APPENDIX H
A SYNTHESIS OF LITERATURE ON THE POTENTIAL IMPACT OF INDUSTRIAL AIR EMISSIONS ON MURUJUGA ROCK ART

Woodside

TABLE OF CONTENTS

Tables

Figures

1. EXECUTIVE SUMMARY

The Burrup Peninsula and surrounding islands of the Dampier Archipelago, traditionally referred to as Murujuga, is widely known for its Aboriginal rock art (in the form of engraved petroglyphs). The area hosts one of the largest and most diverse collections of rock art in the world, which have significant cultural value to local Traditional Owner groups and to Aboriginal people more broadly. The presence of heavy industry on the Burrup Peninsula has generated concerns that industrial emissions may lead to an accelerated weathering or deterioration of the rock art. These concerns centre on the issue that deposition of acidic air emissions from anthropogenic sources have the potential to increase the acidity of the rock surface through chemical and/or biological processes. Subsequently, these acidic conditions may then alter the natural state of weathering of the rock, resulting in a deterioration of the colour and depth contrast of the petroglyph image.

Over the past 15 years, a range of government led monitoring programs and independent scientific research has been conducted to investigate the potential for emissions from new and existing industrial development on the Burrup Peninsula to impact on the Murujuga rock art. It is noted that there have been criticisms of the methodologies used and the interpretation of the findings from some of these research studies and monitoring programs. Uncertainties therefore exist regarding techniques for monitoring and detecting change (both natural weathering rates, and potential for accelerated weathering) and the determination of a critical load of acid deposition at which impacts to rock art may occur. This document provides a synthesis of publicly available scientific investigations and monitoring programs that have contributed to the current state of knowledge of the impact of industrial air emissions on the rock art.

2. INTRODUCTION

2.1 Purpose and Scope

This document presents an overview and synthesis of publicly available literature that has contributed to the current state of scientific knowledge on the potential impact of industrial air emissions on the Murujuga rock art. The information summarised in this report has been used to inform the impact assessment undertaken as part of the North West Shelf (NWS) Project Extension environmental approvals, as presented in the NWS Project Extension Environmental Review Document (Woodside, 2019).

2.2 Murujuga Rock Art

The Burrup Peninsula and surrounding islands of the Dampier Archipelago (traditionally referred to as Murujuga) are located on the Pilbara coastline in Western Australia (WA) and contain one of the largest and most diverse collections of rock art in the world (**Figure 2-1**). It is estimated that Murujuga contains over one million rock engravings (in the form of petroglyphs), at a density of around 218 images per km^2 (McDonald, 2015). Although rock art is difficult to date, the petroglyphs images on Murujuga are estimated to range from 4,000 to 30,000 years in age (Mulvaney, 2011; Pillans and Fifield, 2013). The rock art was created with a range of stone tools using various techniques of pecking, pounding, rubbing and scratching (Vinnicombe, 2002). According to Mulvaney (2015), the collection on Murujuga represents one of the longest continual sequences of rock art in the world and has some of the earliest depictions of the human face. The rock art documents the changing environment of Murujuga from when the land was 100 km inland from the sea and include images of terrestrial and marine fauna including extinct species such as the Thylacine (*Thylacinus cynocephalus*; Tasmanian tiger) which has been extinct on mainland Australia for approximately 3,000 years (Bird and Hallam, 2006; Mulvaney, 2011, 2015).

2.2.1 Cultural Significance

The local Aboriginal people of Murujuga (collectively, referred to as Ngarda-Ngarli) have a deep cultural and spiritual connection to the Murujuga rock art as it provides a record of Aboriginal lore, dreamtime stories, customs and local knowledge of the land and its resources (DEC, 2013). The rock art is central to the continuing culture of the Ngarda-Ngarli and showcase the tens of thousands of years of connection between Aboriginal people and country. As outlined in the Murujuga National Park Management Plan, the protection of the rock art and its cultural value are of the highest priority for the Traditional Owners of the area (DEC, 2013).

2.2.2 Formation of Petroglyphs

The geological landscape of the Burrup Peninsula is dominated by large rocky outcrops and distinctive weathered red/brown rock piles (mainly gabbro and granophyre igneous rock types with small granite exposures), providing an ideal canvas for petroglyph carvings (Donaldson, 2011). Over geological time, the surfaces of these rocks have been subject to natural weathering processes and developed a cm-thick layer of pale orange/yellow weathering skin. Overlayed on the weathering skin is a thin dark brown/black coating, typically referred to as a rock 'patina' or 'varnish'. According to Liu and Broecker (2000) the rock patina comprises mainly of clay minerals and manganese and iron oxides, which forms very slowly at an estimated rate of 1 – 10 micrometres (μm) per thousand years, however the mechanisms for this formation are not well understood. For the purpose of this report, the weathered rocks on Murujuga is described as having three distinct layers: (1) fresh parent rock; (2) pale weathering skin; and (3) dark thin surface coating, commonly referred to as the rock patina.

Petroglyphs are created by breaking through the darker rock patina and into the lighter coloured weathering skin, revealing a colour and contour contrast on the rock surface. The preservation of the rock 'patina' is therefore fundamental to maintaining the integrity and condition of the petroglyphs.

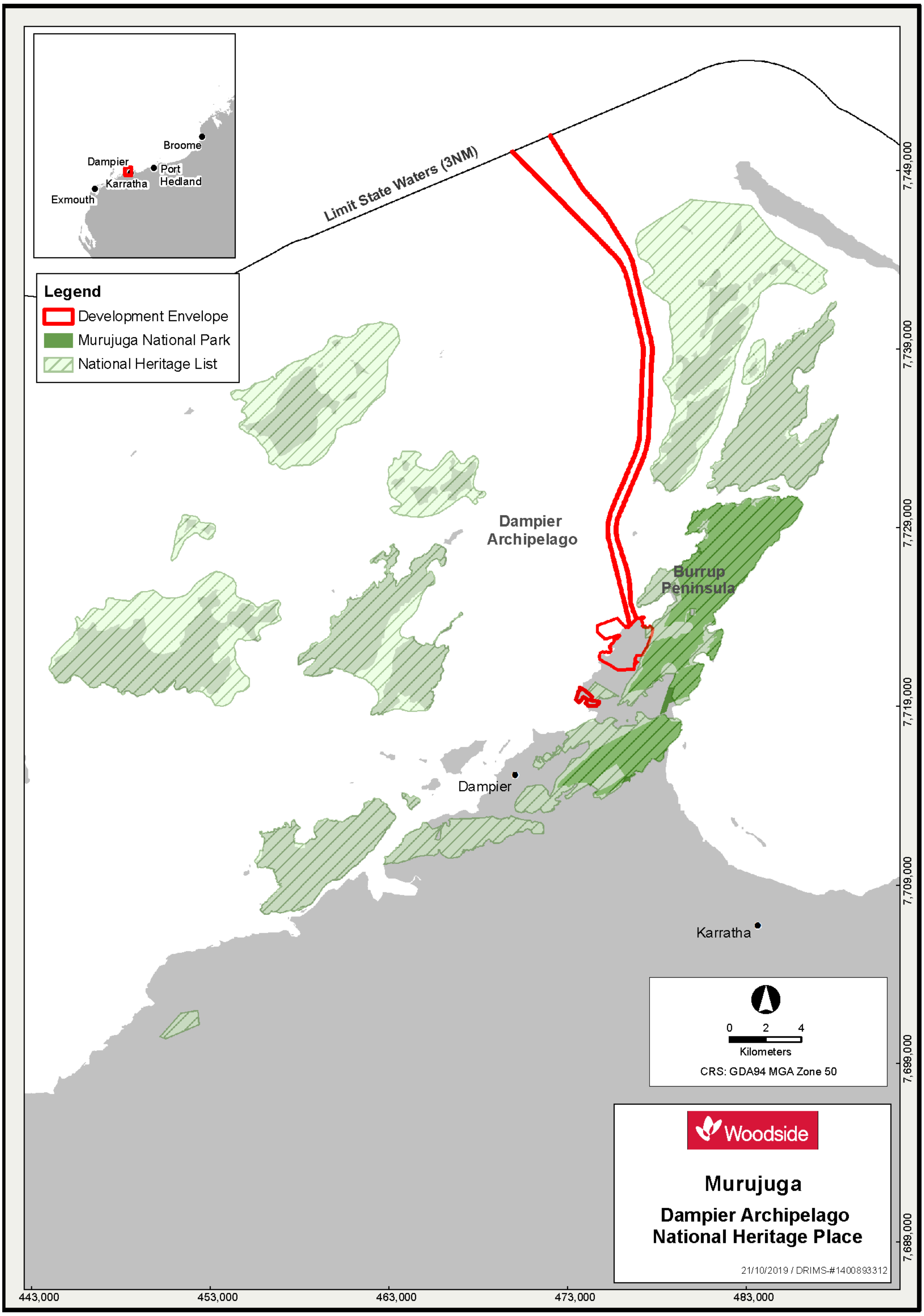

Figure 2-1 Regional Location of Murujuga (Burrup Peninsula and surrounding islands of the Dampier Archipelago)

2.3 Current Protection Status of Murujuga Rock Art

The protection and management of the rock art on Murujuga is covered under a range of State and Commonwealth legislation including:

+ *Aboriginal Heritage Act 1972* (WA)
+ *Aboriginal and Torres Strait Island Heritage Protection Act 1984* (Commonwealth)
+ *Environmental Protection Act 1986* (WA) (EP Act)
+ *Environment Protection and Biodiversity Conservation Act 1999* (Commonwealth) (EPBC Act)
+ *Conservation and Land Management Act 1984* (WA) (CALM Act)

2.3.1 National Heritage Listing

On 3 July 2007, the Dampier Archipelago (including the Burrup Peninsula) was included on the National Heritage List in recognition of Murujuga's unique Aboriginal heritage values, particularly its engraved rock art and stone features (DoEE, 2007). The listing provides robust heritage protection under the Commonwealth EPBC Act.

2.3.2 Murujuga National Park

The Murujuga National Park was established in January 2013 over the northern Burrup Peninsula (**Figure 2-1**) and is jointly managed by the Murujuga Aboriginal Corporation (MAC) and the WA Department of Biodiversity Conservation and Attractions (DBCA) formerly Department of Parks and Wildlife. The Murujuga National Park Management Plan released in 2013 outlines a central objective "to achieve a sustainable coexistence of conservation and industrial development and Aboriginal and other Australian land ownership and use" (DEC, 2013). The plan advocates "protection of the area's internationally important and national heritage listed values, whilst recognising the economic and social benefits of the Burrup Peninsula industries for the people of Western Australia." (DEC, 2013). Classification as a national park ensures further protection for the Murujuga rock art through the application of provisions under the WA CALM Act.

2.3.3 World Heritage Nomination

On 27 August 2018, the Premier of WA, Hon. Mark McGowan, and MAC announced intentions to formally begin the nomination process for UNESCO World Heritage listing. The area is being nominated to be listed specifically for its cultural values. A report by the Australian Heritage Council (AHC) (2011) provides a preliminary assessment of the outstanding universal values of the Dampier Archipelago and any threats to the site. With appropriate management, the WA government considers that industry and tourism can successfully co-exist with the cultural heritage and environmental values of Murujuga (DWER, 2019a).

2.4 Industrial Development on the Burrup Peninsula

Industrial development across the southern half of the Burrup Peninsula began in the early 1960's with the development of deep-water port facilities to support the Pilbara's emerging iron ore industry. In January 2000, the WA government released a notice of intent to acquire land for the construction of heavy industrial estates on the Burrup Peninsula and nearby Maitland Area. On 16 January 2003, the Burrup and Maitland Industrial Estate Agreement (BMIEA) was settled with three local native title claimant groups (the Ngarluma-Yindjibarndi, the Yaburara-Mardudhunera and the Wong-Goo-Tt-Oo).

The agreement allowed for the development of the 'Burrup Strategic Industrial Area' over land across the southern section of the Burrup Peninsula whilst also providing for the development of a new conservation estate (later becoming Murujuga National Park) for the protection of Aboriginal heritage (DWER, 2019a). The BMIEA also led to the formation of the Murujuga Aboriginal Corporation (MAC) in April 2006. MAC represents the five traditional groups in the Murujuga area — the Ngarluma people, the Mardudhunera people, the Yaburara people, the Yindjibarndi people, and the Wong-Goo-Tt-Oo people (MAC, 2016).

The Burrup Peninsula now supports a range of heavy industries and is considered a main export precinct in the North West region (AHC, 2011). Large industrial facilities currently operating on the Burrup Peninsula include Dampier Port and supply base, Yara Pilbara Liquid Ammonium Plant and Technical Ammonium Nitrate Plant, the Karratha Gas Plant, Pluto LNG Plant, Rio Tinto iron ore leases and shipping terminals and Dampier Salt.

3. INDUSTRIAL EMISSIONS AND MURUJUGA ROCK ART

3.1 Theory of industrial related impacts

The rock surface on which petroglyphs are engraved naturally undergo complex physical, chemical and biological weathering processes that alter the mineralogy of the rock surface over time, in turn degrading the colour contrast of the petroglyphs (Ramanaidou and Fonteneau, 2019). In the early 2000's, concerns were raised over potential indirect impacts associated with air emissions from industry and shipping activity, and those emissions having the potential to accelerate the deterioration of the rock art on Murujuga (Bednarik, 2002). Anthropogenic emissions of concern include industrial emissions (namely oxides of nitrogen (NO_X) and oxides of sulphur (SO_X), emissions from shipping, dust from ship loading of iron ore, land clearing and vehicle traffic (DWER, 2019a). These concerns centre on the theoretical potential of SO_X and NO_X increasing the acidity on the rock surface and/or alternatively altering the rock surface microbiology. Subsequently, it is theorised, the natural rates of rock surface weathering are accelerated either through chemical and/or biological processes causing a deterioration in the colour contrast of petroglyphs.

3.2 Government Initiatives

3.2.1 Burrup Rock Art Monitoring Management Committee

The BMIEA Additional Deed[1] included a requirement for the WA government to "organise and fund a minimum four-year study into the effects of industrial emissions on rock art within and in the vicinity of that part of the Industrial Estate that is on the Burrup Peninsula" (DWER, 2019a)

In 2002, the WA government established the independent Burrup Rock Art Monitoring Management Committee (BRAMMC) to oversee a range of scientific studies to address the following research questions:

+ Is the natural weathering of the rock art of the Burrup Peninsula being accelerated by industrial emissions?
+ Is there a significant and measurable problem?
+ If there is a significant issue, what are the management approaches recommended?

To address these questions, the BRAMMC commissioned a range of independent scientific studies. In the subsequent years, the management, name and scope of these WA government led initiatives have altered and are outlined in **Table 3-1** over the page.

1 *The WA Government entered into the Burrup and Maitland Industrial Estates Agreement Implementation Deed (BIMEA) with three Aboriginal groups in January 2003. As part of this agreement an Additional Deed was signed and included requirements under Section 11 to implement a rock art study looking into the effects of industrial emissions on rock art on the Burrup Peninsula. The BIMEA Additional Deed is available from: https://www.dpc.wa.gov.au/lantu/MediaPublications/Documents/Burrup_Additional_Deed.pdf*

Table 3-1 List of scientific studies conducted as part of the ongoing state government Murujuga Rock Art Monitoring Initiatives.

Name	Management	Tenure	Scope[1]
Burrup Rock Art Monitoring Management Committee (BRAMMC)	Department of State Development (DSD)	August 2002 - 2010	+ Air Quality + Microclimate + Dust Deposition + Colour Change + Spectral Mineralogy + Microbiological Analyses + Accelerated Weathering Studies + Air Dispersion Modelling
Burrup Rock Art Technical Working Group (BRATWG)	Department of State Development (DSD)	September 2010 – June 2016	+ Colour Change + Spectral Mineralogy
No Formal Group	Department of Environment and Conservation (DER)	July 2016 – June 2017	+ Colour Change + Spectral Mineralogy + Experimental extreme weathering study + Independent reviews
Murujuga Rock Art Strategy	Department of Water and Environmental Regulation (DWERa)	July 2017 - Ongoing	+ To be confirmed

Note 1: The reports from these studies are publicly available on the DWER website (Murujuga Rock Art Monitoring Program).

In 2009, the BRAMMC released a report on the findings of the studies taking into consideration comments received from international peer reviewers and concluded there was no scientific evidence of any measurable impact of industrial emissions on the rate of deterioration of the Rock Art (BRAMMC, 2009). BRAMMC recommended no environmental management measures were necessary at that time to protect the rock art from industrial air emissions (BRAMMC, 2009).

The BRAAMC recommended a technical working group be established to oversee the continuation of the colour contrast and spectral mineralogy monitoring program on an annual basis for ten years. In response, the Burrup Rock Art Technical Working Group (BRATWG) was established on 20 September 2010 to oversee the colour contrast and spectral mineralogy monitoring program and other studies.

The BRATWG completed its five-year term of engagement on 30 June 2016 and provided a draft report to the WA Minister for Environment. The report concluded monitoring results were consistent with earlier findings from BRAMMC (2009) and state that "there is no scientific evidence that indicates any measurable impact of industrial emissions on the rock art on the Burrup over the period 2004 to 2014" (BRATWG, 2015). The report recommended the continuation of the monitoring program on an annual basis to provide an early warning of any possible impacts to rock art from industrial emissions (BRATWG, 2015). At that point oversight passed to the Department of Environment Regulation (DER), which then became DWER on 1 July 2017 (DWER, 2019a).

3.2.2 Senate Inquiry

On the 30 November 2016, the Australian Government Senate referred a range of matters regarding the management and protection of the Murujuga Rock Art to the Senate Environment and Communications References Committee for inquiry (SECRC, 2018). Through this process, concerns were raised relating to the adequacy and accuracy of the methodologies used and interpretation of results from some of the studies undertaken as part of the WA government rock art monitoring program. The Senate Committee's report, released on 21 March 2018 recommended the development and implementation of a new, fully funded independent monitoring and analysis program (SECRC, 2018).

3.3 Murujuga Rock Art Strategy

On 8 September 2017, DWER released the 'Draft Murujuga Rock Art Strategy' (DWER, 2019a) for public comment. The strategy aims to "build on the previous work on the Burrup Peninsula to deliver a scientifically rigorous, world's best practice monitoring program and risk-based approach to the management of impacts to the rock art, consistent with legislative responsibilities under the EP Act" (DWER, 2019a). The Murujuga Rock Art Strategy will be implemented by DWER in partnership with MAC, representing the Traditional Owner groups of Murujuga. Following consultation and stakeholder feedback the Murujuga Rock Art Strategy was finalised in February 2019. The Murujuga Rock Art Monitoring Program is described further in Section 4 of this document.

3.3.1 Murujuga Stakeholder Reference Group

The Murujuga Rock Art Stakeholder Reference Group was established in September 2018 by the WA Minister for Environment to oversee the finalisation and implementation of the Murujuga Rock Art Strategy and ensure effective engagement between MAC, the WA government and key industry and community representatives (DWER, 2019a). The role of the Murujuga Rock Art Stakeholder Reference Group includes the following:

+ Actively contribute to the monitoring and protection of rock art, being considerate of the views of all stakeholders. This includes the provision of advice to DWER and the Minister for Environment on the design, implementation and analysis of the scientific monitoring and analysis program.
+ Consult, inform and educate other stakeholders on other matters referred by DWER for input or comment, including further development of the strategy, implementation of the strategy and five-yearly reviews.
+ Inform the Government's broader consideration of other strategic issues relating to the protection of the rock art on Murujuga.

The group includes representatives from MAC, the WA museum, research organisations, local and state government departments, industry and the community.

4. PETROGLYPH AND AIR EMISSION STUDIES

4.1 Background

This section of the report provides a synthesis of the scientific investigations and monitoring programs that have been carried out over the last 15 years to understand the potential impact of atmospheric emissions on the Murujuga rock art. The studies summarised in this literature review are listed in **Table 4-1**. Further discussion of each study has been provided including an overview of the study objectives, approach and key findings and a synthesis of how the research has contributed to the current state of scientific knowledge.

Table 4-1 Studies and Reports summarised in this literature review

Subject	Relevant Literature	Section
Air Quality and Deposition Monitoring	+ Pilbara Air Quality Study Summary Report (DoE, 2004). + Burrup Peninsula Air Pollution Study: Report for 2004/2005 and 2007/2008. (Gillet, 2008). + Burrup Peninsula Air Pollution Study: Report for 2004/2005, 2007/2008 and 2008/2009. (Gillet, 2010).	**Section 4.2** **Section 4.4**
Ambient Air Quality Monitoring	+ Burrup Rock Art. Atmospheric Modelling – Concentrations and Depositions (SKM, 2003). + Pluto LNG Development Cumulative Air Quality Study (SKM, 2006). + Burrup Rock Art: Revised Modelling Taking into Account Recent Monitoring Results (SKM, 2009).	**Section 4.3**
Accelerated Weathering Experiments	+ Field Studies of Rock Art Appearance. Final Report: Fumigation and Dust Deposition. (Lau *et al* 2007). + Extreme weathering experiments on the Burrup Peninsula/Murujuga weathered gabbro and granophyre (Ramanaidou *et al* 2017).	**Section 4.5**
Rock Surface Acidity	+ The survival of the Murujuga (Burrup) petroglyphs (Bednarik, 2002). + Effects of moisture, micronutrient supplies and microbiological activity on the surface pH of rocks in the Burrup Peninsula (MacLeod, 2005). + The science of Dampier rock art – part 1 (Bednarik, 2007). + Theoretical effects of industrial emissions on colour change at rock art site on the Burrup Peninsula (Black *et al* 2017).	**Section 4.6**
Microbiological Activity	+ Monitoring the microbial diversity on rock surfaces of the Burrup Peninsula (O'Hara, 2008).	**Section 4.7**
Colour Change and Spectral Mineralogy	+ Burrup Peninsula Aboriginal Petroglyphs: Colour Change and Spectral Mineralogy 2004 – 2016 (Duffy *et al* 2017).	**Section 4.8**

4.2 Air Quality and Deposition Monitoring

To better understand the spatial and temporal composition and concentrations of air contaminants that have the potential to be transferred from the atmosphere to the rock surfaces, a series of air quality and deposition monitoring stations were installed over the last 15 years (see **Table 4-2**). In the early 2000s, the Government of WA implemented the Pilbara Air Quality Study (PAQS), which established important baselines for air quality on the Burrup Peninsula (DoE, 2004). Later, the Government funded the BRAMMC Air Quality Monitoring Program which consisted of three periods of ambient air quality monitoring (2004 – 2005, 2007 – 2008 and 2008 – 2009) on the Burrup Peninsula and the broader region (see Gillet, 2008; 2010). Monitoring stations measured ground level concentrations of air contaminants (nitrogen dioxide (NO_2), nitric acid (HNO_3), ammonia (NH_3), sulphur dioxide (SO_2), micro-climate conditions, rainwater (amount and composition), total suspended particles (TSP) and particulate matter (PM)), which has been a key input into the ambient air quality and nitrogen deposition flux modelling studies (SKM, 2006; 2009).

The BRAMMC Air Quality Monitoring Program was conducted at nine sites, noting not all parameters were measured at every site:

+ five on the southern section of Murujuga (to assess concentrations near the industrial area);
+ two on the northern section of Murujuga (to assess local background concentrations);
+ one at Mardie Station, 81 km southwest of Dampier (to assess background concentrations); and
+ one at Karratha townsite.

More recently (in 2013), Yara Pilbara Nitrates (YPN) Pty Ltd Technical Ammonium Nitrate Plant (TAN Plant) conducted ambient air quality monitoring at three of the original BRAMMC monitoring stations on the Burrup Peninsula as per requirements under Condition 9 of their EPBC Act Approval 2008/4546 (YPN, 2017; Strategen, 2018). The monitoring program includes measurements of ground level concentrations of NO_2, NO_3, NH_3, SO_2, TSP and dust deposition (insoluble and soluble).

Table 4-2 Air Quality and Deposition Monitoring Studies on the Burrup Peninsula

Program	Ownership	Monitoring Period	Reference
Pilbara Air Quality Study	WA Government	1998 – 2000	Pilbara Air Quality Study Summary Report (DoE, 2004)
Burrup Peninsula Air Pollution Study	WA Government	2004 – 2005; 2007 – 2008; and 2008 - 2009	Burrup Peninsula Air Pollution Study (Gillet, 2010)
Yara Ambient Air Quality Monitoring	Yara Pilbara Nitrates Pty Ltd	2013 - Present	Ambient Air Quality Monitoring (Strategen, 2018) Baseline Air Quality Monitoring (YPN, 2017)

4.2.1 Key Findings

Key findings of the Gillet (2010) monitoring program include:

+ Ground level gas concentrations of all measured contaminants were very low in comparison to polluted urban areas
+ Data from the ambient air monitoring showed that NO_2 is typically observed well below the relevant Australian National Environmental Protection Measure (NEPM) (Ambient Air Quality) standard of 120 parts per billion (ppb).
+ There was a small enhancement in SO_2 and HNO_3 ground level concentrations and a larger enhancement in NO_2 at 'industry' sites compared with 'background' sites
+ Annual and monthly averages of NO_2, SO_2 and HNO_3 had little variation across monitoring sites and monitoring periods. The average concentrations of NO_2 at 'background sites' over the three monitoring periods was 0.7 ppb ± 0.1 pbb, whilst at sites closer to industry, average concentrations were slightly higher at 2.1 ppb ± 0.1 pbb.

A report by Strategen (2018) comparing Yara's 'baseline' air quality monitoring program (consisting of data from 2013 – 2017) to their most recent annual monitoring dataset (2017 – 2018) concluded the following:

+ Average ground level concentrations of NO_2 from baseline to 2017/18 are not statistically significant and average concentrations of SO_2 from 2017/18 were lower than baseline
+ TSP concentrations were reasonably consistent across the three sites suggesting an absence of significant direct impacts from individual sources

4.2.2 Discussion

Whilst DWER describes the results from previous air quality monitoring programs as 'reliable and targeted' it is recommended that improvements could be made to inform a detailed cumulative spatial analysis (DWER, 2019a).
In response, the WA government is planning to implement a long-term coordinated ambient air quality monitoring network on the Burrup Peninsula and surrounding areas. The Murujuga Rock Art Strategy outlines that the introduction of a centralised, coordinated and independently run monitoring network will help to build a better understanding of the characteristics of the cumulative air shed and enable more informed decision making (DWER, 2019a).

4.3 Air Quality and Deposition Modelling Studies

Air dispersion modelling was conducted by SKM in 2002, and later revised in 2009 to provide insight into the spatial distribution, dispersion and deposition of air pollutants (namely NO_2, SO_2 and NH_3) on the Burrup Peninsula and determine the contribution of specific emissions sources to the airshed (SKM 2003; 2009). Relevant emission sources included contribution from industries as point sources, shipping and area emissions from biogenic and anthropogenic sources. The TAPM model was used to predict nitrogen dioxide and sulphur dioxide concentrations and deposition in the Dampier region. Publicly available air dispersion and deposition modelling studies as defined in **Table 4-3** have been summarised below.

Table 4-3 Air Dispersion and Deposition Modelling Studies on the Burrup Peninsula

Study	Ownership	Date	Reference
Burrup Rock Art. Atmospheric Modelling – Concentrations and Depositions	WA Government	2003	Burrup Rock Art Atmospheric Modelling (SKM, 2003)
Pluto LNG Development Cumulative Air Quality Study	Woodside Burrup Pty Ltd	2006	Pluto Cumulative Air Quality Modelling (SKM, 2006)
Burrup Rock Art: Revised Modelling Taking into Account Recent Monitoring Results	WA Government	2009	Burrup Rock Art Revised Atmospheric Modelling (SKM, 2009)

4.3.1 Key Findings

+ Key findings of the SKM (2003) and SKM (2009) show a model for SO_2 and NO_2 ground level concentrations for the Dampier region
+ The SKM (2003) report concluded maximum concentrations of SO_2 are found close to shipping berths, while NO_2 emissions from industrial facilities are much hotter emissions with higher release points (stacks) which aids dispersion of NO_2 and causes maximum concentrations to be located further away from these sources
+ Monitoring data showed that influence of wind direction and speed caused the model to either overestimate or underestimate SO_2 and NO_2 ground level concentrations (SKM, 2009)

4.3.2 Discussion

As highlighted in SKM (2003; 2006; 2009) reports, there are significant uncertainties associated with the modelled deposition rates due to assumptions of surface resistance for water, soil and vegetation. Consequently, modelled deposition rates are indicative only and deposition monitoring is recommended for further clarity. As mentioned above, the Murujuga Rock Art Strategy will implement a coordinated ambient air-quality and deposition monitoring network on Murujuga and in the surrounding area. These data will allow ongoing refinement and ground-truthing of ambient air quality models (e.g. TAPM).

4.4 Deposition Flux of NO_x and SO_x

Deposition of NO_x and SO_x to an area of ground over a particular period of time can be calculated from measurements of ambient air quality, and analysis of particle matter and rainwater. Deposition monitoring was included as part of the Burrup Peninsula Air Monitoring Program commissioned under BRAMMC and measured over 2004 – 2005, 2007 – 2008 and 2008 – 2009 at the monitoring sites listed in **Section 4.2**. To understand acid deposition and acid deposition fluxes, Gillet (2010) calculated the wet and dry deposition of all nitrogen and sulphur species in the gas and aqueous phases. This included NO_2, SO_2, HNO_3 and NH_3 gases, and some other species in rainwater.

4.4.1 Key Findings

Gillet (2010) reported that for sites close to industrial activity, the total wet and dry deposition flux of nitrogen and sulphur ranged from 19.3 - 37.2 milliequivalents per square metre per year (meq/m²/year) over the three monitoring periods. For 'background' sites, the average deposition flux was 17.8 ± 4.6 meq/m²/year. Additionally, the average dry deposition flux for the monitoring stations close to industrial sites was composed mainly of NO_2 and NH_3 and accounts for approximately 55% of the total flux (Gillet, 2010).

4.4.2 Discussion

Based on research assessing the sensitivity of different ecosystems to acid deposition based on the buffering capacity of different soil types (Cinderby *et al* 1998), Gillet (2010) suggested that critical loads of deposition below 200 meq/m²/year would not affect the rock surfaces (and consequently the rock art) of Murujuga. Subsequently, the conclusions drawn by Gillet (2008; 2010) that Murujuga petroglyphs could withstand loads of up to 200 meq/m²/year was determined to be inappropriate, when used in the context of rock art on Murujuga (SECRC, 2018). Consequently, currently there is no empirical evidence for an acceptable critical acid load for rock surfaces on the Burrup Peninsula, beyond which rock art would be impacted.

The Murujuga Rock Art Strategy and associated Murujuga Rock Art Monitoring Program tender application includes scope for an atmospheric air quality and deposition monitoring network to provide a long-term dataset on the composition and concentration of atmospheric contaminants of concern (DWER, 2019a). A coordinated long-term monitoring network on Murujuga and the surrounding areas will provide data on the composition and concentrations of contaminants that are potentially transferred from the atmosphere to rock surfaces. The program will assist in understanding the exposure of the rock art to atmospheric contaminants and assessing changes in that exposure over time (DWER, 2019a). The network will be informed by the historical monitoring that has been conducted on Murujuga and will result in more informed decision making.

4.5 Accelerated Weathering Studies

4.5.1 Fumigation and Extreme Exposure Experiments

Laboratory fumigation experiments were conducted exposing Murujuga rock samples to a range of air pollutants including NO_2, SO_2, Benzene, Toluene, Xylene and NH_3 at different concentrations representing future industry levels and 10 x future industry levels (Lau *et al* 2007). Fumigation was conducted on rock samples with and without dust (iron ore) and accelerated aging was imitated through wetting and drying cycles in the fumigation chambers.

In addition, emersion studies were conducted to assess how iron ore hematite powder (a 'proxy' for iron oxide which is a main component of the rock patina) reacts to high concentrations of air pollutants (Lau *et al* 2007). Iron ore hematite powders were exposed to solutions of water, concentrated solvents (including benzene, toluene, xylene), and acids/bases (nitric acid, sulphuric acid and ammonia) for 22 days at both 25°C and 50°C. Mineralogy before and after exposure was characterised using X-Ray diffraction and photospectrometry (colour change) (Lau *et al* 2007).

4.5.1.1 Key Findings

Lau *et al* (2007) concludes that the fumigation studies indicated no significant observable difference was detected between the mineralogy of the rock surfaces exposed to pollutants at varying concentrations compared with unexposed (control) samples. In addition, the samples exposed to dust did not show a significant difference in colour. Lau *et al* (2007) results indicate that iron ore hematite powders do not produce a significant colour change when exposed to concentrated solvent or acid/base solutions, with the exception of concentrated sulphuric acid which produced a colour change after 22 days.

4.5.1.2 Discussion

The study acknowledged that there is a range of variables that contribute to the weathering of a rock surface and therefore it is extremely difficult to replicate these conditions in a laboratory environment. Black *et al* (2017a) highlighted that the statistical analysis of the study and subsequent conclusions drawn are limited by insufficient replication of each treatment. This study represents a preliminary investigation to understand how rock surfaces may alter when exposed to a range of air pollutants and dust.

Concerns were also raised over the inadequate selection of rock samples – petroglyphs occur on a range of rock types and were produced using a variety of methods. As highlighted by Mulvaney (SECRC, 2018) the fumigation experiments were "conducted on samples from a single gabbro rock with only a thin weathering rind rather than on a range of lithologies known to have rock art (granophyre, dolerite and gabbro), nor on differing surface weathering states" (SECRC, 2018). In addition, iron ore dust was used instead of actual samples of rocks from the Burrup Peninsula. A study by Ramanaidou *et al* (2017) was conducted in 2016 to build on Lau *et al* (2007) study and address these limitations.

4.5.2 Extreme Weathering Experiments

In 2016, the CSIRO commissioned a preliminary experimental weathering study (the Extreme Weathering Study) to explore the effects of solutions of different compositions and concentrations on rock weathering (Ramanaidou *et al* 2017). A total of 126 samples of weathered gabbro and granophyre were collected from the original seven sites used for the colour contrast monitoring program (Duffy *et al* 2017) and tested through exposure to industrial pollutants including nitric acid, sulphuric acid, ammonia, and ammonium nitrate (Ramanaidou *et al* 2017). Distilled water was also used as a control. The chemical composition and pH of the solutions were monitored and changes to the rock surface before and after exposure was quantified using a variety of methods including optical and scanning electronic microscopies, photospectrometry and reflectance spectroscopy.

4.5.2.1 Key Findings

The extreme weathering study by Ramanaidou *et al* (2017) was conducted on both of the major rock types that support petroglyphs: granophyre and gabbro. The study concluded that after three days of exposure at 50°C, dissolution of the granophyre started at pH 3.2 (and below) for aluminium, manganese, and iron, and at pH over 11 for aluminium. For the majority of gabbro samples, dissolution started at pH 3 (and below) for aluminium, manganese, and iron, and at pH over 11 for aluminium (Ramanaidou *et al* 2017). Dissolution of these components in laboratory conditions requires quite acidic or quite alkaline conditions. For some samples, the acidity of rainwater (pH 5.5) could cause the dissolution of some minerals, in particular manganese. Furthermore, measurements to detect changes to the rock surfaces before and after exposure had experimental challenges whereby variations in the monitoring methods (microscopy, spectrometry/spectroscopy), were observed to be often higher than the effect of the change to the rock surface (Ramanaidou *et al* 2017).

4.5.2.2 Discussion

Clearly at very high levels of acidity in the laboratory, minerals within the Murujuga rocks can dissolve. However, the relevance of these experiments to the field conditions remain unclear. As mentioned above, some samples showed dissolution of manganese in solutions at neutral pH (7). Ramanaidou *et al* (2017) suggested that these are unexpected results as it would indicate under rainwater (pH 5.5) conditions, manganese would be dissolved from the surface of the weathered rocks in the field, which is not the case given the longevity of the resident rocks on Murujuga.

The study highlights a novel sample preparation method to determine the potential effects of solutions on key elements of rock weathering. As the authors acknowledge, it is a valuable scoping study to target future work and was not intended to describe permissible pollution levels on the Murujuga (Ramanaidou *et al* 2017). As the authors suggest future studies need to use a larger number of samples (Ramanaidou *et al* 2017) and potentially with a broader range of pH treatments. In addition, Ramanaidou *et al* (2017) recommended that future monitoring programs should include measurements of surface pH on gabbro and granophyre rock types on Murujuga.

4.6 Rock Surface Acidity (pH Studies)

A number of studies (Bednarik, 2002; 2007; MacLeod, 2005; Black *et al* 2017) have investigated how the pH (acidity) of the rock surface can potentially alter the rock patina mineralogy (particularly with the mobilisation of iron and manganese compounds). Theoretically, acidic emissions (namely NO_x and SO_x) from industrial and shipping activities on the Burrup Peninsula can decrease pH of nearby rock surfaces on Murujuga through deposition and/or organic acids from nitrate stimulated microbial growth, in turn degrading the mineral composition, integrity and colour of the rock varnish (Black *et al* 2017).

4.6.1 Key Findings

Comparison of samples of "wash water" (using distilled water) from in situ rocks at the Burrup Peninsula compared to those housed within the WA Museum's collection indicated a decrease in pH on the Burrup rocks since industrialisation of the Burrup Peninsula (MacLeod, 2005; Black *et al* 2017b). It is assumed that rock samples at the museum have a surface pH that has not change with 40 years of storage over two museum storage sites.

Black *et al* (2017b) suggested:

+ pH is lower on rock surfaces currently on Murujuga compared to those stored at the WA Museum for the last 40 years
+ pH is variable across rock surfaces of Murujuga (however the spatial and temporal pattern of this variability is unknown)
+ there is a relationship between pH and the concentration of iron and manganese ions on rock surfaces
+ pH changes are theorised to make the rock surfaces lighter, redder and more white/yellow in colour over time. The changes are expected to be greater on engravings than on background rock because the rock varnish will be more recent and thinner on the engravings.

Black *et al* (2017b) theoretical evaluation suggested that pH and microbial activity are deteriorating Murujuga rock surfaces. However, no data was presented to link industrial air emission or subsequent deposition to changes in pH on Murujuga rock surfaces.

4.6.2 Discussion

The theoretical evaluation presented by Black *et al* (2017b) suggests that pH and microbial activity have the potential to accelerate the deterioration of Murujuga rock surfaces. However, no data is presented to link industrial air emissions and/or subsequent deposition to changes in pH on Murujuga rock surfaces. Future studies require a better statistical understanding of the spatial variability of pH on Murujuga rock surfaces and beyond, and the key physical and biological drivers of this variability (both natural and anthropogenic). Moving forward, the Murujuga Rock Art Strategy seeks to understand pH variability on Murujuga rock surfaces and its drivers.

4.7 Microbial Diversity on Rock Surfaces

It is thought that the natural rock weathering process over time may be influenced by the activity of microorganisms (such as bacteria, archaea and fungi) on the rock surface (MacLeod 2005; O'Hara 2008). Research indicates that microorganisms may be instrumental in setting off chemical processes that weather rocks into soil (EMSL, 2012).

The BRAMMC established a program to investigate whether rock surfaces closer to industrial emissions sources hosted different microbial communities as a potential impact pathway for industrial emissions to accelerate weathering of the rock surface, degrading the colour of the petroglyphs (O'Hara, 2008). The microbial diversity study assessed microbiological differences at seven petroglyph sites on Murujuga (five close to the industrial area, and two distant from it) over a four-year period from 2004 to 2008 (O'Hara, 2008).

4.7.1 Key Findings

The key findings of the microbial diversity study were that all monitored sites had very low populations of bacteria, with similar types of bacteria and low numbers of fungi across all seven sites. Based on these findings, the study concluded that there were "no evident differences in the gross number and broad diversity of microorganisms associated with samples collected from sites close to and distant from industrial emissions on the Burrup Peninsula" (O'Hara, 2008).

4.7.2 Discussion

There was no evidence of any relationship between the presence of microorganisms and site proximity to sources of industrial emissions. The Murujuga Rock Art Strategy seeks to undertake monitoring program to support the Environmental Quality Management framework and may include a microbiological component (DWER, 2019c).

4.8 Colour Change & Spectral Mineralogy Monitoring

The CSIRO conducted annual monitoring the surface colour and mineralogy of the Murujuga rock art from 2004 – 2016, with Yara Pilbara Nitrates Pty Ltd independently continuing a modified version of the program in proximity to their facilities from 2017 onwards with independent experts and MAC.

To understand potential changes to colour on petroglyphs on Murujuga, the CSIRO produced a series of reports analysing the colour of petroglyphs at seven sites including:

+ Five sites close to the industrial area on Murujuga, and
+ Two control sites located to the north of the industrial area on Murujuga (Duffy *et al* 2017).

Annual monitoring reports for each year can be found on DWER's website (DWER Murujuga Rock Art Monitoring Program). The analysis included colour measurement of the petroglyphs using spectrophotometric cameras, and spectral mineralogy analysis using an Analytical Spectral Device (ASD) (Duffy *et al* 2017). Colour was repeatedly assessed at multiple petroglyphs both across the years (since 2004) and within each sampling event in L*a*b* format; where 'L' measures lightness, 'a' measures degree of red/green, and 'b' measures the degree of blue/yellow.

4.8.1 Key Findings

The DAA (2016) conducted an independent review of the CSIRO 2015 monitoring report and identified several shortcomings in both the data collected and its subsequent statistical analysis. In response, CSIRO formally withdrew its 2015 monitoring report and reanalysed colour data; reissued in 2017 (Duffy *et al* 2017).

This reassessment was across the entirety of the 12 years available and released in the report 'Burrup Peninsula Aboriginal Petroglyphs: Colour Changes and Spectral Mineralogy 2004 – 2016' (Duffy *et al* 2017). Duffy *et al* (2017) report concluded "Petroglyph lightness monitoring data from the 'KM spectrophotometer' used, showed a decreasing modelled average rate of 0.31 units per year (a total decrease of about 2 units on this scale is just noticeable to the human eye)". However, no colour change in the degree of red/green nor the degree of blue/yellow was established across the years of the study (Duffy *et al* 2017). Duffy *et al* (2017) highlighted the change in lightness indicated by the data is inconclusive, on the basis that true colour change would be expected to affect all three of the colour measurement parameters. It was noted that none of the three spectrophotometers used showed any difference in the rate of change between the northern sites (remote from industry) and the southern sites (close to industry) (Duffy *et al* 2017). The report recommended that future observations could continue to mark out the possible trend more clearly, or, observations will likely continue to fluctuate over time, making the randomness of the recorded variation more apparent (Duffy *et al* 2017).

4.8.2 Discussion

Up until 2016, the CSIRO was comparing the colour measurements year-to-year, only comparing the current year's data with the data from the previous year (SECRC, 2018). Black and Diffey (2016) re-analysed the CSIRO data, and concluded that there were significant changes to the petroglyphs of Murujuga over the time of the CSIRO studies (Black and Diffey, 2016).

Following the production of the paper by Black and Diffey (2016), the WA Government requested that Data Analysis Australia (DAA) conduct an independent review of the CSIRO data. The report by DAA (2016) agreed with the statistical analysis methods used by Black and Diffey, concluding that the “statistical methods in the draft paper are highly appropriate (with some minor modifications) and they represent a substantial step forward in effective monitoring of the Burrup Peninsula rock art sites” (DAA 2016).

Over the years of the colour change study, different instruments were used (usually when instruments reached the end of their operational life span), and DAA identified “significant problems of cross-calibration between instruments, inconsistent error-prone data management, and clear errors in the data” (DAA 2016).

In response to the report by Black and Diffey (2016) and the findings by DAA (2016), Duffy *et al* (2017) concluded that if a true colour change was occurring, changes in the degree of red/green and/or the degree of blue/yellow would be expected to accompany the changes to lightness, and the results are currently inconclusive.

The CSIRO also concluded that while issues with cross-calibration and error-prone data management have not been able to be completely resolved, none of the three spectrophotometers used showed any difference in the rate of change between the northern sites (remote from industry) and the southern sites (close to industry) (Duffy *et al* 2017).

While criticism exist for these programs (Black and Diffey, 2016; SECRC, 2018), the longitudinal dataset is globally unique and provides useful baseline to inform future research. Recommendations that the addition of complimentary, non-invasive analytical techniques such as portable X-Ray Diffractometry and/or portable X-Ray Fluorescence Spectrometry, may prove useful in better understanding the natural geological weathering processes (SECRC, 2018).

5. FUTURE MONITORING

5.1 Murujuga Rock Art Strategy

As acknowledged by DWER (2019c), the integrity and condition of the Murujuga rock art is influenced by complex interactions of a range of extrinsic ('environmental') and intrinsic (characteristics of the rock and the petroglyph, including its weathering history) factors over different temporal and spatial scales. Due to the dynamic, non-linear nature of rock weathering processes, it is extremely challenging to identify definitive casual links between changes in environmental quality (including from industrial emissions) and the accelerated weathering/alteration/degradation of the rock art.

In February 2019 DWER released the final Murujuga Rock Art Strategy to guide future monitoring and management of the Murujuga Rock Art (DWER, 2019a). The Murujuga Rock Art strategy identified that:

+ "There are currently no existing or default guideline 'trigger values' for protecting the rock art from anthropogenic emissions that could be used as criteria."
+ There are also very few examples in the scientific literature where limits of 'acceptable' change have been identified that could be used to protect materials of cultural heritage." (DWER, 2019a)

As outlined by DWER (2019a) the strategy 'builds on the previous work on Murujuga to deliver a scientifically rigorous approach to monitoring, analysis and management that will provide an appropriate level of protection to the rock art".

The implementation of the strategy will be primarily managed through DWER and in partnership with MAC. The Murujuga Stakeholder Reference Group will enable effective consultation with stakeholders including industry, scientific organisations and the community.

The Murujuga Rock Art Strategy (DWER, 2019a) includes the following five scopes:

1. Establish an Environmental Quality Management Framework, including the derivation and implementation of environmental quality criteria (Murujuga Environmental Quality Management Framework (DWER, 2019b)).
2. Develop and implement a robust program for monitoring and analysis to determine whether change is occurring to the Murujuga Rock Art (Murujuga Rock Art Monitoring Program (DWER, 2019c)).
3. Identify and commission scientific studies to support the implementation of the monitoring and analysis program and management.
4. Establish governance arrangements to ensure that:
   + Monitoring, analysis and reporting are undertaken in such a way as to provide confidence to the Traditional Owners, the community, industry, scientists and other stakeholders about the integrity, robustness, repeatability and reliability of the monitoring data and results; and
   + Government is provided with accurate and appropriate recommendations regarding the protection of the rock art, consistent with legislative responsibilities.
5. Develop and implement a communication strategy in consultation with stakeholders (Murujuga Stakeholder Reference Group).

5.2 Murujuga Rock Art Environmental Quality Management Framework

In March 2019 the DWER released the Murujuga Rock Art: Environmental Quality Management Framework (EQMF) to establish "long-term management and monitoring to protect the rock art (petroglyphs) on Murujuga from the impacts of anthropogenic emissions" (DWER, 2019b). DWER intends that the EQMF will "provide a transparent, risk-based and adaptive framework for monitoring and managing environmental quality to protect the rock art on Murujuga from anthropogenic emissions" (DWER, 2019b).

The elements of the structural and conceptual framework behind the EQMF to protect the Murujuga Rock Art can be found in the DWER website (see DWER 2019 Murujuga Rock Art Draft EQMF).

5.3 Murujuga Rock Art Research and Monitoring Program

A fundamental part of the Murujuga Rock Art Strategy and the EMFQ, is the implementation of a program to monitor, evaluate and report on changes and trends in the integrity of the rock art and specifically to determine whether anthropogenic emissions are accelerating the natural weathering of the Murujuga rock art. The development and implementation of the monitoring program will be informed by the findings and lessons from the past 15 years of scientific studies and monitoring of the rock art on Murujuga, as well as information available in the scientific literature. A staged approach is proposed, including focused monitoring studies to inform the design of the program and the development of the EQMF.

The objectives of the monitoring program are to:

+ obtain data for comparison against the environmental quality criteria to ascertain whether the environmental quality objective is being achieved and the environmental value (Murujuga Rock Art) protected;
+ provide the WA government, MAC, industry and the community with robust, replicable and reliable information on the changes and trends in the integrity or condition of the Murujuga rock art;
+ ensure decisions regarding the protection of the Murujuga rock art are based on the best available science; and
+ inform the evaluation of the effectiveness of any measures taken to mitigate adverse effects on the rock art, including efforts to protect the rock art.

An independent review of the monitoring program will be conducted at least every five years. These reviews will address matters such as experimental design and effectiveness, whether best practice methodologies and techniques are being implemented, changes in environmental risks and any relevant emerging environmental issues

6. CONCLUSIONS

Over the past 15 years, numerous studies have been conducted to investigate the potential for industrial emissions from new and existing industrial development on the Burrup Peninsula to impact on the Murujuga rock art. It is recognised that whilst there is anecdotal evidence and stakeholder concerns that observable changes may have occurred, no published peer reviewed studies have identified measurable or observable changes to rock art as a result of industrial emissions to date.

Criticisms have been raised over the design, data collection and statistical analysis elements of some of the previous monitoring programs and studies, and therefore it is acknowledged that uncertainties exist regarding techniques for monitoring and detecting change (both natural weathering rate, and potential for accelerated weathering) and the determination of a critical load of acid deposition at which impacts to rock art may occur. Notwithstanding these criticisms the studies remain the most comprehensive large-scale investigation into the potential for industrial emissions to impact rock art.

To resolve these issues, it has been recommended by the State Government and DWER that an independent integrated monitoring program should be developed based upon well-established principles of experimental design to ensure robust reliable results are provided to inform management and decision making (DWER, 2019a). The Murujuga Rock Art Strategy will look to use existing data to form the basis of an independent world best practice rock art monitoring program to monitor, evaluate and report on changes and trends in the integrity or condition of the Murujuga rock art.

7. REFERENCES

Australian Heritage Council (AHC) 2011. *The potential outstanding universal value of the Dampier Archipelago site and threats to that site.* Unpublished report prepared for the Australian Goverment. Available from: https://www.environment.gov.au/system/files/pages/5b14f51b-b7e1-432f-8049-1e653713607d/files/outstanding-universal-values-may2012.pdf [Accessed May 2019]

Bednarik, R 2002. The survival of the Murujuga (Burrup) petroglyphs. *Rock Art Research*, vol.19, no.1, pp. 29-40.

Bednarik, R 2007. The science of Dampier rock art – part 1. *Rock Art Research*, vol. 24, no. 2, pp. 209-246.

Bird, C and Hallam, S 2006. *Archaeology and rock art in the Dampier Archipelago*. Unpublished report prepared for the National Trust of Australia (WA). Available from: https://www.nationaltrust.org.au/wp-content/uploads/2017/01/20060920-Dampier-Rock-Art-ROE35.pdf [Accessed May 2019]

Black, JL and Diffey, S 2016. *Reanalysis of the Colour and Mineralogy Changes from 2004–2014 on Burrup Peninsula Rock Art Sites*. Unpublished report. Available from: https://www.der.wa.gov.au/images/documents/our-work/consultation/Burrup-Rock-Art/Reanalysis-of-the-CSIRO-2014-Report.pdf [Accessed May 2019]

Black, JL, Box, I and Diffey, S 2017a. Inadequacies of research used to monitor change to rock art and regulate industry on Murujuga ('Burrup Peninsula'), Australia. *Rock Art Research*. vol. 34, no. 2, pp. 130-148

Black, JL, MacLeod, ID and Smith, BW 2017b. Theoretical effects of industrial emissions on colour change at rock art sites on Burrup Peninsula, Western Australia. *Journal of Archaeological Science: Reports*, vol. 12, pp. 457-462

Burrup Rock Art Monitoring Management Committee (BRAMMC) 2009. *Report and Recommendations to the Minister for State Development*. Report for the Government of Western Australia, Perth WA. Available from: http://pandora.nla.gov.au/pan/103684/20090805-1626/www.dsd.wa.gov.au/documents/090115_Burrup_Rock_Report_(1).pdf [Accessed May 2019]

Burrup Rock Art Working Group (BRAWG) 2015. *5 Year Review Draft*. Unpublished Report. Report prepared for Government of Western Australia, Perth WA.

Cinderby, S, Cambridge, HM, Hererra, R, Hicks, WK, Kuylenstierna, J, Murray, F and Olbrich, K 1998, *Global assessment of terrestrial ecosystem sensitivity to acidic deposition*, Stockholm Environment Institute Edition. Available from: https://www.researchgate.net/publication/265925445_Global_Assessment_of_Terrestrial_Ecosystem_Sensitivity_to_Acidic_Deposition

Data Analysis Australia (DAA) 2016. *Review of Statistical Aspects of Burrup Peninsula Rock Art Monitoring*. Report prepared for the Department of Environment Regulation, Government of Western Australia, Perth WA. Available from: https://www.der.wa.gov.au/images/documents/our-work/consultation/Burrup-Rock-Art/DAA--independent-review-report---Nov-2016.pdf [Accessed May 2019]

Data Analysis Australia (DAA) 2017. *Review of CSIRO report on Burrup Peninsula rock art monitoring*. Report prepared for the Department of Water and Environment Regulation, Government of Western Australia, Perth WA. Available from: https://www.der.wa.gov.au/images/documents/our-work/consultation/Burrup-Rock-Art/DAA-independent-review-report---May-2017.pdf [Accessed May 2019]

Department of Environment (DoE) 2004. *Pilbara Air Quality Study Summary Report*. Air Quality Management Branch, Department of Environment, Government of Western Australia, Perth WA. Available from: https://www.der.wa.gov.au/images/documents/your-environment/air/publications/pilbara-air-quality-report-2004.pdf [Accessed May 2019]

Department of Environment and Conservation (DEC) 2013. *Murujuga National Park Management Plan 78*. Department of Environment and Conservation, Bentley WA. Available from: https://www.dpaw.wa.gov.au/images/documents/parks/man agement-plans/decarchive/murujuga-national-park-management-web-final.pdf [Accessed May 2019]

Department of Environment and Energy (DoEE) 2007. *National Heritage Places - Dampier Archipelago (including Burrup Peninsula)*. Department of Environment and Energy, Australian Government, Canberra ACT. Available from: http://www.environment.gov.au/heritage/places/national/dampier-archipelago [Accessed April 2019]

Department of Water and Environmental Regulation (DWER) 2019a. *Murujuga Rock Art Strategy*. Department of Water and Environmental Regulation, Government of Western Australia, Perth WA. Available from: https://www.der.wa.gov.au/images/documents/our-work/programs/burrup/Murujuga_Rock_Art_Strategy.pdf [Accessed May 2019]

Department of Water and Environmental Regulation (DWER) 2019b. *Environmental Quality Management Framework: Murujuga Rock Art*. Department of Water and Environmental Regulation, Government of Western Australia, Perth WA. Available from: https://www.tenders.wa.gov.au/watenders/tender/display/tender-details.do?id=42499&action=display-tender-details&returnUrl=%2Ftender%2Fsearch%2Ftender-search.do%3Faction%3Ddo-advanced-tender-search%26noreset%3Dyes [Accessed July 2019]

Department of Water and Environmental Regulation (DWER) 2019c. *Murujuga Rock Art Monitoring Program: Tender Documentation*. Department of Water and Environmental Regulation, Government of Western Australia, Perth WA. Available from: https://www.tenders.wa.gov.au/watenders/tender/display/tender-details.do?id=42499&action=display-tender-details&returnUrl=%2Ftender%2Fsearch%2Ftender-search.do%3Faction%3Ddo-advanced-tender-search%26noreset%3Dyes [Accessed July 2019]

Donaldson, M 2011, 'Understanding the Rocks: Rock Art and the Geology of Murujuga (Burrup Peninsula)'. *Rock Art Research: The Journal of the Australian Rock Art Research Association*, vol. 28, no. 1, pp. 35-43.

Duffy, N, Ramanaidou, E, Alexander, D and Lau, D 2017. *Burrup Peninsula Aboriginal Petroglyphs: Colour Change and Spectral Mineralogy 2004 – 2016*. Report prepared for CSIRO Mineral Resources, Western Australia. Available from: https://www.der.wa.gov.au/images/documents/our-work/consultation/Burrup-Rock-Art/Burrup-Peninsula-Aboriginal-Petroglyphs-Colour-Change--Spectral-Miner.pdf [Accessed May 2019]

Environmental Molecular Sciences Laboratory (EMSL) 2012. *New data suggest bacteria have a direct effect on rock weathering*. Science X, Isle of Man. Available from: https://phys.org/news/2012-09-bacteria-effect-weathering.html

Gillett, R 2008. *Burrup Peninsula Air Pollution Study: Report for 2004/2005 and 2007/2008*. CSIRO Marine and Atmospheric Research, Report prepared for the Government of Western Australia, Available from: https://web.archive.org/web/20091002135029/http:/www.dsd.wa.gov.au/documents/2008_Burrup_Peninsula_Air_Pollution_Study(1).pdf [Accessed April 2019]

Gillet, R 2010. *Burrup Peninsula Air Pollution Study: Report for 2004/2005, 2007/2008 and 2008/2009*. CSIRO Marine and Atmospheric Research, Report prepared for the Government of Western Australia, Available from: https://www.der.wa.gov.au/images/documents/our-work/programs/burrup/CSIRO%20Burrup%20Peninsula%20air%20pollution%20study.pdf [Accessed August 2019]

Lau, D, Ramanaidou, E, Furman, S, Cole, I, Hughes, T and Hoobin, P 2007. *Final Report: Fumigation and Dust Deposition*. Report prepared for CSIRO Division of Exploration and Mining, Perth WA. Available from: http://web.archive.org/web/20091002111652/http:/www.dsd.wa.gov.au/documents/BI_BurrupRockArtCSIROFieldStudies.pdf [Accessed May 2019]

Lui, T and Broecker, WS 2000. How fast does rock varnish grow?, *Geology*, vol. 28, no. 2, pp. 183-186.

MacLeod, ID 2005. Effects of moisture, micronutrient supplies and microbiological activity on the surface pH of rocks in the Burrup Peninsula. *In 14th Triennial Meeting, The Hague, 12-16 September 2005*, Preprints 2005: pp. 385 - 393.

McDonald, J 2015. I must go down to the seas again: Or, what happens when the sea comes to you? Murujuga rock art as an environmental indicator for Australia's north-west. *Quaternary International*, vol. 385, pp. 124-135.

Mulvaney, K 2011. About time: towards a sequencing of the Dampier Archipelago petroglyphs of the Pilbara region, Western Australia. *Records of the Western Australian Museum Supplement*, vol. 79, pp. 30 – 49.

Mulvaney, K 2015. Burrup Peninsula: Cultural Landscape and Industrial Hub, a 21st Century Conundrum. *Landscape Research*, vol. 40, no. 6, pp. 759-722.

Murujuga Aboriginal Corporation (MAC) 2016. *Murujuga Cultural Management Plan*. Murujuga Corporation, Dampier WA.

O'Hara G 2006. *Monitoring of microbial diversity on rock surfaces on the Burrup Peninsula*. Summary report, School of Biological Sciences and Biotechnology, Murdoch University. Report prepared for the Government of Western Australia. Available from: https://web.archive.org/web/20091002030831/http:/www.dsd.wa.gov.au/documents/BI_BurrupRockArtMicrobialDiversityStudy.doc [Accessed March 2019]

O'Hara, G 2008. *Monitoring of Microbial Diversity on Rock Surfaces of the Burrup Peninsula*. Final Report for the Burrup Rock Art Monitoring Management Committee, School of Biological Sciences and Biotechnology, Murdoch University, Report prepared for the Government of Western Australia. Available from: https://web.archive.org/web/20091002135201/http://www.dsd.wa.gov.au/documents/Microbial_Diversity_on_Rock_Surfaces_-_Sept2008(1).doc [Accessed March 2019]

Pillans, B and Fifield, K 2013. Erosion rates and weathering history of rock surfaces associated with Aboriginal rock art engravings (petroglyphs) on Burrup Peninsula, Western Australia, from cosmogenic nuclide measurements. *Quaternary Science Review*, vol. 69, pp. 98–106.

Ramanaidou, ER and Fonteneau, LC 2019. Rocky relationships: the petroglyphs of the Murujuga (Burrup Peninsula and Dampier Archipelago) in Western Australia. *Australian Journal of Earth Sciences*, vol. 66, no. 5, pp. 671-698.

Ramanaidou, E, Walton, G and Winchester, D 2017. *Extreme Weathering Experiments on the Burrup Peninsula / Murujuga Weathered Gabbros And Granophyres*. Report prepared for CSIRO Mineral Resources, Western Australia. Available from: https://www.der.wa.gov.au/images/documents/our-work/consultation/Burrup-Rock-Art/Extreme-Weathering-Burrup-Report-2017-.pdf [Accessed May 2019]

Senate Environment and Communications References Committee (SECRC) 2018. *Protection of Aboriginal rock art of the Burrup Peninsula*. Report prepared for the Parliament of Australia, Canberra ACT. Available from: https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Environment_and_Communications/BurrupPeninusla/Report [Accessed June 2019]

Sinclair Knight Merz (SKM) 2003. *Burrup rock art: atmospheric modelling – concentrations and depositions*. Report prepared for the Department of Environment and Resources, Government of Western Australia, Perth WA. Available from: https://web.archive.org/web/20091002031556/http:/www.dsd.wa.gov.au/documents/BI_BurrupRockArtAtmosphericModelling.pdf [Accessed July 2019]

Sinclair Knight Merz (SKM) 2006. *Pluto LNG Development Cumulative Air Quality Study*. Report prepared for Woodside Energy Limited, Perth WA. Available from: http://www.epa.wa.gov.au/sites/default/files/PER_documentation/1632-PER-Technical%20Report%20-%20combined.pdf [Accessed May 2019]

Sinclair Knight Merz (SKM) 2009. *Burrup Rock Art: Revised Modelling Taking into Account Recent Monitoring Results*, Final 1. Report prepared for Department of Industry and Resources, Government of Western Australia, Perth WA. Available from: https://web.archive.org/web/20091002135300/http:/www.dsd.wa.gov.au/documents/Burrup_Rock_Art-_Revised_Modelling_Jan2009(1).pdf [Accessed July 2019]

Strategen 2018. *Ambient Air Quality Report 2017 – 2018*. Strategen Environmental, Report prepared for Yara Pilbara Nitrates, Perth WA. Available from: https://www.yara.com.au/siteassets/about-yara/reports/air-quality-monitoring-reports/650-200-rep-sec-0004.pdf [Accessed July 2019]

Vinnicombe, P 2002. Petroglyphs of the Dampier Archipelago: Background to Development and Descriptive Analysis. *Rock Art Research*, vol. 19, no.1, pp. 3–27.

Woodside 2019. *North West Shelf Project Extension Environmental Review Document*. Woodside Energy Limited, Perth WA. Woodside ID: G2000RF1401194374

Yara Pilbara Nitrates (YPN) 2017. *Yara Pilbara Nitrates, EPBC Approval 2008/4546 Baseline Air Quality Monitoring Report*. Yara Pilbara Nitrates Pty Ltd, Western Australia. Available from: https://www.yara.com.au/siteassets/about-yara/reports/air-quality-monitoring-reports/250-200-rep-ypf-0002.pdf [Accessed July 2019]

8. TERMS

Terms	Definitions
AHC	Australian Heritage Council
ASD	Analytical Spectral Device
BMIEA	Burrup Maitland Industrial Estates Agreement
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
BRAMMC	Burrup Rock Art Monitoring Management Committee
BRATWG	Burrup Rock Art Technical Working Group
C	Celsius
CALM Act	*Conservation and Land Management Act 1984 (WA)*
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAA	Data Analysis Australia
DBCA	Western Australian Department of Biodiversity, Conservation and Attractions
DSD	Western Australian Department of State Development
DEC	Department of Environment and Conservation
DER	Western Australian Department of Environmental Regulation
DoEE	Commonwealth Department of Environment and Energy
DWER	Western Australian Department of Water and Environmental Regulation
EPA	Western Australian Environmental Protection Authority
EP Act	*Environmental Protection Act 1986* (WA)
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999* (Commonwealth)
EQMP	Environmental Quality Management Framework
Gabbro	Igneous rock formed from the slow cooling of magnesium-rich and iron-rich magma into a holocrystalline mass deep beneath the Earth's surface
Granophyre	Subvolcanic rock that contains quartz and alkali feldspar in characteristic angular intergrowths
HNO_3	Nitric acid
LNG	Liquefied Natural Gas
m^{-2} yr^{-1}	Square metres per year
MAC	Murujuga Aboriginal Corporation
meq	Milliequivalent
Murujuga	Traditional name for the Burrup Peninsula and surrounding islands of the Dampier Archipelago.
National Heritage Place	National Heritage Place – Dampier Archipelago (including Burrup Peninsula)
Ngarda-Ngarli	Collective term for Aboriginal people of the Murujuga area
NEPM	National Environment Protection Measures
NH_3	Ammonia
NO_X	Oxides of nitrogen
NO_2	Nitrogen dioxide
NWS	North West Shelf

Terms	Definitions
NWS Project Extension Proposal	The Proposal as described in the NWS Project Extension **Section 38** Referral Supporting Information (November 2018) to continue to use the existing NWS Project facilities for the long-term processing of third-party gas and fluids and NWSJV field resources through the NWS Project facilities; and Ongoing operation of the NWS Project to enable long-term processing at the NWS Project facilities, currently expected to be until around 2070.
PAQS	Pilbara Air Quality Study
pH	Measure of acidity or basicity of a solution
PM	Particulate matter
ppb	Parts per billion
SECRC	Senate Environment and Communications References Committee
SO_2	Sulphur dioxide
SO_x	Oxides of sulphur
TAN Plant	Yara Pilbara Nitrates Pty Ltd Technical Ammonium Nitrate Plant
TSP	Total suspended particles
WA	Western Australia
Woodside	Woodside Energy Ltd