipes making up the test section. This shortcoming gave rise to concern that in some circumstances the integrity of some of the pipe in the test section, or perhaps even the coating, might suffer damage during the testing process.

The output of the project was a software package ("*Hydro*") that enables the design of test sections to be optimised while minimising the risk of overstraining any pipe. The project included testing to assess the effects of strain rate and the state of stress on the material yield strength. The software was validated by comparison with a full scale pipe test.

A most concerning aspect of the full scale test was that the test pipe burst after only 2% hoop strain. This matter is still under active consideration and has piqued the concern and interest of a number of the industry's colleagues in North America and Europe. The test pipe was taken from a sample batch that is representative of many that are in service in recently constructed pipelines. This unexpected result has important ramifications for the selection of high level hydrostatic test end points. The outcome of the burst test makes it essential for the industry to carry out further research on the changes to pipe steel properties that occur during high temperature coating processes – such as the application of fusion bonded epoxy or tri-laminate.

Project Title: Adhesion of Field Joint Coatings to Extruded Polyethylene

Most pipeline owners and operators have been troubled by the failure of tape and shrink sleeve joint coating on pipelines coated with high density polyethylene. Failure of the joint coating has often resulted in active corrosion, which requires frequent and expensive dig-ups and repairs, often at 18 metre intervals (the length of a typical joint of pipe). This prompted research into the means by which cross-linked polyethylene shrink sleeves could be made to bond to the surface of the high density polyethylene parent coating to form a water-tight joint. The project recognised that it is nearly impossible to get material to bond to the surface of polyethylene, unless the surface is pre-treated to develop a form of surface activation.

A very effective process of surface activation was developed and was found to provide an excellent bond with proprietary adhesives used for joint coating. There is still considerable work to be done on developing a process for applying the technique in the field. Work will proceed in 2004/5 on the application of the technique for field repairs to polyethylene coating on operating pipelines.

Project Title: Sulphur Deposition Within Natural Gas Transmission Pipelines

The deposition of sulphur within certain natural gas transmission pipeline facilities in Australia is a problem to pipeline operators and large gas consumers, such as electricity generating stations. It represents a considerable cost burden to the industry, particularly in WA and to a lesser extent in Queensland and other regions in Australia. The sulphur is being deposited on the internal surfaces of the fuel systems for gas turbines used for power generation, in the fuel nozzles of pipeline turbine-compressor units, within gas turbine meters, and within gas regulation and pressure reduction equipment. The fundamental causes of this phenomenon have been determined. Reports by Australian pipeline operators, supported by direct observations in earlier research work, have indicated that the problem is much more wide spread than originally recognised. The phenomenon is not unique to Australia and has been encountered, albeit to a lesser extent, in New Zealand, Hong Kong and in gas processing plants in Europe. There is little or no overseas work in the public domain on the problem and our colleagues from PRC-I and EPRG are most interested in the project.

Sulphur is a very complex element and can have many different forms depending upon pressure and temperature conditions. Sulphur vapour is also soluble, to varying degrees, in a number of the common natural gas components. The clogging of well-bore tubing and underground natural gas reservoirs by elemental sulphur, especially with sour-gas compositions, is well documented.

A large pressure reduction in natural gas containing sulphur vapour in solution, and the consequent temperature quenching, provides the mechanism for the sulphur vapour to become supersaturated, and is hence conducive for the sulphur desublimation process.

The transition of the sulphur vapour to solid state (commonly referred to as S_8) occurs because at normal pipeline operating conditions the partial pressure of the sulphur vapour is well below the triple points. (Note: sulphur has more than one triple point). The sulphur particles are formed by nucleation; therefore the presence of other particles and liquid droplets in the gas stream will assist with this process.

The trend with new natural gas pipelines is to have them operating at 10MPa and above, therefore it is anticipated that the occurrence and magnitude of this 'sulphur deposition' process will increase. Although elemental sulphur is referenced as the deposition element, there are clearly many other elements and compounds involved. Extensive studies have been undertaken into the potential chemical reactions within a natural gas transmission pipeline system with respect to the formation of sulphur and its related compounds.

The studies into this complex phenomenon are still ongoing. However, it is now believed that the kinetics associated with this formation/deposition processes have been identified. Further analysis is still required. Clearly this costly and inconvenient problem for natural gas pipelines, and associated infrastructures, can be minimized through the careful control of pressure reduction processes and ensuring that pipeline contaminants are kept to an absolute minimum. The role of alkanes and other hydrocarbon fluids, sulphur vapour, hydrogen sulphide and associated compounds, moisture, electrophiles and nucleophiles, have varying degrees of influence on the observed 'elemental sulphur' formation and deposition processes.

The saturation level of sulphur vapour natural gas is a function of both pressure and temperature, with temperature being the dominating influence. The sulphur vapour saturation level increases at an exponential rate to the gas temperature increase. This will mean that the resulting elemental sulphur desublimation rate will be greater the higher the inlet gas temperature is into a transmission pipeline system. This of course assumes that the inlet gas is at, or near, supersaturation conditions for the sulphur vapour in the gas stream.

This saturation condition can be extended to the transmission pipeline where, for a given pressure reduction at a metering / pressure regulation station, the higher the inlet gas temperature to the station, the greater will be the elemental sulphur desublimation rate. This statement assumes that there will be minimal pressure and temperature variation between the transmission inlet gas conditions and the referenced metering / regulation station.

Unfortunately, the amount of sulphur vapour in the gas stream is an unknown quantity. This research work has demonstrated that processes within the natural gas transmission pipeline system have the potential to add to the sulphur vapour and / or contribute directly to the formation of elemental sulphur.

Of significant importance for this deposition phenomenon is the very large contribution from liquid hydrocarbons, which have most likely been generated through retrograde condensation, and the lubricating oils, greases, gas conditioning agents, pipeline rust inhibitors, and other introduced compounds. Having solid particle matter in the gas stream also is shown to contribute to the 'elemental sulphur' deposition process. The analysis of the deposited materials has consistently shown that the amount of elemental sulphur in the deposits is just a small fraction of the total. Hydrocarbon based liquids and solids being by far the dominant contributor in the observed samples.

Clearly the presence of H_2S plays a very significant, yet very diverse, role in the formation of elemental sulphur. The presence of water / water vapour and oxygen are also important contributing factors.

Once the supersaturation level for the sulphur vapour has been attained in the gas mixture, the nucleation phase quickly becomes established. However, the number of nuclei formed is very small which means the sulphur nuclei condensation / coagulation processes are going to be very limited without the presence of other particles within the gas stream. If the gas stream at the point of desublimation (pressure control valve) is subjected to very high turbulence then the particle – particle collision rate will be significantly enhanced. This means that the design of the pressure regulator cage housing is also a factor in the desublimation process.

The natural gas composition and the pressure and temperature conditions at the pressure reduction point will influence the conditions conducive for retrograde condensation. From investigations made into the operating conditions and gas composition at affected sites, a significant number demonstrated a very high probability of experiencing retrograde condensation. This, therefore, means that the potential exists at these sites for the concurrent processes of desublimation and retrograde condensation. As most affected sites have ball valves and other equipment that requires the regular application of greases and other compounds, there is the potential for additional foreign material in the gas stream. Collectively, these materials will greatly enhance the coagulation / agglomeration processes.

The presence of ‘elemental sulphur’ deposits is not only a concern for the transmission pipeline operators – it is a total industry problem. Such deposits in a pipeline system can be just of a nuisance value, or can have serious consequences. Unfortunately, some of the greater threats from ‘elemental sulphur’ deposition are seen to be in downstream facilities. As transmission pipeline operating pressures increase, so the occurrence and intensity of the deposition problem will increase unless there is some form of remedial action.