Nomination of the

NORTH WEST SHELF PROJECT

For an Engineering Heritage Australia Heritage Recognition Award

GAS FIELDS OF PLENTY

Prepared By Engineering Heritage Western Australia
Engineers Australia, Western Australian Division
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ENGINEERS AUSTRALIA

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

In 1971, the North Rankin gas field was discovered in the Carnarvon Basin in water 125 metres deep, 135 kilometres north-west of the port of Dampier. The gas reservoirs ranged from 2,400 to 3,100 metres below the seabed. The discovery was followed in 1972 by additional major discoveries of gas and condensate in the nearby Goodwyn and Angel fields. The discoveries were technically challenging and commercialisation solutions required then-unprecedented levels of investment. Only a world-scale development project would prove to be financially viable. Such a project required the production of liquefied natural gas (LNG) for delivery to export markets. This would be the first LNG project in Australia and would also represent the forerunner of a major new industry and significant contributor to the economy of Australia.

This nomination covers the first two phases of the North West Shelf Project (NWS Project). The first phase involved the concept and development of the North Rankin A (NRA) offshore drilling and production platform, a large diameter submarine pipeline to shore at Mermaid Sound in the Port of Dampier and domestic gas facilities for delivery of gas into a Western Australian Government pipeline to Perth and Bunbury, as well as export of residual condensate. The second phase saw the construction of two liquefied natural gas (LNG) processing trains, supported by storage tanks, export facilities and transportation tankers.

The overall scope of the project is shown schematically in Figure 1 below. At the end of Phase 2 in 1989, North Rankin was the only field then in production.

With initial Phase 1 and 2 investments of $7.1 billion[1] and total investment of more than $34 billion since the late 1970s, the NWS Project is one of the largest resource development projects in Australian history. In terms of engineering challenge, the project can be compared to the iconic Snowy Mountains Scheme. During its initial construction phase in the 1980s, it was the largest engineering project underway worldwide in the oil and gas industry. The project was and remains underpinned by vast hydrocarbon reserves with activities ongoing to extend the life of the project.

To succeed with a project of this scale in such a remote location, the NWS Project had to overcome many engineering, political and organisational challenges. In doing so, the development team, (comprised of members from Woodside, the NWS Project participants and specialist companies engaged for the project) broke new ground in many areas.

As this document is a nomination for engineering heritage recognition, it focuses on the engineering challenges and difficulties that emerged in the initial pioneering development stage of the NWS Project, and identifies the solutions the engineering team developed. The project also faced many business and political challenges that were addressed by people such as then Woodside Chairman Geoff Donaldson and then Premier of Western Australia, Sir Charles Court. For further information on the project's business and political challenges, readers are referred to the books by Robert Murray, Rick Wilkinson and Ronda Jamieson.

The NWS Project has, from the outset, been of national and international significance reflected in the special status given by both Commonwealth and WA State governments. To date, the NWS Project participants have paid in excess of $26 billion of royalties and excise. The NWS Project injects more than $900 million a year directly into the Australian economy and with Australian businesses through payroll, operating costs and capital expenditure.

The NWS Project is of fundamental importance to the development of the north-west of Australia by helping to demonstrate the ability of the Australian industry to complete projects of global scale and establish Australia as a reliable and important exporter of LNG. As Australia is set to be the world's largest exporter of LNG by 2020, it is arguable that this pre-eminent position in global energy production owes much to the successes and lessons learnt from the pioneering NWS Project.

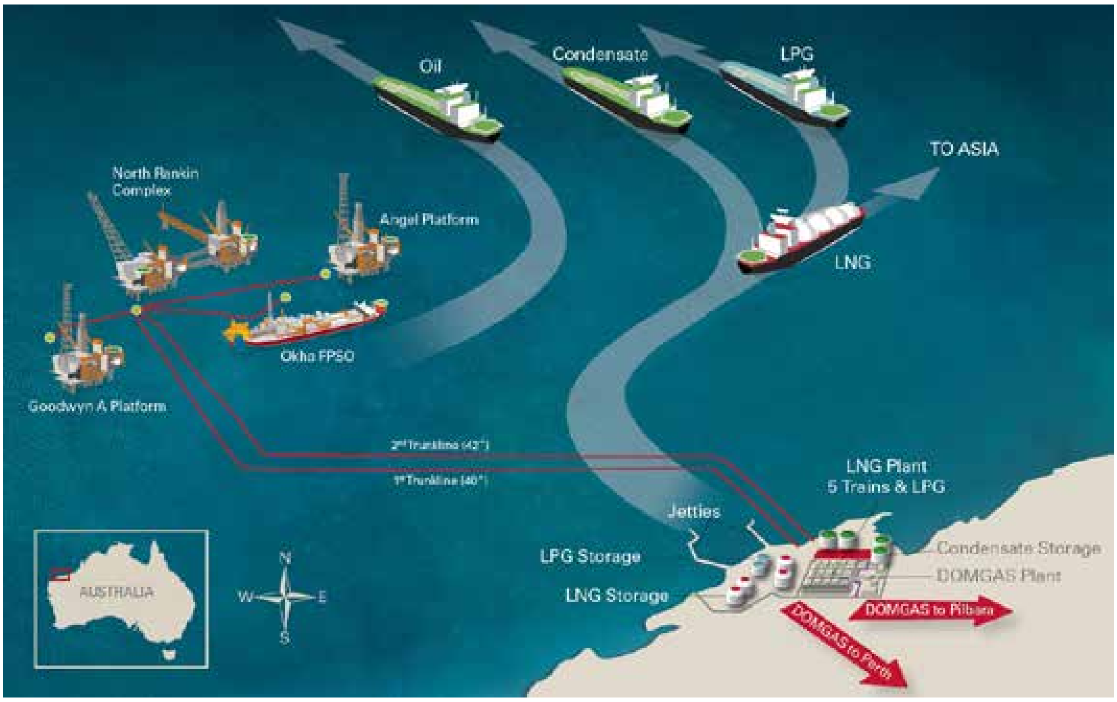

Figure 1: Overview of the NWS Project

1 *Please note all dollar figures refer to Australian Dollars unless otherwise specified.*

PROJECT DATA

Project name	North West Shelf Project (NWS Project) – Phases 1 and 2
Owners	Domestic Gas Project – Phase 1 North West Shelf Gas Pty Ltd (“NWSGPL”), a venture comprised of all NWS project participants except China National Offshore Oil Corporation (CNOOC), oversees the domestic gas marketing activities of the project. NWS LNG Project – Phase 2 The six participants in the NWS Project are: ▪ BHP Billiton Petroleum (North West Shelf) Pty Ltd ▪ BP Developments Australia Pty Ltd ▪ Chevron Australia Pty Ltd ▪ Japan Australia LNG (MIMI) Pty Ltd ▪ Shell Australia Pty Ltd ▪ Woodside Energy Pty Ltd (Woodside) CNOOC is also a participant in the NWS Project but does not have an interest in its asset infrastructure. Woodside is the project operator of both ventures on behalf of the other participants.
Current use	1. Export of up to 16.9 Mtpa (46,000 tonnes per day) of LNG predominantly to Asia. 2. Supply of pipeline specification natural gas into the Dampier to Bunbury Natural Gas Pipeline to the south-west of Western Australia at a rate of up to 12,600 tonnes per day. 3. Export of condensate at the rate of up to 10,000 tonnes per day. 4. Export of LPG at an average rate of 1,500 tonnes per day.
Designer	Various. Managed by Woodside with technical advice from Royal Dutch Shell.
Builder	Many thousands of people contributed to the development of the NWS Project. There were hundreds of contractors and suppliers and a list of contracts valued at $20 million and over is available in Woodside’s publication titled ‘Beyond the Flame’, page 134.
Year started	1971 – Offshore hydrocarbon discovery at North Rankin 1978/9/80 – Preliminary engineering – Phase 1 works 1980/84 – Detailed engineering and construction – Phase 1 1985/89 – Detailed engineering and construction – Phase 2
Year completed	Phase 1 – 1984 Phase 2 – 1989 Phase 3 – 1993 Phase 4 – 1999 Phase 5 – 2008
Physical description	Phase 1 – Domestic gas Initial offshore production platform (“NRA”) located over the North Rankin Field. Pipeline from NRA to shore near Withnell Bay in Mermaid Sound. Onshore production facilities to provide pipeline specification gas for the Western Australian market. Condensate storage and export facilities. Offshore supply base and tug pens at King Bay and an adjacent materials offloading facility to support onshore construction together with general cargo and fuel imports.

PROJECT DATA *(cont.)*

Physical description	Housing and other facilities in Karratha for Woodside personnel during the construction and operations phases. Phase 2 – LNG export Two LNG production trains for LNG export at the Karratha Gas Plant. Storage and export facilities for LNG. Six LNG carriers. Further detail of Phase 1 & 2 assets is included in Appendix 1
Physical condition	Currently operating to capacity
Modifications and dates	1992 Modification of LNG trains 1 and 2 to improve production rates to 2.5 Mt per year each (aggregate total 5 Mtpa). 1993 Addition of a 3rd LNG production train at a rate of 2.5 Mt per year (7.5 Mtpa). 1995 Addition of a 2nd offshore production facility over the Goodwyn Field (GWA). 1995 Installation of Cossack Pioneer FPSO over Wanaea-Cossack fields with oil production of 6 kt per day. 1996 Addition of a LPG plant, storage and export facilities at Withnell Bay. 2004 Addition of a 4th LNG production train at a rate of 4.4 Mt per year (11.9 Mtpa). 2004 Installation of second parallel pipeline from NRA to Withnell Bay. 2008 Addition of a 5th LNG production train at a rate of 4.4 Mt per year (16.3 Mtpa). 2009 Installation of 3rd platform at Angel location and pipeline to NRA. 2011 Replacement of Cossack Pioneer FPSO with Okha FPSO with heavy gas pipeline to NRA. 2013 Completion of the North Rankin Redevelopment Project including installation of NRB platform adjacent to and bridge- connected to NRA. 2015 First production from the Greater Western Flank Phase 1 Project. Further detail of additional assets is included in Appendix 2.
Historical notes	The NWS Project has been the recipient of Engineers Australia Engineering Excellence Awards as follows: 1990 The North Rankin A Platform Foundations Project was awarded the inaugural Sir William Hudson Award for the best engineering project in Australia. (refer Engineers Australia Insert, v62, n6, April 6 1990) 1992 The Trunkline Remedial Stabilisation Project was awarded a Western Australia Division's engineering excellence award. 1993 The Remote Offshore Warning System was awarded a Western Australia Division's engineering excellence award and the Pipeline Emergency Isolation System was highly commended. 1994 Both the Goodwyn A platform remedial works and the North Rankin reliability upgrade were awarded Western Australia Division's engineering excellence awards. 2015 The North Rankin Redevelopment Project was awarded the Engineers Australia, Western Australia Division's engineering excellence award.
Heritage listings	Dampier Archipelago (including Burrup Peninsula) is on the National Heritage List in the indigenous class, as the Archipelago contains one of the densest concentrations of rock engravings in Australia. Some sites contain thousands or tens of thousands of images. Also refer to Western Australian Heritage Council place number 16867. Western Australian Heritage Council has also identified the NWS Project as place number 12666, but there is no associated statutory or other heritage listing.

STATEMENT OF SIGNIFICANCE

The North West Shelf Project (NWS Project) was, at the time of commencement in 1979, the largest single non-government project ever undertaken in Australian history. The NWS Project's significance can be compared with the development of the Snowy Mountains Hydro-Electric Scheme of the 1950-60s. Both:

- comprise of very large facilities at a number of remote and difficult to access locations;
- utilised leading-edge international technology and engineering practice in their design and construction;
- are required to operate in a wide range of weather conditions with a high level of reliability and safety; and
- are of national significance in their impact on Australia's economic prosperity.

The NWS Project's successful development played a key role in establishing Australia as a reliable supplier of liquefied natural gas (LNG) to international markets. The project, along with subsequent developments have positioned Australia as the world's second largest exporter of LNG. In Western Australia, the value of petroleum products produced in 2014-15 amounted to $24 billion.

The NWS Project remains of major significance in the history of offshore facilities and LNG development both in Australia and internationally. The NWS Project contributed to the development of Perth as a centre of excellence in the oil and gas industry, comparable with Houston and Aberdeen.

Achievements of the NWS Project can be categorised in the areas of engineering, management and marketing. These achievements are summarised below.

Engineering:

- Development of sampling, data acquisition and analysis techniques necessary to derive the engineering parameters required for the design and construction of offshore structures. These included data for weather patterns and cyclones, ocean currents and temperature profiles, seabed topography and the unusual platform foundation materials.
- Planning, design and construction of the largest capacity offshore gas and condensate platform in the world at the time. The engineering and quality of the initial facilities proved to be sufficiently reliable and robust to permit significant additions and life-extensions required by new discoveries and expanding markets since 1989.
- Conversion of traditional LNG plant design from seawater-cooled to air-cooled and successfully building and commissioning the air-cooled LNG process facilities. This approach also included a change from steam turbines to gas turbines driven by both local environmental considerations and by the need for capital cost reduction.
- Establishment of a classification system and engineering design methodology for carbonate (calcareous) sediments as encountered on the North West Shelf and other offshore areas of the world.
- Sharing with industry and researchers the benefit of the NWS Project's experience in rectifying the foundation problems on the NRA platform through the sponsorship and publishing of state-of-the-art reports in the 1988 Conference on Calcareous Sediments.
- Sharing the NWS Project's unique liquid holdup and pressure loss calibration data for the design and operation of two-phase pipelines with the oil and gas industry.
- Installation of a structural and environmental monitoring system on the North Rankin A (NRA) platform to measure structure motions with the forcing wind, waves and currents during tropical cyclones. The continuous monitoring since installation has proved invaluable for the ongoing verification of NRA structure storm loadings and foundation integrity and instrumental in deriving environmental design criteria for other facilities off north-west Australia.

Management:

- Demonstration of a step change in Australian management of safety and quality throughout the design, construction, commissioning and operating phases of the project.
- Development of a remote offshore warning system that allows LNG carriers to maximise time at the loading wharf when threatened by tropical cyclones, leading to additional cargoes and on-time deliveries. Some of the concepts developed for this system have since been adopted by the iron ore industry for management of under-keel clearances in shipping channels.
- Determination of the physical scale and dimensioning of tropical cyclones off north-west Australia, which enabled correct wave generation 'fetch' distances to be used in determining design wave heights for the project. These studies delivered new methodologies providing a high level of confidence in the design wave heights and benefited subsequent wave height studies for many operators off north-west Australia.

Marketing:

- Establishment of marine bases and associated infrastructure in the Dampier area. Provision of housing in Karratha and contribution to facilities that supported the significant growth and development of Karratha.
- Establishment of new industries and the development/expansion of fabrication, construction and wharf facilities in the Perth/Cockburn Sound area.
- Setting a new benchmark for government and industry cooperation, evidenced by the Western Australian Government underwriting the domestic gas supply contract and building the 1,500 km pipeline to Perth and Bunbury.
- Provision of technical support, personnel and funding for research, testing and development of technologies applicable to many facets of the oil and gas industry. Research and testing has covered areas such as soil mechanics, new LNG processes, ceramic fuel cells and gas dehydration.
- Provision of unique opportunities for Western Australian universities to participate in the research and development programmes necessary for metocean data acquisition, sampling, testing, interpretation and application in off-shore structural design. These are now considered world-class.

Figure 2: Karratha Gas Plant under construction

HERITAGE RECOGNITION NOMINATION FORM

The Administrator
Engineering Heritage Australia
Engineers Australia
11 National Circuit
BARTON ACT 2600

Name of Work: North West Shelf Project

The above-mentioned work is nominated for an award under the terms of Engineering Heritage Australia's Heritage Recognition Program.

Location, including address and map grid reference:

- North Rankin A Platform, North West Shelf, Indian Ocean
  -19.5866 S, 116.1372 E
- Karratha Gas Plant, Burrup Road, Dampier WA 6713
  -20.6007 S, 116.7765 E
- Submarine pipeline is located between the above facilities.

Operator (name & address):

Woodside Energy Ltd
Woodside Plaza
240 St Georges Terrace
PERTH WA 6000

Karratha Town Office
3747 Balmoral Road
KARRATHA WA 6714

The operator has been advised of this nomination and their letter of agreement is attached.

Access to sites:

The North West Shelf Project is an operating facility and there is no public access to North Rankin A Platform or the Karratha Gas Plant. The Karratha Gas Plant can be viewed from the North West Shelf Project Visitors Centre, which is accessible from Burrup Road, Dampier, WA.

Nominating Body:

Engineering Heritage Western Australia, Engineers Australia, Western Australia Division.

Karen Riddette
Chair
Engineering Heritage Western Australia

OWNER'S LETTER OF AGREEMENT

woodside

Please direct all responses/queries to:
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Our reference: DRIMS#10459808

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29 September 2015

Attn: Mr Ian Maitland
Chair
Engineering Heritage WA
712 Murray Street
West Perth WA 6005

Dear Ian

North West Shelf Natural Gas Project – 1980 to 1989
Nomination for Engineering Heritage Recognition Award

Thank you for your letter of 16 June 2015 advising of the proposal by Engineering Heritage Western Australia to nominate the North West Shelf Natural Gas Project – 1980 to 1989 for an engineering heritage recognition award.

We are very pleased to support this initiative of Engineering Heritage WA and on behalf of the participants in the NWS Project, we give our permission for this nomination and for this letter to be included in Engineering Heritage Australia's recognition documentation.

If the nomination is successful, we would be happy to sponsor the design and manufacture of an interpretation panel and assist with the organisation of a dedication ceremony.

If you have any queries please contact Stephen Munday on 08 9348 3719 or stephen.munday@woodside.com.au

Yours sincerely

Niall Myles
Senior Vice President North West Shelf

HISTORICAL BACKGROUND

Ownership

The original North West Shelf Project joint venture participants comprised of Woodside, Shell Development Australia and Burmah Oil Company of Australia (Burmah). In the mid 1960s, the joint venture was expanded by the addition of local subsidiaries of Chevron Corporation and British Petroleum plc. In 1976, Burmah sold its equity in Woodside-Burmah Oil NL (a merger of Woodside and Burmah) , with its share in Woodside taken up by Shell and BHP. In 1984, the joint venture was expanded to include as a one sixth partner Japan Australia LNG (MIMI) Pty Ltd, a venture between Mitsubishi Corporation and Mitsui & Co. In 2001, BHP became BHP Billiton through its merger with Billiton plc. The China National Offshore Oil Corporation (CNOOC) is now also part of the NWS Project, but it does not have an interest in its production infrastructure.

North West Shelf Gas Pty Ltd (NWSGPL), an agency established by the NWS Project, is responsible for marketing pipeline gas to customers in WA and LNG to major industrial customers around the world. It comprises of all participants except CNOOC.

Woodside is the project operator on behalf of the other participants.

Early years

Woodside was established as an oil and gas exploration entity soon after Australia's first oil discovery, the 1953 Rough Range find near Exmouth in Western Australia. Woodside (Lakes Entrance) Oil Co NL was registered in 1954, adopting the name from the small town of Woodside in south-east Victoria, with plans to explore onshore for oil and gas on land adjacent to Ninety Mile Beach in Gippsland.

After nearly 10 years without significant success in south-eastern Australia, in June 1963, Woodside was awarded offshore exploration rights over multiple permits covering more than 367,000 km² off north-western Australia in what is known as the North West Shelf (NWS). These exploration permits covered a significant part of the offshore continental shelf from the Monte Bello Islands in the south to the Timor Sea offshore Darwin in the north. Water depths in the permit areas ranged from about 60 m to greater than 3,000 m.

Woodside agreed to form a joint venture to cover its interests in the licence areas, initially with Burmah Oil (as it then was, which acted as venture operator), and then-with the Royal Dutch Shell Group, each with a one third share of all costs and any eventual profits. Subsequently, multi-national oil and gas companies Chevron and BP also farmed into various permits held by the joint venture.

Significant gas and condensate discoveries were eventually made in 1971, initially at Scott Reef 425 km north of Broome, and then, in quick succession, at the North Rankin, Goodwyn and Angel prospects, located 130, 135 and 100 km north of Dampier in WA respectively. Gas from these three fields was found to be condensate-rich, considerably enhancing the value of the reserves. Further appraisal of the size of these southern fields in the following years identified potential commercial development opportunities and subsequently provided the reserves basis of the NWS Project, Australia's largest resource project of the 20th century.

Historical context

At the time of the initial gas discoveries in the early 1970s, the NWS was considered a very large frontier area, characterised by its remoteness and limited knowledge regarding its harsh environment. The Pilbara area adjacent to the NWS was undergoing development following the commencement of iron ore exports in the late 1960s, but supporting infrastructure, services and communications were still of a basic nature.

Baseline meteorological data, including wind-speed and air temperature, was limited, and no reliable tropical cyclone database was available from which to extrapolate a 100-year event design criteria. Additionally, only general assessments of critical oceanographic parameters such as wave heights and persistence, water current speeds, water temperatures, marine growth and the presence of major ocean currents was available. This information is crucial for offshore development and ongoing operations. Furthermore, quantitative information on the nature, stability, strength and seismic susceptibility of the seabed did not exist, unless these aspects had been specifically investigated as part of the oil and gas exploration and appraisal programmes.

The frontier aspects of the NWS environment, such as the relatively deep water, distance from shore, distance from markets and availability of supporting infrastructure, meant that only commercial production on a relatively large scale would justify development. During the early 1970s, the other near-shore frontier development areas of the Gulf of Mexico and the North Sea were maturing and planned to extrapolate existing production technology into water depths exceeding 100 m. Support services and industries rapidly developed at these frontier focus areas. By contrast, there was no offshore oil or gas production off Western Australia. Oil production was confined to the onshore Barrow Island oil and Dongara gas production. The focus of Australian offshore oil and gas development was in the Bass Strait, between Victoria and Tasmania, where developing fields were closer to shore and in relatively shallower water depths.

The North Rankin Field, the prime location for development with its large gas reserves, lies under 125 m of water on a seabed composed of very low strength calcium carbonate sediments. There were no onshore construction facilities with suitable capabilities and no offshore construction support vessels available in the southern hemisphere to assist in construction of the required offshore facilities; all such equipment would need to be mobilised at high cost from other global centres. These factors presented very significant challenges to the development of the required offshore production facilities and the associated shore-based processing plants.

HISTORICAL BACKGROUND *(cont.)*

The market for gas

In the early 1970s, the market for the sale of natural gas in Western Australia was limited, although there was potential for the future supply to both industrial and domestic consumers. To ensure a satisfactory economy of scale for development and return on investment, export of a large proportion of the gas, as liquefied natural gas (LNG), was considered essential. At that time, LNG was a fledgling industry promoted and developed in Alaska, Algeria, Brunei, Malaysia and the Middle East to monetise natural gas as a by-product of oil production. No projects existed that were primarily based on producing LNG.

From 1972 to 1975, as gas reserves offshore Dampier were being appraised and proven, the Commonwealth Government planned to acquire and pipe NWS gas to the Eastern States. This direct political intervention significantly slowed the pace of concept evolution and convergence for the NWS development. It was only in 1976, under a new Commonwealth Government, with support from the Western Australian Government that the constraints were lifted and the project owners were permitted to progress on a more predictable commercial basis.

During 1977, heads of agreement were reached with the Western Australian Government on the long-term sale of gas to the Western Australian market. A head of agreement was also entered into with the Commonwealth Government with respect to the taxation regime that would apply to the development of the NWS Project. A contract with the State Energy Commission of Western Australia for the supply of domestic gas to industries and homes was signed in September 1980, effectively committing the State Government to constructing the pipeline from Dampier to Perth and beyond, and gas deliveries began in August 1984.

The initial Domgas Supply Agreement was for 10.9 million m^3 per day of gas to be supplied domestically under contract for 25 years. There was still much debate about the state market's ability to absorb all the available domestic gas, but its use was strongly promoted. Approximately half of the domestic gas volumes were contracted to Alcoa's three alumina plants in southern West Australia. The remaining volumes were distributed primarily to Perth area homes and industry. Domestic gas demand only amounted to a quarter of what the shelf was designed to produce later in the 1980s, when the LNG export phase was planned to be brought online in addition to the domestic gas supply.

Development of the LNG phase was deferred for five years due to market uncertainties. However, as plants were required to be in close proximity for both domestic gas and LNG production, substantial site works were performed in preparation for the LNG plant during the construction of the domestic gas facilities. Following completion of sales arrangements, sanctioning by regulatory bodies and the joint venture partners in 1985, engineering and construction work proceeded on the LNG plant. LNG was first shipped in 1989 to the joint venture's foundation customer in Japan.

Project financing

A key enabler for the initial domestic gas phase were the arrangements orchestrated by Woodside to finance its share of the project. Woodside raised US$1.4 billion across 63 banks –then the largest non-recourse financing package ever negotiated. Woodside subsequently reduced its share in the NWS project to one sixth in order to finance the planned LNG phase.

Figure 3: Burrup Peninsula prior to project activity

CHALLENGES AND ACHIEVEMENTS

General

The Pilbara in the 1970s

Initial iron ore developments had commenced onshore in the remote Pilbara area in the mid to late 1960s and subsequently, large-scale exports began in 1969. However, there was very little established infrastructure except to support iron ore mining and the solar salt works that were constructed at various points along the Pilbara coast in the early 1970s. The scale of the planned industrial development of the Pilbara area did not support a significant onshore gas market. Even with the addition of potential industrial and domestic consumers in the south-west of the state, the overall gas market in Western Australia was relatively small.

Landfall for gas from North Rankin was chosen to be located at Withnell Bay, on the remote, rocky and undeveloped Burrup Peninsula near the iron-ore port of Dampier. Summer temperatures in this dry and dusty region reach 40-50°C, while winters are mild, with sporadic rainfall. The area is regularly subject to tropical cyclones, usually in the months from November to April.

Woodside chose to base its personnel in the new township of Karratha, located 10 km east of Dampier. At the time, the town of Karratha was small and undeveloped, with minimal facilities able to support a major project.

Knowledge of the environment in the North West

When Woodside commenced exploration activities on the NWS, there was no substantive knowledge or data describing the oceanography, meteorology (operational weather and storm events), seismicity and geotechnical conditions of the area. Imprecise assessment of the prevailing metocean conditions was based on historical shipping almanacs and records related to permit exploration activities. However, the safe establishment of significant oil and gas production assets on the NWS would require quantitative information and the derivation of extreme storm loading design criteria. The details of how this data and associated design criteria were established are set out in Appendix 3.

Gas production and reliability

The delivery system for LNG production, storage, export, shipping and delivery is extremely capital intensive, requiring large volume exports of LNG on a take-or-pay basis accompanied by very high reliability during each stage of the delivery process, ensuring timely delivery to customers. Likewise, the NWS Project was essentially the sole supplier to multiple customers up to 1,500 km away in the south-west of the state, and this also required high levels of reliability. Accordingly, through its ownership arrangements, Woodside as operator was significantly supported by Shell International with management and technical personnel for the LNG plant development and its marketing and shipping arrangements.

Technical and management skills

In the late 1970s, technical and management expertise in offshore and onshore oil and gas facilities was limited in Australia and south-east Asia. Planning and engineering work for the Bass Strait development had essentially been imported from the Gulf coast of the United States and only limited local resources were orientated towards the ongoing offshore developments. As a condition of development, Woodside was required to maximise the local content of the engineering, material supply, construction and commissioning of facilities for both offshore and onshore components of the project. As a result, Woodside established a project team with the requisite technical capability by gathering an experienced group of expatriate engineers and managers who were integrated with selected Shell and BHP resources and expert consultants, both local and international.

Designers and engineers had to be familiar with Australian codes, standards and practices when working on all facets of the project during preliminary design. Both Woodside and its contractors sought to recruit multi-discipline oil and gas industry personnel locally and interstate, to fill the many positions needed during the detailed engineering phase. Whilst being a formidable challenge, Woodside initiated an innovative 'Aussie Come Home' campaign focused primarily on Australian engineers who had moved overseas to work on international projects, particularly in the North Sea. This campaign ultimately raised the profile of the NWS Project and assisted in finding experienced personnel for engineering, construction planning and supervisory roles.

Safety

In the late 1970s, statistical data on incident frequency and severity in Australian mining and construction industries indicated that Australian safety performance had to improve drastically to meet the standards demanded by Woodside and the NWS Project joint venture. This was achieved prior to contracting any services for Phase 1 activities in 1979 by actively involving safety management in the process of pre-qualification of bidders, ensuring that safety was a significant component of the tender evaluation process, assigning necessary resources to improve safety education and ensuring that contractors continuously improved safety performance throughout the duration of their contracts.

In 1991, Woodside had achieved a remarkable safety record for the NWS Project, a record that saw the company receive the Australian Petroleum Production Exploration Association Annual Safety Award. Additionally, Woodside's primary LNG contractor was the recipient of a four star rating by the International Safety Rating System for its safety performance on the Burrup Peninsula construction site. This rating had never previously been achieved on a construction site in Australia.

Safety is now highly regulated and integral across the resources industry and wider community in Australia. The NWS Project was an exemplary development which demonstrated a step change in safety performance could be achieved.

CHALLENGES AND ACHIEVEMENTS *(cont.)*

Quality

The NWS Project facilities required a high level of quality and integrity in fabrication to ensure the reliability of both the offshore and onshore facilities. As the primary supplier of energy to Western Australian industry, power stations and domestic gas consumers, long-term gas supply contract obligations also drove the need to develop a reputation as a reliable supplier of energy in remote and environmentally demanding locations.

From the very outset, the NWS Project was tasked with the challenge of significantly elevating the quality expectations and performance of a wide range of suppliers and fabricators. The project needed to instil a step change from the status quo which was primarily an inspection regime. To achieve this, a comprehensive suite of quality systems and procedures was established for use on all project phases from initial procurement of materials, fabrication, installation and mechanical testing to manage, demonstrate and deliver integrity. These procedures were designed to ensure that the quality and performance standards specified in design were achieved with supporting documentation, to validate and verify the integrity demanded on all elements of the project.

The quality requirements surpassed previous standards adopted in Western Australia and Australia. Initially, Woodside's suppliers and contractors resisted demands for compliance with the project's quality systems. However, ultimately, they did meet the required standard of inspections and documentation, as practical completion of their contracts depended on compliance with the project's quality systems.

Woodside contracted independent specialist organisations to ensure the specifications, regulatory and insurance requirements were being met. Their role was to witness, review, audit and report their findings progressively to independently certify that facilities met the requirements of the project's design specifications.

Woodside overcame many challenges in cultivating industry performance and instigating cultural change to embrace its requirements in order to achieve the NWS Project safety and quality objectives. Learning how to meet the high quality standards set by the project effectively prepared the Australian fabrication industry to meet the needs of subsequent Australian oil and gas projects, including later phases of the NWS Project.

Continuity of supply

A major risk to the overall reliability of the NWS Project's supply of both domestic gas and LNG was its vulnerability to industrial action. Following serious industrial action offshore in 1986, Woodside negotiated competitive new employment conditions for its operations' personnel. In parallel, it also negotiated a continuity of operations agreement with the maritime unions covering their involvement in not only the offshore production operations but also the export of LNG in Australian flag vessels. These agreements have endured and continue to support the NWS Project's reputation as a reliable supplier.

NRA Platform

Planning

When assessing development options for the southern gas discoveries during the early-mid 1970s, Woodside focused on the optimum configuration of the offshore production facilities to be centred on the North Rankin Field that contained a significant proportion of the discovered gas. The water depth over North Rankin, at 125 m, was comparable with the deepest water developments of Gulf of Mexico and North Sea at the time.

The offshore configuration would require facilities to drill producing wells, condition the produced gas and condensate for pipeline export and provide living quarters for those personnel engaged in these activities. These facilities would be more than three times the size of comparable offshore developments in the Bass Strait. Moreover, the high reliability required to sustain LNG and domestic gas supply chains dictated that the facilities had the capacity to be manned during tropical cyclones to ensure earliest possible start-up and maintenance of continuity of supply following any disruption caused by these events.

Woodside faced significant challenges in determining the:

- extreme condition design criteria that would permit continued serviceability of facilities during the anticipated duration of operations;
- foundation support mechanism on the soft seabed sediments;
- type of platform required for the production facilities at North Rankin, including assessment of where the components might be constructed;
- design basis of the production facilities to safely condition and transport the gas and condensate to shore;
- structural design contingencies that would be prudent to incorporate in a frontier development area; and
- optimal project management of this multi-faceted engineering process, where elements would be determined at centres of excellence around the world.

These aspects are detailed more fully in Appendix 4.

Design

At 125 m, the water depth over the North Rankin Field dictated that a tubular space-frame tower or jacket substructure anchored to the seabed by foundation piles at its corners should support the production well and treatment facilities. This configuration differed markedly from the shallower water Bass Strait platform structures that were duplicates of the conventional Gulf of Mexico 'jackets' or templates, where topsides production facilities are supported directly by foundation piles installed through the template legs and extended above water level. The gross weight of topsides facilities for NRA of 16,000 tonnes was in the order of three times that of the largest Bass Strait platform.

CHALLENGES AND ACHIEVEMENTS *(cont.)*

Accordingly, the basic platform substructure required to safely support the topsides facilities would be approximately 15,000 tonnes. However, when the structural capability was increased to cater for additional loading resulting from its sea transport and its installation at site, this substructure weight increased to approximately 21,500 tonnes. This size of the structure was considered well beyond the capabilities of Australian fabricators who, at that stage, had only constructed the much smaller Bass Strait platforms. The substructure or jacket would need to be constructed in East Asia and transported to site by barge.

It was determined that other components of the NRA platform could and should be fabricated in Australia. The following aspects are considered in further detail in Appendix 4.2:

- flare support structure and associated flare bridge construction;
- topsides production modules and packages fabrication;
- transportation of all platform components to the NRA location;
- installation and completion of the platform at site;
- special issues with production conductor installation; and
- foundation remedial works programme.

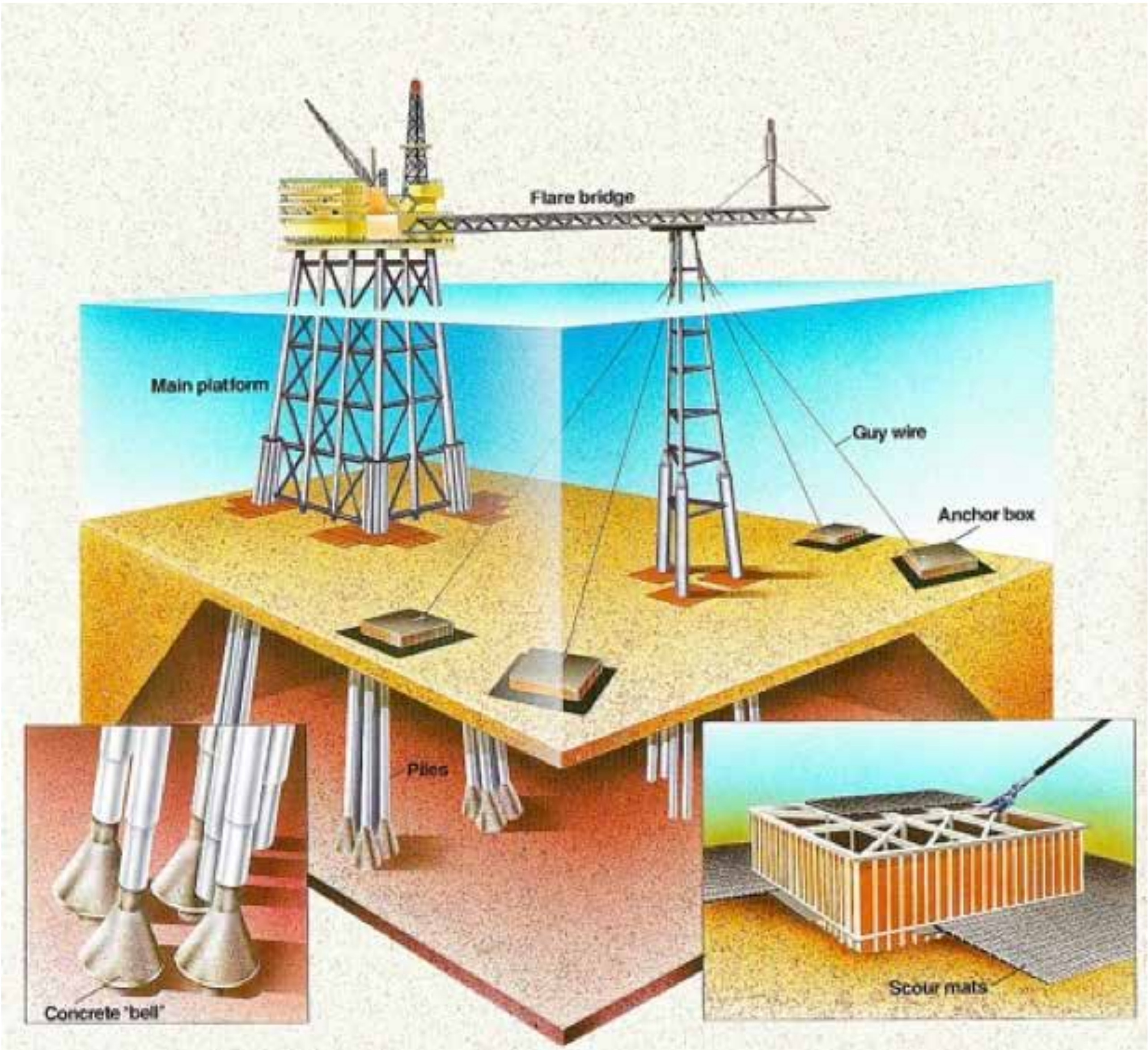

Figure 4: NRA Platform - foundation remedial programme

CHALLENGES AND ACHIEVEMENTS *(cont.)*

Two-phase pipeline from NRA to shore

Two-phase flow system

Significant volumes of condensate were recovered during testing of the original North Rankin gas discovery and appraisal wells. Since NRA was not intended to store and export stabilised condensate offshore, associated liquids had to be piped to the onshore treatment facilities. As the cost of parallel pipelines would greatly outweigh the cost of a single "two-phase" pipeline (gas and liquid phases flowing together), there was a strong incentive to prove the viability of the two-phase option. After much evaluation, the project proceeded on that basis.

When the subsea pipeline system from NRA to Withnell Bay came into operation, it was the largest two-phase flow system operating globally, on the basis of both pipeline diameter (1.02 m or 40 inch) and also the ratio of liquid to gas mass flows. The parameters were a significant step-out from the then-current global practice. With a volume of 5,560 m^3, the slug-catcher at Withnell Bay was, at the time, the largest ever built. The fluid mechanics design of the pipeline system represented a significant engineering achievement.

Pipeline stabilisation

The North Rankin to shore subsea pipeline was stabilised over much of its length by an innovative technique known as 'ploughing', which had been used at that time in the North Sea for stabilising smaller diameter lines. In principle, a plough-like device is towed along the pipeline using the line itself as a guide, creating a V-shaped trench beneath it, into which the pipeline then settles. The NWS Project plough was the largest such device ever deployed for subsea pipeline stabilisation.

Appendix 4 discusses two-phase flow and the pipeline stabilisation process in greater detail.

Figure 5: The 380 tonne subsea plough underwent a series of land tests at Jervoise Bay, south of Perth

Site preparation and the domestic gas facilities - Phase 1

Site preparation for the onshore plant started in 1980 and was completed in November 1982, transforming about 250 ha of the rugged Burrup Peninsula. The plant is located on a relatively level site at approximately +20 m elevation, but some siteworks were located in very rough terrain with extremely hard rock.

Two process trains for the domestic gas phase of the project were constructed and commissioned from 1983-84. The domestic gas facilities involve gas dehydration using molecular sieve beds, followed by condensate removal. Condensate removal is achieved by cooling of natural gas to approximately minus 60°C through a turbo-expander unit.

Domestic gas flows south from Withnell Bay through Australia's longest pipeline - 1,530 km - to Perth and the southwest of the State. This onshore pipeline, built by the State Energy Commission of Western Australia (SECWA), as it then was, was completed in late January 1984 in readiness for commissioning. The Domestic gas facilities were completed and brought online with first gas delivered to SECWA in August 1984.

More detail on site preparation works and the domestic gas facilities are included in Appendix 4.

LNG Plant – Phase 2

With the signing of the sales and purchase agreements for 6 Mtpa of LNG with Japanese buyers, the LNG project commenced with a final investment decision in July 1985. This commitment covered only the first two LNG production trains.

The refrigerant cycles consist of compression, cooling and pressure reduction to deliver the required cooling effect. Although gas turbines had been used on the Kenai LNG plant in Alaska, normal practice then was to use steam turbine-driven compressors. The NWS Project chose to use Frame 5 industrial gas turbines to drive the compressors. This decision significantly reduced capital costs and operating complexity.

Eliminating the steam system also meant that the flare needed to differ from conventional designs, because up until that point, steam had been used for flare smoke suppression. As steam was no longer available, a sophisticated 4-stage multi-burner system was installed in the elevated flare.

The liquefaction process requires the removal of heat to enable cooling and compression. LNG plants built prior to this time had used seawater cooling for heat rejection. The sensitivity of the environment in Mermaid Sound adjacent to the plant was such that seawater cooling was rejected in favour of air-cooling. The NWS Project was a pioneer in the optimisation of LNG production from an air-cooled plant.

See Appendix 4 for more detail on this subject.

Product storage

Phase 1 (domestic gas) required condensate storage in the form of conventional single barrier steel tanks with bunded areas for secondary containment. Phase 1 also included extensive siteworks for the future LNG storage tanks.

No LNG storage facilities existed in Australia at the time of the initial NWS Project. Engineering of LNG storage tanks was evolving and the project's tank design was based on Shell standards.

Once processed, LNG is maintained as a liquid at minus 161°C, much colder than other liquefied petroleum products. Primary containment of the LNG at such low temperatures requires a high nickel, non-brittle steel that is difficult to both fabricate and weld. This membrane containment is thermally insulated by pearlite and supported by concrete walls, reinforced by high nickel steel providing secondary containment. An earthen or rock embankment surrounds the concrete wall to protect against any external dynamic forces or impacts.

CHALLENGES AND ACHIEVEMENTS *(cont.)*

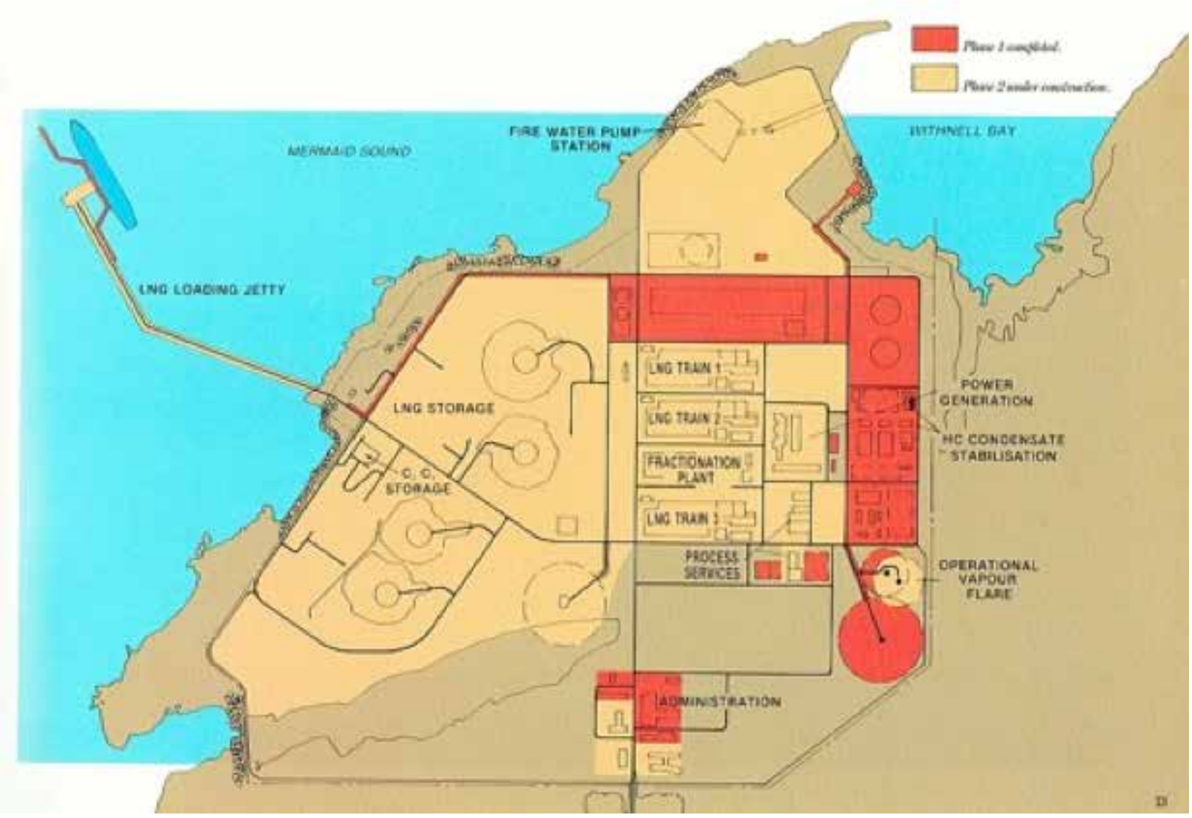

Figure 6: Phase 1 works and planned Phase 2 layout

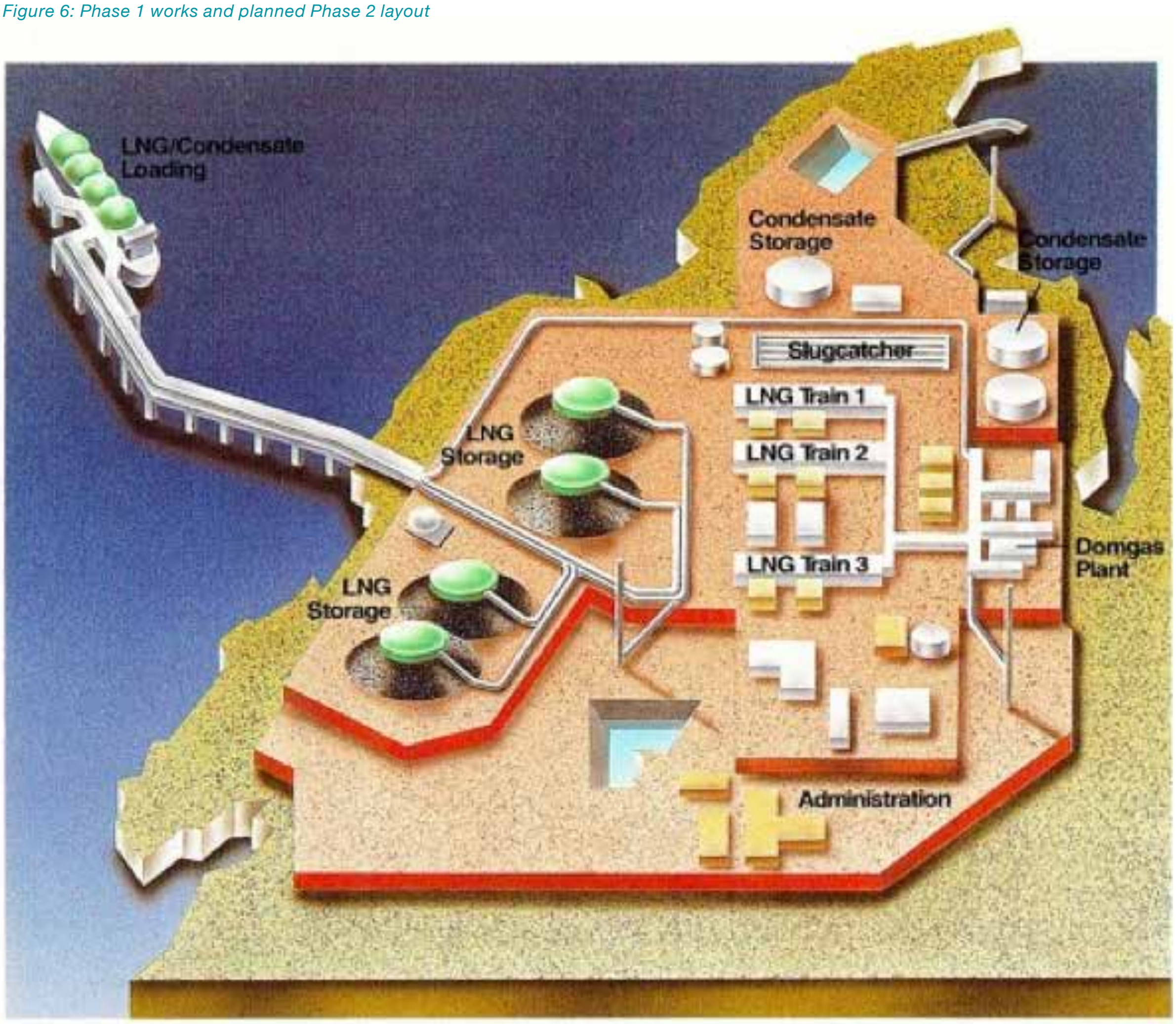

Figure 7: Phases 1 and 2 schematic layout

CHALLENGES AND ACHIEVEMENTS *(cont.)*

Export facilities

During Phase 1 operations from 1984, condensate was exported using a remote set of berthing and mooring dolphins with a small loading platform connected to onshore storage tanks by underwater pipelines. This configuration allowed for later construction of the LNG jetty connecting the loading platform to shore and installation of the LNG loading lines.

The design basis for the LNG jetty was to load a vessel in less than one day while accommodating the 5.5 m tidal range in Mermaid Sound. To load the specified LNG carriers and the large size range of condensate tankers then in use, the loading arms for both LNG and condensate transfers had to be the largest built to date. LNG loading rates of 10,000 m^3 per hour were required and ultimately was achieved.

An access channel and turning basin had to be constructed to allow the specified LNG carriers to berth. The world's largest cutter-suction dredger was employed for this task, but it had difficulty removing very hard outcrops of rock underwater. To clear these obstacles, Woodside used world-leading very close pattern blasting and removal techniques.

LNG loading activities during the cyclone season were, and still are, controlled using the Remote Offshore Warning System (ROWS), developed as part of the NWS Project to predict cyclone-generated wave heights in Mermaid Sound. It also calculates when a LNG carrier must leave the berth to gain the required sea room before a cyclone arrives. The system consists of four deep ocean directional wave measurement buoys located 120 to 280 km north and north-east of the port to provide the wave spectral energy expected at the port, up to 4 hours ahead of time. Essentially, the ROWS buoys form a 'tuned' deep ocean wave detector.

When first commissioned, the NWS Project's ROWS was one of the first systems in the world to use the Inmarsat-C data transmission system. It was the first 'tuned' ocean wave array and in operation it has a proven record of providing wave forecasts some 10 times more accurately than is achievable with conventional methods.

More detail on this topic is provided in Appendix 4.

Figure 8: Aerial view of Karratha Gas Plant

KEY PERSONNEL ASSOCIATED WITH THE PROJECT

As can be expected on a project of this scale, there were many people associated with the social, economic and political issues that needed to be addressed between first discovery in 1971 and first shipment of LNG to Japan in 1989. Some of the people who were key to successful development were:

- Geoff Donaldson, Chairman Woodside (1956 – 1984)
- Charles Allen, Woodside Chief Executive and Managing Director (1980 – 1996)
- Peter Tapper, Woodside Executive General Manager (1982 – 1990)
- Sir Charles Court, Premier Western Australia (1974 – 1982)
- Peter Jones, Minister for Resources Development (1980 – 1983)
- Bruce Kirkwood, Chairman State Energy Commission of Western Australia

However, this document is focused on the engineering associated with development and management of the NWS Project during its design and construction. Of the many people who were involved, some of the key engineering personnel were:

Ian Henderson: Development Manager (1977 – 1984); secondee from Shell. Responsible for the engineering development of the hydrocarbon reserves, their extraction and the offshore facilities to bring the gas and condensate to shore.

Arnold Ploum: Manager (1978 – 1983) , Onshore Plants for both domestic gas facilities and LNG; secondee from Shell. Responsible for the engineering development, construction and commissioning of the Withnell Bay onshore domestic gas plant including offplot works, storage, export facilities and pre-investment for the LNG project.

Mike Lodge, AM: Offshore Engineering and Construction Manager (1974 – 1989); Woodside employee. Responsible for the engineering development, construction and commissioning of the offshore production facilities including the NRA platform and the two-phase trunkline to shore.

Frans Mittertreiner: Manager LNG Project (1984 – 1989); secondee from Shell. Responsible for the engineering development, construction and commissioning of LNG trains 1 and 2, LNG storage tanks and export facilities.

Wim Kemper: Engineering and Construction Chief Engineer Onshore (1980 – 1989), seconded from Shell for domestic gas and LNG Trains 1 and 2. Responsible for off-plot civil/structural works, storage and export facilities.

Dr Errol Seymour: Pipeline Engineering Manager (1973 – 1996); Woodside employee. Responsible for engineering design and construction of the subsea pipeline, slug-catcher and subsea plough. Subsequently LNG detailed design coordinator in Yokohama.

Stan Stroud: Project engineer (1968 – 2015); Woodside employee and contractor. Responsible for initial development concept, recognised the North Rankin seabed sediments not conforming to conventional soil mechanics behaviour, and instigation and development of all metocean design bases.

Bob King, OAM: Project engineer (1972 – 1995); Woodside employee. Responsible for initial offshore surveys / investigations and NRA foundation design and subsequently platform installation. Subsequently, Project Manager of Goodwyn A Project.

Ed Ryan: Project Engineer (1976 – 1993); Woodside employee. Responsible for NRA Platform facilities design (1976 – 1981); Australian engineering input to LNG Trains 1 and 2 (1984 – 1986); GWA Topsides design, procurement and fabrication as Topsides Manager (1987 – 1992).

Figure 9: NRA Platform

INTERPRETATION PLAN

It is proposed to install a 1200 mm x 600 mm interpretation panel mounted together with the engineering heritage marker disc outside the entrance to the North West Shelf Project Visitors Centre, Burrup Road, Dampier. The Engineering Heritage Australia document titled ‘Guide to Engineering Heritage Recognition Program’ describes the recommended design and manufacture of the interpretation panel and steel frame.

This nomination document will be updated when award details and interpretation panel have been finalised. Electronic copies of this document will then be made available on the Engineers Australia Heritage Recognition Program website and added to the Western Australian engineering heritage collection maintained by the State Library of Western Australia.

ACKNOWLEDGEMENTS

Nomination Document

Engineers Australia wishes to thank the following people who have contributed both their personal time and invaluable knowledge gained from working on the NWS Project to prepare this nomination document:

- Mr Brian Haggerty;
- Mr Bob King;
- Dr Peter Hopwood;
- Mr Rob Male;
- Mr Ed Ryan; and
- Mr Stan Stroud.

Engineers Australia would also like to thank Mr David Agostini, Mr Peter Ellery and Professor Mark Bush who provided an independent review and feedback on the draft document.

Photographs and Diagrams

Engineers Australia thanks Woodside Energy Ltd for providing all of the photographs and diagrams that are included in this document.

Nomination Proposal and Compiler

Proposal and management of this nomination was by Mr Mike Taylor, member of the Engineering Heritage Western Australia Committee.

APPENDIX 1 – NWS Project Phases 1 And 2 – Details

Offshore facilities

Commissioned in 1984, the North Rankin A platform (NRA) was the then largest gas production platform in the world, with a nameplate capacity for production and treatment of reservoir gas at the rate of 34.3 Mm^3 per day. Following commissioning, capacity was progressively increased by 50% through debottlenecking modifications to 51.4 Mm^3 of gas and 5,000 tonnes of condensate per day. This production capacity was used after start-up and before LNG production through enhanced condensate recovery following the commissioning of a gas–recycling package. In this package, condensate was stripped from the well stream and injected into the pipeline to shore whilst excess dry gas was re-injected into the reservoir for later production.

Even today, the NRA Complex is one of the largest offshore producers of hydrocarbons in the world with an aggregate production capacity of 66,000 tonnes of dry gas and 6,000 tonnes of condensate per day.

NRA is located 135 km northwest of Karratha in 125m of water and could accommodate up to 320 personnel when drilling and production operations commenced. It has drilling facilities, 33 available well conductors and services 25 production wells into the North Rankin and adjacent Perseus fields.

NRA to Withnell Bay pipeline

Produced gas and condensate is transported from NRA to shore at South Withnell Bay via a 1.02 metre diameter 130 kilometre long subsea pipeline operating in transient two phase flow. A liquids receiving terminal or slug-catcher of 5,560 m^3 capacity is located at the end of the pipeline to arrest produced liquids prior to introduction of gas to the onshore plants.

Domestic gas facilities at Karratha Gas Plant

The domestic gas facilities at Karratha Gas Plant, together with the associated condensate storage, metering and shipping facilities, were constructed and commissioned to coincide with the contracted delivery of sales gas to the Western Australian market in August 1984. This two production train facility has 100% redundancy and produces pipeline specification gas for the domestic market, together with stabilised condensate for the export market. It is located at South Withnell Bay on the Burrup Peninsula, north of Dampier. The plant layout allowed for the adjacent safe construction of a three-train LNG plant together with associated storage and export facilities without impacting operations.

LNG production facilities

Following successful negotiation of LNG sales contracts in 1985, the NWS Project committed to construct and commission two LNG production trains for first export deliveries in 1989. Each train was planned to produce LNG at the rate of 2.2 Mt per year and provision was made for construction and tie-in of a further similarly sized third LNG train. Following start-up and minor equipment modifications, the output of each train was increased to 2.5 Mt per year.

LNG storage and export facilities

Tankage and loading facilities were constructed for the storage and export of LNG product from all three trains. Four insulated storage tanks of 65,000 m^3 were constructed to store LNG at -161°C.

LNG carriers

To export the LNG product to Japan, the NWS Project initially established a fleet of six LNG carriers specifically designed for the long sea voyages to East Asia. The LNG ships are powered using ‘boil-off’ gas vapour emanating from the LNG cargo tanks to fuel steam turbines. Each of the ships is equipped with four spherical tanks giving each a total nominal capacity of 125,000 m^3. The LNG ships were both purchased and leased.

In Mermaid Sound, a dedicated fleet of purpose built tugs, owned and operated by the NWS Project, supports both the LNG and condensate export vessels.

APPENDIX 2 – Subsequent Expansions of the NWS Project

On completion of the Phase 1 – domestic gas in 1984 and Phase 2 – LNG Trains 1 and 2 in 1989, the completed facilities and supporting infrastructure of the NWS Project proved to be a reliable, flexible and robust basis for future expansion.

New oil and gas fields were discovered, appraised and considered ready for progressive sequential development, given the market outlook and system capacity, combined with the reliable delivery reputation that the NWS Project had achieved.

The expansion plans and development sequence embodied in the 1979 development concept which were then completed in 1989 were effectively superseded by new and changed opportunities. In addition, well productivity and platform and plant delivery capacity had been enhanced during the gas re-injection and condensate acceleration programme, enabling more ambitious plans to be developed.

These plans in the NWS Project permit areas were developed to enable additional offshore facilities, pipelines and onshore LPG and LNG trains to be sequentially developed and integrated into the original project scope with minimal disruption to production.

Offshore production facilities

At a cost of $2 billion, the Goodwyn (GWA) drilling, production and accommodation platform was, when commissioned in early 1995, the largest single offshore oil and gas investment ever made in Australia. Initial production of up to 68.6 Mm³ of gas and 8,400 tonnes per day of condensate is exported initially through a 20 km pipeline to NRA platform, then to shore. GWA is designed for up to 30 production wells, including five re-injection wells, and accommodates up to 137 personnel. In late 2001, GWA was linked to the Echo Yodel gas and condensate fields by a 23 km subsea pipeline.

In 2004, the throughput and performance of the NRA – Withnell Bay subsea trunkline system was supplemented by a parallel 1.07 m pipeline. At the time of its installation, modifications were also made to the subsea pipeline configuration and controls to permit uninterrupted supply when the Angel facilities were brought on stream at a later date.

In 2009, the gas and condensate reserves of the Angel field were incorporated into the NWS Project through the commissioning of the Angel platform. With a focus on operability, reliability and maintainability, the Angel development was designed and built to operate as ‘not normally manned’. When completed, the Angel facility was the largest gas separation and dehydration platform in Australia being operated on this basis. It is located 40 km east of NRA and is powered and operated remotely from NRA. Produced gas and condensate is exported via a subsea pipeline to NRA where it is comingled with other production streams before being flowed to shore.

Development of the standalone Wanaea–Cossack oilfields was achieved when the Cossack Pioneer Floating Production Storage and Offloading vessel (FPSO) was commissioned in 1995 and produced up to 6,000 tonnes per day of crude oil stored onboard. The oil is periodically offloaded via a flexible line to oil tankers moored astern. Located 34 km north east of NRA, the Cossack Pioneer was moored to a riser turret connected by flexible flowlines to subsea production wells at the Wanaea–Cossack fields and later to the Lambert–Hermes fields. In 2011, the Okha FPSO replaced Cossack Pioneer. A dense-phase, high LPG content gas line connects the Okha FPSO to NRA for commingling and export to the Withnell Bay plant.

In March 2008, the NWS Project approved the $5 billion North Rankin Redevelopment project to underpin supply commitments to customers in East Asia beyond 2013. The major component of this project was the installation of the North Rankin B (NRB) compression platform adjacent to NRA platform, with two 100 m connecting bridges and upgraded living quarters for the North Rankin complex. The NRB platform takes low-pressure gas from the depleting North Rankin, Perseus and Goodwyn gas fields and compresses the gas and condensate for delivery into the two submarine pipelines to shore.

Onshore treatment plants

Commitment to a third LNG production train was made in 1988 and this train was subsequently brought on stream in 1993.

In 2004, a fourth LNG train with a capacity of 4.4 Mt per year was added and finally, in 2008, the LNG plant production capability was increased to 16.3 Mt per year with the commissioning of a fifth, 4.4 Mt per year LNG production train. Both these later trains required separate plot areas and increased export wharf facilities. Later improvements allowed production to reach 16.9 Mtpa.

Production of gas from the LPG-rich Goodwyn, Echo - Yodel and Lambert - Hermes fields required the onshore construction and commissioning of a liquefied petroleum gas (LPG) facility adjacent to the LNG Plant at South Withnell Bay. These production and storage facilities were completed in 1996 to enable export of LPG to the international market.

The first LNG shipments were shipped to Japan in 1989. Over 200 shipments, totalling more than 16 million tonnes, are now made annually in purpose-built LNG carriers. Markets include sales to long-term customers in Japan and spot buyers in China, Spain, South Korea and the United States. To date, the NWS Project has also produced more than 1,000 cargoes of condensate. Condensate is sold on the international energy market.

The NWS Project is still WA’s largest single producer of domestic gas, providing about 45% of total state production. Pipeline gas is processed at the Withnell Bay plant, and transported via the 1,530 km Dampier-to-Bunbury Natural Gas Pipeline to customers in southern Western Australia (including large industrial customers) and to AlintaGas, which distributes gas to domestic customers in south-west Western Australia.

APPENDIX 3 – Development of Metocean Design Criteria

Background

In the early to mid-1970s the metocean (winds, waves, currents, tides) conditions and parameters for project planning and design were unknown. No definitive studies had been undertaken for tropical cyclone (TC) extreme design conditions off North West (NW) Australia. Advice from Woodside's technical adviser was that a TC study was necessary, supported by extensive oceanographic measurements for TC model calibration. In addition, the operational metocean conditions including reported high non-cyclonic currents near North Rankin (NR), and the effects of tsunamis and earthquakes required detailed investigation. This advice was based on experience in both the Gulf of Mexico and the North Sea where initial assessments of storm conditions had been underestimated as evidenced by criteria re-evaluation following the devastating effects of hurricane Camille in the Gulf of Mexico in 1969.

At that time, there was no guidance providing TC design wave height off NW Australia, and deficiencies were recognised with the then Australian Wind Loading Code in the Australian tropics following the destruction of Darwin by TC Tracy in December 1974. Further, seismic loadings for the NRA platform and trunkline needed to be re-evaluated following the unexpected motions and loadings experienced in Perth during the 1968 Meckering earthquake.

As a result of these deficiencies, Woodside undertook a series of comprehensive studies and investigations, many innovative, to provide tropical cyclone calibration data, and define the extreme design and operational ambient conditions.

Tropical cyclone storm tracks

For storm modelling, TC storm tracks were required with intensity estimates. In the 1970s, examination of the Australian Bureau of Meteorology historical TC storm track database showed the useful portion to be the post-satellite period 1960 to 1977. Prior to this, many storms were missed as they did not cross the coast and were not reported by shipping, and storm intensity values were absent as satellite methods to estimate these were not in general use until the 1970s. For the storms assessed, the track locations were checked, and their central pressures were critically reviewed and adjusted accordingly. The resulting storm track database formed a solid basis for TC wind, wave and current modelling, although the duration of only nineteen TC seasons was recognised as marginal for determination of 'return period' estimates.

Tropical cyclone scale study

In modelling TC wave-fields, storm 'scales' are required as these determine the fetch lengths over which waves are generated within the storm. However, in the 1970's, no information was available on storm scales off NW Australia. In contrast, in the Gulf of Mexico and the Atlantic Ocean, the National Oceanic and Atmospheric Administration (NOAA) was operating the Storm Fury programme of flying aircrafts into and through hurricanes. Out of necessity, Woodside undertook a study that investigated storm scales off NW Australia using all TC wind and air pressure measurements available from the Bureau of Meteorology coastal stations between Carnarvon and Darwin and at Willis Island in the Indian Ocean. The study resulted in a storm intensity and scale relationship as a function of latitude for intense storms in the NW Australian tropics. This scaling study was unique at the time and was a key factor in providing confidence in the modelled wave heights for the historical storm tracks.

North Rankin and trunkline extreme design criteria

The newly determined storm scale relationship and the Woodside revised TC database were used to model the winds, waves, currents and storm surges at the North Rankin location and along the trunkline route for determination of the 100 year return period conditions. These design parameters were subsequently used in preliminary and final designs of the project facilities. This work included TC model calibration against measured data.

Mermaid Sound extreme design criteria

Similar modelling studies and measurements were conducted to provide the design conditions in Mermaid Sound for the product export and associated jetties. Importantly, these studies included forecasts of storm surge in addition to local waves and currents, but accepted the then revised Australian Wind Loading Code for design wind speeds. The studies used a TC simulation process that was later adopted widely in industry.

Oceanographic measurement

Woodside embarked on a comprehensive and sophisticated wind, wave, ocean current and tide data collection programme in 1977 and 1978 at the North Rankin location, along the pipeline route and at the port site in Mermaid Sound. This included measuring currents at various levels in the water column to define the ambient conditions for construction and fatigue applications and to collect data through TCs for calibration of the storm models.

One of the aims of the field measurements was to investigate strong currents in the water column at North Rankin and near the seabed slightly inshore, as reported by drilling vessels in the period 1968 to 1972. This work necessitated the use of prototype, high-frequency current meters to define the currents that had short durations (1 to 10 minutes), with measured current speeds to up to 2 m/s (4 knots). In the late 1970s, these currents were identified as resulting from ocean 'internal waves'. It was known that these 'waves' form from depression of the horizontal seawater density interface, between the warm, less dense tropical surface layer and the underlying cooler waters. As tidal sea levels rise and fall, resulting in tidal currents, the deformation of the density interface causes additional currents, both above and below the interface. The occurrence and driving forces for these currents has been the focus of research over the past 25 years.

APPENDIX 3 – Development of Metocean Design Criteria *(cont.)*

Figure 10: NRA Platform jacket being lowered

Rate of storm current downward penetration

A new and innovative process of three-dimensional storm current modelling was used in 1979 for determining potentially critical TC storm currents acting on the trunkline. An important factor in this type of modelling is the rate that the surface TC storm current mixes the water column down to the seabed, which at the time was derived theoretically, however, no measured data was available to confirm this mixing rate. The mixing and the thermocline re-establishment rates were investigated by field measurements in 1979 using expendable bathy-thermographs deployed from a helicopter across the shelf and out to the North Rankin location, immediately prior to TC Hazel, then three days and three weeks after the passage of that storm. Such a measurement sequence was unique at that time, providing evidence supporting the theoretical work and vital input for the pipeline stability design.

Major ocean current investigation

In the early to mid-1970s, the presence or absence of major ocean currents at the NR location was unknown. Major ocean currents cause significant loadings, structural fatigue, and operational problems to offshore platforms and construction equipment. In the early 1970s, no oceanographic information was available off NW Australia to define the presence or absence of strong ocean currents within the development area.

Ocean currents present a temperature differential to the surrounding ocean, and can be investigated by mapping the ocean sea-surface temperature. Consequently, ship-reported surface temperatures for the Indian and Southern Oceans were obtained from NOAA for the 1950 to 1970 period, as satellite data was not available at that time. Analysis of this data revealed the seasonal sea water temperature range at North Rankin including inter-annual variability and the presence of a strong major ocean current (later called the Leeuwin Current), originating near North West Cape and flowing southward past Perth into the Great Australian Bight. Importantly, this current was not present at either North Rankin (to the north-east of the North West Cape) or the trunkline route offshore from Dampier. The results of this study were subsequently provided to the CSIRO.

Structural and environmental monitoring system

As a central strategy to continue to measure and better understand the impact of the offshore marine environment on facilities, NRA was fitted with a structural and environmental monitoring system (SEMS), at the time of installation. This package measures air pressure, waves, wind, current and tides as well as the motions of the platform using accelerometers at deck level and at 3 levels down one leg. Since installation, this system has provided accurate data through major TC events including severe TC Orson in 1989[2], but has not detected any adverse trends in the behavioural response of the platform. It has also provided information contributing to platform design life extensions under increased wave loadings, valuable data for the recent NRB platform design and has delivered increased confidence in structural integrity evaluations of the NRA platform.

2 Further information is available in a paper titled 'Tropical Cyclone Orson – a Severe Test for Modelling' by Harper, BA; Mason, LB; Bode, L and presented at the 11th Australasian Conference on Coastal and Ocean Engineering at Townsville, Qld. in 1993. Paper available from Engineers Australia 'informit'.

APPENDIX 4 – NWS Project Challenges and Achievements

NRA production platform design

Platform environmental loading

For security of supply, the platform was required to sustain, without damage, 100 year return period cyclonic wave, current and wind speed events and provide acceptable safety of personnel during the then expected design production life of 25 years. The design wave height required the underside of the production deck to be elevated to +22 m above tidal low water – a very high elevation by world standards at the time, representing major challenges for both the platform substructure design and the offshore installation of the topsides production, accommodation and drilling modules.

During the period to 1979, various studies and data measurement programmes were performed to converge on the oceanographic, meteorological and earthquake criteria for design. These included detailed assessments of the design extreme and operating wave, ocean current and wind conditions. In addition, prediction of marine fouling was necessary to provide critical input to the platform design process. As there were no existing offshore structures in the area, marine fouling forecasts were based on limited measurements from an oceanographic mooring at North Rankin and other conventional deep water developments augmented by empirical data from tropical water sites. This step was crucial as inadequate allowance for marine growth can lead to a requirement for load-relief cleaning of substructure tubulars throughout the operational life of the platform.

Platform foundations

Reconnaissance seabed composition investigations were carried out at the drilling sites at North Rankin, Goodwyn and Angel during respective field appraisal programs in the early to mid 1970s. These investigations indicated the existence of deep deposits of calcareous (calcium carbonate) sediments over the fields, with more competent calcarenite layering at depths below 120 m. These calcareous sediments have a low density, are extremely weakly cemented but are friable, and do not accord with all the soil mechanics principles attributed to normal terrestrial soils. Limited experience in founding offshore structures on these sediments indicated the need for great caution in the selection of a suitable foundation system and its associated design criteria. Driven piles in the Bass Strait located in sediments similar to those at NR were found to have low skin friction capacities and the alternative drilled and grouted piles experienced hole stability issues. Investigative test holes and piles were installed in the NR sediments during an extension of the field appraisal drilling program in 1974. These tests demonstrated that large diameter drilled holes were stable over short periods in the soft sediment and that driven piles had unexpectedly low skin friction.

As a consequence of the above tests and reported problems in Bass Strait, and as a precursor to preliminary design, an innovative, comprehensive, site-specific platform site investigation was performed in 1978 to provide data for the design of the initial NRA platform foundations. This program included, for the first time offshore in Australia, in-situ testing using a cone penetrometer and other special loading tests in addition to conventional sampling, laboratory testing and classification of the sediments. Subsequent data analyses suggested that sufficient foundation capacity could be provided through a combination of some side-wall skin friction and end-bearing support of tubular steel piles driven to the more proficient calcarenite layers 120 m below the seabed.

Model pile testing indicated that the anticipated skin friction could be enhanced through the use of a step-tapered driving shoe on each pile. This solution was attractive, as the installation of driven piles would result in significant savings to the project. In the event that the skin friction resistance component was not fully mobilised during driving, contingencies to plug the pile tips and engage full end-bearing resistance were included.

Due to the very low shear strength of the first 20 m of seabed sediments, special attention was also necessary to ensure the stability of the substructure when initially set on the seabed in an un-piled state and before large buoyancy tanks (used in substructure upending) were removed.

Platform substructure

The preliminary design of the NRA platform resulted in a tower-type substructure, supported by cluster piles at its four corners. This design contrasted with the more conventional jacket template with both corner and skirt piles that directly support the topside deck packages. However, the cranes available at the time did not have the capacity to support the size and weight of the required deck packages.

Initial on-bottom support was provided through the incorporation of extensive mudmats at each corner of the substructure. The size and weight of the topside facilities required modularisation that in turn dictated the use of a module support frame and skid beams integrated with the substructure. However, this also meant that the substructure had to be installed to a level tolerance of 1:100 in any direction to ensure satisfactory hook-up and subsequent operation of the installed facilities. This would be achieved through conservative design of the platform mudmats at the base of the substructure. During installation, a skid-beam level of 1:800 was achieved. The modularised topside packages were subsequently lifted and skidded into final position and then levelled to an optimum operating elevation.

The regulatory requirement to safely flare or vent the platform hydrocarbon inventory in the event of a platform emergency required that a remote flare be located about 170 m from the platform. This flare would be connected to the platform via a flare bridge structure that in turn would be supported by a tripod support structure located adjacent to the NRA substructure.

Topsides production facilities

Prior to commencement of preliminary design in 1978, various studies concluded that the most efficient configuration for NRA development was an integrated drilling, production and living quarters platform. In shallower water, separate function platforms would most likely have been employed as a more cost effective solution. As designed, NRA should drill and produce from up to 34 wells, and condition and export 34.3 Mm^3 per day of gas and associated condensate. As such, it would then become the world's largest and tallest integrated

APPENDIX 4 – NWS Project Challenges and Achievements *(cont.)*

gas production platform. The well-stream fluids composed of gas, condensate and water would need to be separated and dehydrated offshore to permit multiphase gas and condensate flow to shore via a single carbon steel pipeline.

The demands for a low water content in the two-phase flow export pipeline to shore demanded dehydration on a scale never previously attempted offshore. Considerable testing and trials were required to ensure that the production stream entering the pipeline was always within exacting corrosion and hydrate formation limitations.

New grades of steel and alloys were selected for the NRA topsides piping to meet the platform's required service life of the process piping and utility systems. For example, the material for the production flow lines and wellhead manifolds passing the raw, untreated reservoir fluids from the wellheads to the separators were subjected to high pressure and temperature and a fluid composition comprising, hydrocarbon gas, condensate, water, sand, hydrogen sulphide and carbon dioxide, the latter two being active corrosion agents. A new flow line material developed by Sandvik, a duplex (2205) stainless steel, was selected for its anti-corrosive and erosion resistant qualities. This material had not been used before in the offshore oil and gas industry. Extensive development and testing was therefore required prior to in-service use. This piping material required parallel development of techniques for forging elbows, flanges and tees, together with development of welding techniques and consumables to ensure all welding achieved equivalent properties of the parent materials for these complex piping systems. These duplex alloys were subsequently adopted and thereafter used widely in the offshore oil and gas industry in similar harsh service.

Structural design contingencies

Without extended field experience to precisely define various design parameters prior to preliminary design, contingency allowances were either carried in the design or within the operating procedures for the platform to ensure continuous post-installation operation. In this regard, where the dynamic performance and motions of the platform could not be accurately defined, a structural monitoring system was incorporated into the substructure to measure the motions of the jacket under storm conditions. It would also provide calibration and confidence in the design of the structure and its foundations. Likewise, as there was no definitive data on marine growth thickness on the substructure below the water line, a contingency robotic cleaning system was planned and eventually manufactured to permit periodic removal of excess marine growth from critical tubular members of the substructure. Marine growth was eventually assessed as being thicker and deeper than predicted and robotic cleaning systems have subsequently been successfully used for its routine removal.

Management interfaces

Specialist engineering consultants were engaged to provide the necessary preliminary, detailed and construction support engineering for all facets of the offshore platform development. This included the engineering of topsides facilities, drilling packages, accommodation modules, support substructures and their foundations, together with interfaces with the export pipeline to shore. Managing the respective multiple interfaces, to deliver coherent components in a systematic and timely fashion was one of the major challenges faced by Woodside's engineering team. Effective interface control procedures, modified from the aerospace industry, resulted in an iterative and thorough evaluation process, which were managed in a progressive and timely manner. This approach proved to be robust over the project execution and operation phases.

The topsides preliminary design locations for the process modules, drilling rig and the accommodation modules contract design locations were spread across different geographical regions and time zones, presenting significant coordination, staffing and communication challenges. At that time, only rudimentary word processing and telex/facsimile transmission capabilities existed, with the Internet still 15 years in the future.

Other key interfaces with the topsides design included the NRA substructure and integral module support frame designs performed in San Francisco. Pipeline design was performed in both Singapore and Perth.

NRA platform fabrication and installation

Flare bridge and support structure

Fabrication of the relatively smaller flare support structure, its associated piling and the flare bridge were fabricated in Adelaide. This decision meant that both the flare support structure and the flare bridge had to be towed across the perilous Great Australian Bight without any possibility of a safe-haven during the southern hemisphere winter period to permit installation to be completed prior to the North West cyclone season.

Transportation to site – NRA structure

Detailed knowledge of prevailing meteorological and oceanographic conditions was required to define the design and acceptance criteria for all sea tow routes to the NRA site and also to assure safe installation at the NRA site. Studies to determine the governing sea-state criteria were performed to gain prior acceptance by the project insurers of the planned tow configurations, the commencement of tows and the initiation of critical offshore installation activities.

Offshore installation and critical piling of the platform substructure and flare support structure was essentially constrained to the winter months (May through October) to avoid the unacceptable risk of irreparable structural damage resulting from a tropical cyclone. The North Rankin location lies in 'cyclone alley' of the NWS and is only three or so days distant from cyclone generation areas. As a result, fixed platforms are extremely vulnerable to these intense storms particularly during their initial installation sequence. It was considered essential that the substructures be secured to the seabed and cyclone-safe prior to the cyclone season starting in November.

This meant that the platform substructure would need to be transported from its potential East Asian fabrication yard during the northern hemisphere typhoon season from May to August. Sea transport of the substructure would require use of one of the largest transport barges in existence at the time.

APPENDIX 4 – NWS Project Challenges and Achievements *(cont.)*

Motions of that barge during transit to the NRA site, together with subsequent launching and up-ending operations would ensure that the design of about half of all substructure tubular members was controlled by these temporary conditions. Indeed, many of the longer tubulars had to be helically wrapped with large diameter synthetic rope to reduce the impact of vortex induced vibration loading and significant fatigue during the tow to site. The maximum tow speed for this barge and substructure configuration was approximately 6 knots under still water conditions, thus requiring the need for accurate weather forecasting both prior to and during the transit.

Transportation to site – flare bridge/support structure

Being a tripod structure, the size and configuration of the 2,500 tonne flare support structure did not lend itself to being readily lifted and installed at site. Together with a 600 tonne auxiliary buoyancy raft, the flare support structure was towed as a self-floating structure in a horizontal attitude and then upended with crane assistance at site. This flare support structure tow configuration resulted in a very low transit speed of about 3 knots, thus making crossing of the Great Australian Bight a potentially very hazardous activity. At 185 m long, the flare bridge structure was transported to site using the NRA jacket transport barge together with the six flare support structure foundation piles. Tow speed for this barge was double that of the self-floating flare support structure but finding a suitable weather window to start the tow remained challenging.

Topsides facilities fabrication

While fabrication and completion of the NRA topsides facilities were considered within the capabilities of Australian fabricators, award of all the required packages in Australia would have saturated the available fabrication facilities, leading to uncertainty about completion to the exacting delivery schedule. As a result, all production and accommodation modules were constructed in Western Australia at Jervoise Bay and Geraldton respectively, and the drilling packages were fabricated in Singapore. Towing to site from these locations, through relatively benign waters, provided far fewer challenges.

Fabrication of the topsides production facilities presented a variety of issues for Australia as:

- the weight, size and thickness of both the primary separator and dehydration pressure vessels challenged the fabrication capacity in Australia and transportation of these vessels to the module fabrication site also proved challenging;
- upscaling fabrication capability in Perth was required to meet the sizes, quality and quantities of thick, high-strength structural steel specified with high fracture toughness and thru-thickness properties. Work of this scale on such high-strength materials had rarely previously been attempted in Australia; and
- welding skills in Western Australia were limited. A welding school was therefore established in Perth with the cooperation of the Western Australian Government. Contractors had to recruit and train welders in the various manual and automated welding processes and steel grades specified, across all positions. Welders were required for both the fabrication workshops and at the assembly sites.

Various large diameter process and export valves presented significant challenges to Australian manufacturers and could not be sourced in Australia. For example, both surface and subsea 1.02 m diameter ball valves were required to isolate the platform process equipment from the export pipeline and also permit tie-in of other product streams to the platform. These devices were substantial items in terms of weight, physical size and technical complexity and were fully imported from international oil and gas suppliers.

Platform offshore installation

Offshore installation and the associated logistics for the North Rankin offshore development presented a major challenge for Woodside. Marine installation equipment, such as the derrick barge for substructure and topside modules installation and lay barge for the 1.02 m diameter pipe line installation, were not active in the region and had to be mobilised from the North Sea or Gulf of Mexico.

To address this risk, and enable maximum module weights to be determined early in preliminary design, the planning, installation and contracting strategies had to resolve whether to award module, substructure and pipeline installation scopes as combined or separate contracts. Separate contracts were evaluated and adopted to secure two heavy-lift barges of similar capacity on the project and to provide contingency in the event a replacement barge is required.

This provided some lift barge ‘contingency’ and avoided full dependency on a single, but larger latest generation barge. That arrangement would have incurred a large premium and presented a resultant higher risk profile for the offshore phase.

This was a decision that addressed engineering, fabrication, transportation and construction logistics. It also provided certainty on sizing and weight/radius envelopes for use early in the preliminary engineering phase. Engineering work performed in remote and diverse locations proceeded within the crane capacity curves for each part of the North Rankin offshore scope, including module sizing, substructure installation, piling, flare structure, flare bridge and pipe laying activities.

Experience during pile installation indicated that the skin friction component of the pile capacity could not be dependably mobilised and that reliance on end-bearing capacity would be necessary for foundation support. During installation, the piles self-penetrated between successive layers of cemented formations, reaching velocities of up to 3 metres per second. The piles slowed down when approaching the lower stronger calcarenite layers and then had to be driven to final penetration. Grout plugs were subsequently installed at the tips of all piles.

The NRA topsides facilities were comprised of twelve permanent modules, five drilling packages and a temporary accommodation unit with maximum dry weights up to 1,100 tonnes and an aggregate dry weight of 11,500 tonnes. Lifting these modules to the jacket skid beam height of 22 m above sea level required one of the few offshore heavy lift vessels available at the time with a crane capacity in excess of 1,800 tonnes.

Following installation, setting in final position and levelling, the modules and packages were hooked-up and commissioned

APPENDIX 4 – NWS Project Challenges and Achievements *(cont.)*

offshore using a multi-skilled workforce accommodated in both temporary and permanent accommodation on the platform. This activity was completed in 15 months and following drilling of initial production wells, first gas was delivered to the onshore terminal at Withnell Bay for commissioning in July 1984. Sales gas deliveries commenced in the following month.

Installation of production well conductors

At 0.76 m diameter, the surface well conductors or casings were much smaller and therefore more flexible than the platform foundation piles. When driven through soft upper sediments that provided little lateral restraint and then encountering harder layering before being driven through, the conductors tended to bend and become deviated below the hard layer with the deviation azimuth being random. Given that 34 conductors needed to be installed, the potential for collision and subsequent loss of conductors was significant. Also, after drilling a number of wells through the conductors to completion and whilst on production, further conductor installations carried the risk of loss of well control directly under the platform. This situation was managed using some innovative control techniques developed at the time.

Platform foundation remedial works

Following completion of platform installation, questions remained over the capacity of the piles after installation and testing of the production well conductors from the platform. As a result, several studies were initiated to evaluate the safety of the platform for the 100-year return period storm design conditions. In the meantime, Woodside decided to demobilise the platform when tropical cyclones threatened, as the safety of the platform could not be assured for the full design loads.

Woodside and the NWS Project participants independently undertook studies to evaluate the capacity of the piles and to determine what remedial action could be undertaken, should the piles need rectification. A conscious decision was undertaken to ensure that the designers understood the fundamental behaviour of the soils and its response to design storm loading. Three universities, CSIRO and other geotechnical consultants were all commissioned to undertake fundamental studies of the sediment behaviour. In addition to these studies, large-scale pile load tests were performed on NRA during the installation of well conductors to more realistically model the pile behaviour.

Following these extensive studies of the alternatives, the final solution adopted required placing maximum 4.5 m diameter concrete bell footings at the tips of four of the eight piles at each corner leg. This involved drilling out of the pile tips, creating a bell-like void and filling with concrete. Only central reinforcing within the bell was practical and hence the design included a significant unreinforced concrete structure capable of ultimate loading up to 10,000 tonnes. Further complicating the design was the required high-strength of the mass concrete mandating advanced mix design to limit heat of hydration and hence the temperature reached during curing. A fine aggregate concrete mix using silica fume and direct injection of liquid nitrogen was successfully placed in 16 bells. A chemical grout 'Eposand' was injected below the piles prior to drilling the tips of the piles to stiffen their response and to stabilise the soil during the bell drilling operation. This ensured that none of the piles could become overloaded due to load redistribution, when adjacent piles were drilled out for bell installation.

The flare support structure pile configuration and higher tensile loads rendered it unsuitable to use the bell footing solution. Instead, pre-tensioned guys were used to directly resist the lateral loads on the structure and reduce the tensile loads in the piles. The guys were licensed copies of the design used for the Exxon Lena Tower in the Gulf of Mexico. At the time, the NRA platform was operational and the flare could have been required at any time to burn off gas created from operations or emergency depressurisation. The installation of temporary facilities including a jib crane, pile drill rigs, permanent strand jacks and guy system had to be carried out under a temporary heat shield and adjacent temporary refuge. For the flare support structure, tensioned guy wires were attached to iron-ore filled anchor boxes located some 150 m from the structure. The guy wires reduced the loads in the piles to the extent that the tip grouting was sufficient.

The NRA platform received full certification in February 1988, following the successful installation of the bells, guy wires and the removal of all the temporary structures needed for the remedial works. This work was performed on a fully operational platform whilst meeting contracted gas supplies.

Woodside published results of all the foundation studies undertaken for the project, in Volume 2 of the Proceedings of the International Conference 'Engineering for Calcareous Sediments' Perth, 15-18 March 1988. This volume has become the international reference for engineering in carbonate sediments.[3]

Transmission pipeline to shore

Two-phase flow operations

In the late 1970s, when options were being evaluated as part of the NWS Project feasibility study, there were no large diameter pipelines operating anywhere with the ratios of liquid to gas that were predicted for North Rankin. The methods of predicting flow regimes and frictional pressure losses in two-phase flow were not precise. There were many correlations of data obtained in laboratory or pilot scale testing, with very limited confirmation in full-scale operations and it was not obvious how a two-phase pipeline would behave dynamically, especially at low flow rates. Experience in the Gulf of Mexico and in the North Sea indicated that liquids would not arrive steadily, but could collect in the pipeline such that part of the pipeline would eventually fill with liquid, creating so-called 'slugs' of liquid that could produce severe operational difficulties and potentially damage downstream onshore equipment if they were not intercepted in some manner. Slugs could arrive at any time, unpredictably, unless measures were taken to limit the size of slugs to manageable volumes.

3 *Further information is also available in a paper titled 'The Planning and Design of Coastal and Ocean Engineering Projects' by Male, R and presented at the 11th Australasian Conference on Coastal and Ocean Engineering at Townsville, Qld. in 1993. Paper available from Engineers Australia 'informit'.*

APPENDIX 4 – NWS Project Challenges and Achievements *(cont.)*

In 1978, Woodside was able to test a 100-mile long subsea section of the Blue Water pipeline system in the Gulf of Mexico, a 36-inch diameter pipeline operating at about one-third of the ratio of liquid to gas forecast for North Rankin. This testing allowed Woodside to determine which correlations were most reliable for calculating pressure drop and hence the diameter of the NRA to shore two-phase flow pipeline.

Woodside was also able to draw on Shell's experience with two-phase flow through its technology group in The Hague. Shell had significant operational experience in the large-scale gas developments in the southern North Sea that supplied the Netherlands with natural gas. This support provided confidence that the two-phase pipeline option was viable for the NWS Project.

The onshore slug catcher

The upstream onshore facilities included a slug catcher to receive the two-phase flow from the pipeline and to provide the initial separation into condensate and vapour. Although its primary function as a liquid-vapour separator is straightforward, the required size was larger than anything previously built. It consisted of 14 'bottles' of 1.2 m diameter high-pressure pipe, each 350 m long, with cross headers at both ends, arranged in two parallel 7-bottle units so that one unit could be operated while the other underwent maintenance. The design was verified through both simulated and physical models that were built at the University of Western Australia.

The design pressure of the slug catcher was selected to be less than the settle-out pressure in the upstream pipeline and was protected by relief valves upstream of the specification break.

Initial operation of the pipeline was at low flow rates, when the project was supplying only domestic gas. To limit the volume of liquid accumulating in the pipeline under low flow conditions to manageable proportions, the pipeline was regularly pigged. Operation of the pipeline during this phase required very careful management and frequent pigging to avoid liquid inventories larger than the slug catcher capacity. This provided an extra operational challenge on both NRA and the onshore plant. Pigging was less frequently required once the LNG plant achieved full production, because the higher gas flow rates were able to prevent significant build-ups of liquid within the pipeline.

Stabilising the pipeline on the seabed

Once laid on the seabed, a pipeline must be stabilised to resist the effects of currents passing over the line, potentially eroding sediment beneath the line and exposing it to unsupported spans and fatigue loading. Such currents were expected to be particularly strong during tropical cyclones. A robust solution to pipeline stabilisation was required.

The seabed over long stretches of the North Rankin pipeline route is composed of relatively flat, hard and cemented calcareous sediments interspersed by zones of carbonate silts and sands. In the 1970s, some subsea pipelines had been successfully stabilised by a purpose-built 'plough' which, guided by the pipeline itself, was towed along the pipeline route while cutting a trench or groove below the pipeline into which the pipeline would settle. Natural movement of seabed material then, in time, covered and protected the pipeline. This method had been used on well flow lines and small-diameter pipelines in the North Sea and the Gulf on Mexico, but never at the scale required for Woodside's pipeline.

To prove the technique at the scale required for the NWS Project, test ploughs at 1/20, 1/5 and 1/3 scale were fabricated and tested onshore and offshore, at various points along the proposed pipeline route. Data from these tests led to the design and fabrication of a full-scale plough, which was tested at Jervoise Bay, south of Perth before being deployed to site for pipeline trenching.

Ploughing operations extended from a point 6 km off the Dampier coastline to the 124 km mark, except for areas of hard rock close to shore, and at a reef near the 22 km mark where trenching had to be achieved by blasting and dredging.

Subsea inspections of the pipeline route then determined if the ploughing had been successful. Where the plough had failed to establish the required depth of trench, other methods of stabilisation such as rock armouring were used. Pipeline stability has subsequently required periodic repairs, due to the high water current environment through which the pipeline passes.

Onshore process plants and facilities

Site preparation

The signing of the domestic gas sales agreement in 1980 and an overall vision for future LNG export meant that a decision needed to be made by the venture to invest in infrastructure for the total project having only the surety of the first domestic gas phase. The platform and pipeline were sized for the combined domestic gas and three train LNG phases. Components of the onshore slug catcher, receiving facilities and the site preparation were also pre-invested.

Site preparation for the onshore plant started in 1980 and took 17 months to complete. The plant site resulting from this challenging civil work is relatively level, at an elevation of approximately +20 m.

Figure 11: Trunkline 1 under construction

APPENDIX 4 – NWS Project Challenges and Achievements *(cont.)*

Domestic gas facilities at Karratha Gas Plant

To deliver the contracted 414 Tj/day for 25 years, two 100% capacity process trains for the domestic gas phase of the project were constructed and commissioned in 1984. The domestic gas facilities at Karratha Gas Plant involve gas dehydration using molecular sieve beds, followed by condensate removal. Condensate removal is achieved by cooling to around minus 60°C through a turbo-expander unit. The turbo-expander was initially designed to enable LPG to be extracted from the domestic gas stream and exported separately. LPG extraction was not implemented in Phase 1, although Wesfarmers subsequently built a LPG extraction unit in Kwinana to supply the commercial and retail markets in the south of the state.

LNG Plant – Phase 2

When sales and purchase agreements for LNG with Japanese buyers were finalised, the NWS Project participants were able to take the final investment decision to proceed with the design and construction of two LNG trains to meet the contracted demand. This commitment to proceed occurred in July 1985. The venture later committed to a third LNG train and design for this commenced in 1989.

The production trains firstly treat incoming gas to remove carbon dioxide, hydrogen sulfide, water and any mercury, before scrubbing to recover heavier hydrocarbon components. The scrubbing separates out ethane and propane for use as refrigerants in the liquefaction process. Liquefying the gas commences with pre-cooling, using propane refrigerant, followed by liquefaction with a mixed refrigerant (MR), a mixture of nitrogen, methane, ethane and propane. The heart of the liquefaction process is the main cryogenic aluminium spiral-wound heat exchanger.

Each of the refrigerant cycles (propane and MR) consists of compression, cooling and pressure reduction to deliver the required cooling effect. The compressors are driven by Frame 5 industrial gas turbines. This was a break with usual practice at the time, as most existing LNG production facilities used steam turbines to drive the compressors. This changed approach needed care in design and operations planning, but the reductions in capital cost and operating complexity were significant.

The elimination of the steam system required a new approach to elevated flare design, as steam had been used for flare smoke suppression. A single flare could not burn gas efficiently (i.e., without visible smoke) across the full range of flow rates the flare was expected to dispose of (from minor gas releases to major emergency relief), so a sophisticated multi-burner system was designed and installed. This system progressively increases the number of operating burners as the flow rate of gas to the flare increases. This approach became an exemplar for other projects in Australia with similar problems, such as at Port Bonython in South Australia.

The decision to use air-cooling for system heat exchange was a major step-out from then-current practices in LNG plants. The high ambient air temperatures that occur in the region in summer posed an additional challenge to designers of the heat transfer system. Nevertheless, efficient thermodynamic solutions to the problem of discharging heat into an already-hot environment were found. Following the decision to use air-cooling, extensive wind tunnel testing was undertaken to ensure that the discharges from the fin-fan air-coolers and the discharges from the gas turbine vents would not be recirculated to the inlet of the air-coolers, thereby reducing their efficiency. The design was modified as result of the testing.

LNG becomes liquid at atmospheric pressure at minus 161°C. Increased production can be achieved by running down the LNG at a slightly higher pressure and temperature and then cooling and flashing some LNG vapour during pressure letdown. This 'end-flash' gas is then used as fuel gas, with the residual passing to the domestic gas facilities. The maximisation of production from the plant complex requires the optimisation of domestic gas, fuel efficiency and LNG production.

Export facilities

Ship-loading facilities for condensate, which were brought into operation with the domestic gas facilities in 1984, were located such that the later construction of the LNG loading platform and the jetty to shore could proceed without interfering with ongoing operations. Construction of the LNG ship-loading facilities was thus deferred until required, and were only committed as part of the final investment decision for the first two LNG trains.

Due to the need to minimise product loading times, most LNG loading jetties are located in protected harbours. Although subject to attenuated ocean swells, Mermaid Sound had sufficient protection from the surrounding islands of the Dampier Archipelago that it did not need a breakwater. Mooring and loading on a NW-SE alignment ensured that incoming swells would be on the bow of a ship at the berth. The original jetty design was for a series of steel jackets with long bridge spans between them. With the delay in Phase 2 LNG export from 1984 to 1989, the LNG jetty was redesigned to include bellows for expansion and contraction of the loading lines instead of conventional expansion loops, saving significant costs on the support structures. Introduction of these bellows required a very stiff jetty structure (40 mm deflection under maximum loads and 25 mm under service loads). This was achieved with a high deck level necessary to keep the insulated cryogenic LNG lines above wave crests during design storms.

To meet the loading criteria of less than one day on the jetty, the loading arms for LNG were the largest built to that date to accommodate the specified LNG carriers. Condensate loading arms were also the largest built to that time, due to the need to load a large range of condensate tankers down to 20,000 DWT, all within the 5.5 m tidal range experienced in Mermaid Sound. Loading rates of 10,000 m^3 per hour were required to meet these criteria.

It was also necessary to dredge an access channel and turning circle for the LNG carriers. The largest cutter-suction dredger in the world was employed for this task, but it had significant problems in removal of outcrops of the hard calcarenite and similar granophyre substrate that existed on the Burrup Peninsula. Removing these outcrops required sophisticated underwater, very close pattern blasting and removal techniques. Even with this technology, port operations had to be modified accordingly. Spar buoys were used rather than piles for navigation marks for the channel to avoid pile driving in the calcareous rock and soils.

Figure 12: LNG and condensate loading wharves

Remote Offshore Warning System

Woodside developed and commissioned a Remote Offshore Warning System (ROWS) to predict cyclone-generated waves in Mermaid Sound, and to forecast when an LNG carrier must leave the berth to gain the required sea room before the cyclone arrives.

Prior to LNG export commencing, the procedure at the Port of Dampier was for all ships to leave whenever a tropical cyclone came within 400 km of the port. Woodside's review of this procedure demonstrated that only 50% of storms approaching within that distance caused adverse wave conditions at the port as affecting tanker wharf mooring loads (wave and period envelopes) or port exit under-keel clearances, which are critical at the entrance to Mermaid Sound.

Woodside demonstrated that use of four deep-ocean directional wave measurement buoys (reporting in near-real time) in a rectangular array, located some 120 to 280 km north and north-east of the port, would provide the wave spectral energy expected at the port (using reverse wave refraction) in 1, 2, 3, and 4 hours ahead of time. Essentially the ROWS buoys formed a 'tuned' deep ocean wave detector.

The system was tested against historical cyclones and by test system (Mini-ROWS) installed over one tropical cyclone system prior to test approvals and installation of the operational ROWS. The system has worked over every tropical cyclone season since installation just prior to LNG tanker operations commencing in 1989.

At the time of installation the system was considered an innovation as it was one of the first systems in the world to use the Inmarsat-C data transmission system. It was also the first 'tuned' ocean wave array and has a proven record of providing accurate wave forecasts (predicted wave heights +/- 0.15 m) being some 10 times more accurate than conventional wave forecasts. The pilots hold the system in high regard. With over 25 years in operation, the ROWS has allowed many cargoes to be loaded on schedule, improved wharf efficiency and minimised tanker-waiting time to load.

APPENDIX 5 – TERMINOLOGY AND ABBREVIATIONS

Term	Definition
Condensate, or Associated Liquids	Hydrocarbons existing as liquids at the conditions of pressure and temperature established within the system. Usually these are C_5+ with small proportions of dissolved lighter fractions, with C_{10}+ fractions in small to vanishing proportions.
Granophyre	A sub-volcanic rock that contains quartz and alkali feldspar in characteristic angular intergrowths. Granophyres typically are intrusive rocks that crystallised at shallow depths, and many have compositions similar to those of granites.
Hydrate	Gas hydrates are crystalline, water-based solids physically resembling ice, with gas molecules trapped within. Hydrates can form at high pressure in a hydrocarbon stream flowing in a pipeline such as those on the NWS. If they form, hydrates can cause operational difficulties, including blockages. Hydrates are prevented from forming in a pipeline by upstream dehydration.
Metocean	Meteorological and oceanographic, or meteorology and oceanography.
Pig and pigging	In its simplest form a pig is a compressible ball or "sphere" which is introduced into an operating pipeline and which passes along the pipeline, driven by the pressure of the fluid behind it. Pigs may be simple, for such purposes as collecting and moving liquids towards the discharge end of the pipeline, or more complex, carrying instrumentation to inspect the pipeline for wall thickness reduction or weld imperfections.
Slug	In a two-phase (gas-liquid) pipeline, a slug is a moving volume of liquid that fills the cross-section of the pipeline. Slugs can be of any length, so their volume can be very large if they are not controlled.
Stabilisation of hydrocarbons	Hydrocarbons (alkanes with the general formula C_nH_{2n+2}) lighter than pentane (C_5) cannot exist as liquids at normal atmospheric temperature and pressure. At high pressure, these lighter fractions can partially dissolve into multi-component mixtures of heavier fractions (see "Condensate", above). If such a mixture is brought to atmospheric pressure and temperature, the dissolved lighter fractions change phase to gas and "evolve" from the liquid mixture. Stabilisation is a controlled process under which the evolved light fractions are captured safely.
Thermocline	A thermocline is a thin but distinct layer in a large body of fluid in which temperature changes more rapidly with depth than it does in the layers above or below. In the ocean, a thermocline divides an upper mixed layer of water from calm, deeper water below.

UNITS	
Bbl	Barrel, the common measure for liquid volume in the oil industry at the time of the NWS Project. It is approximately 159 litres ($1m^3$ = 6.2898 bbl)
Mtpa	Millions of metric tonnes per annum
kt	Kilo-tonne; 1000 metric tonnes
Inch	Soft conversion; 1 inch = 25mm
Tj	Terajoule; common practice in the oil industry at the time of the NWS Project was to describe energy content in terms of "barrels of oil equivalent", or BOE. Also used is Pj, or Petajoule, where 1 Pj = 103Tj.
Liquid content in two-phase flow	At the time of the NWS Project this was usually quoted in terms of barrels per million standard cubic feet, or "bbl/MMSCF". A precise way to express the liquid/gas ratio in a pipeline is as the ratio of the respective mass flowrates.

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ENGINEERING HERITAGE INTERNATIONAL MARKER

On 7 June 2017, Engineering Heritage Australia advised Engineering Heritage WA that its nomination of the North West Shelf Project met the assessment criteria set down in the Engineering Heritage Recognition Guidelines for the award of an Engineering Heritage International Marker (EHIM). There are three levels of award, with an EHIM being the highest level in recognition of the North West Shelf Project's special significance on an international scale.

With support from the North West Shelf Project, a ceremony to celebrate the award of the EHIM and to unveil an interpretation panel was held at the North West Shelf Project Visitors Centre on 2 August 2017. An image of the interpretation panel is on the following page. A copy of the ceremony booklet and ceremony report is available from www.engineeringheritage.com.au.

ENGINEERS AUSTRALIA

GAS FIELDS OF PLENTY
NORTH WEST SHELF PROJECT (PHASES 1 & 2)

History

The North Rankin, Goodwyn and Angel gas fields were discovered in 1971 and 1972. These gas fields are located 130 kilometres north-west of Dampier in 125 metre water depth. The technical and engineering challenges facing development of these remote gas fields were significantly greater than anything faced by earlier offshore developments in Australia. Only the creation of a new Australian Liquefied Natural Gas (LNG) export industry could make the development of these large gas fields economically viable.

Phase 1 of the North West Shelf (NWS) Project was constructed between 1980 and 1984. This phase included the North Rankin A offshore drilling and production platform, a large one metre diameter submarine pipeline from the platform to the Burrup Peninsula, the King Bay Support Facility, the Karratha Gas Plant and facilities for export of residual condensate. In parallel with Phase 1, the Western Australian Government constructed the 1,530 kilometre long Dampier to Bunbury Natural Gas Pipeline. Phase 2, constructed between 1985 and 1989, included two LNG processing trains, storage tanks, export wharf facilities and six LNG tankers.

With Phase 1 and 2 investments of $7.1 billion and a total investment of more than $34 billion since the late 1970s, the NWS Project is one of the largest resource development projects in Australian history. At the time of construction, it was the largest engineering project underway worldwide in the oil and gas industry. Including additional phases, current capacity of the NWS Project is 46,000 tonnes per day of LNG for export, 12,600 tonnes per day of gas for Western Australia and 10,000 tonnes per day of condensate. Present day capacity is now four times larger compared to Phase 2 capacity in 1989.


Karratha Gas Plant under construction


LNG and condensate loading wharves


North Rankin platform under construction

Achievements

Significant achievements during Phases 1 and 2 include:

- development of new information for the Pilbara and offshore region on meteorology, cyclones, ocean currents, seabed foundation materials and topography;
- planning, design and construction of the largest capacity offshore gas and condensate platform in the world at that time;
- introducing a step change for LNG plant design from seawater-cooled to air-cooled facilities and from steam turbines to gas turbines;
- overcoming foundation problems associated with the carbonate sediments encountered on the North West Shelf and sharing this experience with industry;
- development of new design criteria and operational procedures for the transfer of both liquids and gas through the single submarine pipeline from North Rankin A platform;
- demonstration of a new standard for Australia in the management of safety and quality throughout all stages of the NWS Project;
- establishment of long-term domestic gas supply and LNG export contracts; and
- cementing the NWS Project's reputation as a reliable provider of domestic gas and exporter of LNG.

Project Impacts

In addition to construction on the Burrup Peninsula, local impacts included significant contributions to Government infrastructure, employee housing and other community facilities in Karratha.

At the state level, the NWS Project helped establish new industries in Western Australia including initial development of the area in Cockburn Sound that has become the Australian Marine Complex. The NWS Project also supports Western Australian universities' participation in world-class industrial research in the areas of oil and gas processing, oceanography and offshore foundation design.

The NWS Project has driven long-term economic benefits at a national level. To date, it has contributed in excess of $26 billion in royalties and continues to inject more than $900 million a year directly into the Australian economy.

Key People

There were many people from the project's joint venture participants and the State Government who supported the NWS Project between gas discovery in 1971 to first shipment of LNG to Japan in 1989. Some of the key individuals include:

- Geoff Donaldson, Chairman Woodside (1956 – 1984);
- Charles Allen, Woodside Chief Executive and Managing Director (1980 – 1996);
- Peter Tapper, Woodside Executive General Manager (1982 – 1990);
- Sir Charles Court, Premier Western Australia (1974 – 1982); and
- Peter Jones, Minister for Resources Development (1980 – 1983).

Engineers from Woodside, Shell and various contractors had to overcome the significant technical and engineering challenges faced by the project. The NWS Project would not have been possible without their ingenuity and leading international practice.

Engineering Excellence

In 1990, Engineers Australia awarded the North Rankin A Platform Foundations Project the Sir William Hudson Award for the best engineering project in Australia. Other aspects of the NWS Project have also been awarded Western Australia Engineering Excellence Awards.


Sir Charles Court and Project participants announcing domestic gas project

North West Shelf Project

BHP bp Chevron MIMI Woodside

The China National Offshore Oil Corporation is also a participant in the Project but does not have an interest in its infrastructure

An Engineering Heritage International Marker was awarded to the North West Shelf Project (Phases 1 and 2) by Engineering Heritage Australia on 2 August 2017.

For more details of this and other engineering heritage awards, go to www.engineeringheritage.com.au

Engineers Australia thanks Woodside Energy for their help in producing this interpretation panel and for providing photographs.

For more details of the North West Shelf Project, go to www.woodside.com.au


North Rankin A Platform foundation remedial programme


North West Shelf Project Phase 1 and 2 layout


Overview of North West Shelf Project today

Nomination of the

NORTH WEST SHELF PROJECT

For an Engineering Heritage Australia
Heritage Recognition Award

GAS FIELDS OF PLENTY

Prepared By Engineering Heritage Western Australia
Engineers Australia, Western Australian Division
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ENGINEERS
AUSTRALIA