Government of **Western Australia**
Department of **Water and Environmental Regulation**

Murujuga Rock Art Monitoring Program: Independent Peer reviews of Monitoring Studies Data Collection and Analysis Plan

Department of Water and Environmental Regulation
and Murujuga Aboriginal Corporation
April 2022

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Acknowledgements

The Department of Water and Environmental Regulation recognises the Traditional Owners and Custodians of Murujuga; the past, present and future generations of Ngarda-Ngarli, and their ongoing connection to this sacred country. All aspects of the program will be conducted with respect for, and be guided by, the cultural law, knowledge and practices of the Circle of Elders, Traditional Owners and Custodians of Murujuga.

This document has been jointly approved by the Murujuga Aboriginal Corporation and the Department of Water and Environmental Regulation, who jointly oversee the implementation of the Murujuga Rock Art Strategy.

Contents

1 Background

The Murujuga Rock Art Monitoring Program will monitor, evaluate and report on changes and trends in the integrity or condition of the rock art and determine whether the rock art is being subject to accelerated change; specifically, whether anthropogenic emissions are accelerating the natural weathering / alteration / degradation of the rock art. The monitoring program will underpin the Environmental Quality Management Framework (EQMF) for managing environmental quality to protect the rock art on Murujuga. This will enable timely and appropriate management responses by the Western Australian Government and stakeholders to emerging issues and risks.

In June 2021, Calibre Group was appointed to continue the development and implementation of the monitoring program. Calibre is working with technical experts from Curtin University, ArtCare and ChemCentre to deliver the program.

Reports and documents produced as part of the monitoring program are subject to independent peer review by experts of national and international reputation in relevant fields.

The Department, in consultation with MAC, engaged six peer reviewers to undertake the independent peer reviews of the Monitoring Studies Data Collection and Analysis Plan. The peer reviews were undertaken in a staged process commencing in October 2020 with the proposed Detailed Study Design (referred to in the peer reviews as Part A). Following further refinement of the proposed studies and selection of sites, the Detailed Study Design was updated, and peer reviewers undertook a second round of reviews of the full Monitoring Studies Data Collection and Analysis Plan (combined Part A and B document) prior to providing their close out report in January 2022.

This document collates all peer reviews undertaken for the *Murujuga Rock Art Monitoring Program: Monitoring Studies Data Collection and Analysis Plan* (April 2022). Readers are encouraged to refer to this plan for the final monitoring studies design. The department has not edited the content of reviews other than to correct minor errors and therefore references to page numbers and sections may have changed in the final plan.

2 Rock art

2.1 Dr Jillian Huntley – Statement of Advice and Review comments sheet for Detailed Study Design (Part A)

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27 October 2020

Government of Western Australia
Department of Water and Environment Regulation
Reference Number: DWERT5321

Attention: Naomi O'Hara
Senior Environmental Officer Policy
Environmental Policy
Locked Bag 10 Joondalup DC
Perth WA 6919

Via email: <murujugarockart@dwer.wa.gov.au>

Dear Ms O'Hara

Re: PART A, Peer Review of Monitoring Studies Data Collection and Analysis Plan (Part A and B) (Murujuga Rock Art Monitoring Program)

In this statement of advice I provide a peer review of the first stage of a five year program continuing the Murujuga Rock Art Monitoring Program (MRAMP). A significant body of research and environmental monitoring has been conducted, especially since 2004, to determine if anthropogenic emissions are accelerating natural weathering processes affecting the petroglyphs (engraved and abraded rock art assemblage) and surrounding rock surfaces of Murujuga (the Burrup Peninsula). The proposed five year program has been designed to assess, monitor and manage remaining uncertainty over the levels of anthropogenic emissions that would accelerate weathering of the rock art, and to consider how anthropogenic input could accelerate agents of deterioration.

My advice assesses and fosters improvement of the scientific and technical methodology, clarify the evidence base, criteria, assumptions, extrapolations, inferences and interpretations made by the contractor Puliyapang, a registered Aboriginal business and joint venture between Calibre Ventures Pty Ltd and Tocomwall Pty Ltd, partnering with subject matter experts from Curtin University, Artcare and the ChemCentre (hereafter Puliyapang).

I would like to begin by congratulating Puliyapang for assembling a highly qualified team with requisite expertise in the multidisciplinary approaches required to achieve the aims of their commission (as outlined in DWER 2019a, 2019b). I endorse the underlying principle of the MRAMP, taken from s.3A of the *EPBC Act 1999*, that "if there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation". I commend DWER's implementation of rigorous oversight of the

MRAMP through expert peer review by the Murujuga Aboriginal Corporation (MAC), Murujuga Rock Art Stakeholder Reference Group and discipline specialists.

CONCEPTUAL MODEL

The objectives of the overarching and sub-conceptual models are to develop a framework to communicate current understandings of the Murujuga rock art system to a lay audience, as well as demonstrate links to the MRAMP and; show how the results from the program will underpin the Environmental Quality Management Framework described by DWER, 2019b. The Conceptual Models presented by Puliyapang acquit these criteria. The team is to be congratulated for developing thoughtful, interconnected frameworks and for their approach of collective design, which will only serve to enhance collaborations by their individual specialists, benefiting the MRAMP going forward. The introduction to the conceptual modelling makes clear that these are adaptable and will be revised as new information about the Murujuga rock art system is acquired as a part of the detailed studies and data collection in the MRAMP.

I see no major elements in the Conceptual Model that require revision, noting Puliyapang have clearly stated the critical caveat that: "While the Pilot Study is likely to increase our knowledge of many aspects of the system, it is important to note that the aim is not to develop a model that captures the complexity of the entire system, but one that underpins a feasible management system." I do, however, provide the following specific feedback on the Conceptual Model to Puliyapang for their consideration.

Element One: Pressure-Response Model and Narrative

The model narrative does not specifically talk about human-accelerated climate change which appears to be an important oversight. While increased local pollution is mentioned, the specific consideration of increasing global temperatures, and more frequent and severe weather events from global green-house gas emissions have serious implications for the acceleration of rock art weathering. That is to say that stress in the global scale environmental system **will change** 'natural' weather patterns and weathering catalysts, especially sunlight and moisture, in the local Murujuga rock art system, which is in turn being stressed by local anthropogenic activities (industry, tourism, shipping and associated pollution).

The pressure response narrative shows a deep understanding by the Puliyapang team of the complex processes of rock art degradation/preservation. While this is plainly written, I heartily agree that this output should be tested by a non-specialist audience to assess clarity of communication (p.4).

Element Two: Sub-Conceptual Models

These elements are designed to provide detailed (technical information) about the variables, processes and interactions. The use of example questions to illustrate the reasons for investigating, measuring and monitoring the variables contributing to the condition of the rock art works very well. Where a sub-conceptual model is not addressed below, I have no suggestions for consideration.

Processes on Rock Surface

The sample questions refer to natural weather conditions. As previously stated, Puliyapang may wish to clarify that natural conditions (especially evaporation rates and dew points) are likely to change in the short and medium terms as a result of human-induced, green-house gas climate forcing (see details in the review of the Detailed Study Design to follow).

DETAILED STUDY DESIGN

Puliyapang present a well-reasoned program that identifies and thoughtfully designs mechanisms to establish the baseline condition of the engravings and the complex environmental drivers of rock art weathering on Murujuga. Potential natural and anthropogenic agents of rock art deterioration, and their potential for interaction, are well understood by the team. The multidisciplinary expertise assembled by Puliyapang cover the diverse array of specialist fields and analyses that are needed to establish the baseline condition of the rock art and monitor it for change going forward.

I recommend that the following three issues **must be addressed** prior to finalisation of the Detailed Study Design[1]:

1) It is difficult to judge the efficacy of the sampling strategy with no information regarding the database of rock art sites/motifs that will underpin it. Section 2.2.1 tabulates the data collected in previous studies upon which Puliyapang's spectrophotometry program will be based. I strongly suggest a table be added that explicates the sources and limitations of previous (and ongoing) rock art data, carefully evaluating effective survey coverage.

The strategy for sample selection and monitoring locations should be strengthened to ensure a representative sample of the chronological variation in the Murujuga petroglyph assemblage. At present, it is unclear how the modelling scenarios that will generate a randomised, statistically robust geographic sample (monitoring locations and laboratory sample sites) will account for temporal variation across the five identified chronological phases of art production (Mulvaney 2013). Human occupation of Murujuga began at least 21,000 years ago (McDonald et al. 2018) with every reason to think people were marking their landscape from the time they arrived. While direct dating with scientific techniques is yet to be successfully undertaken on Murujuga's rock art[2], detailed research on the stylistic character, imagery superimposition and subject matter has shown discrete phases of art production likely pre- and post-date the flooding of the flooding of the coastal plain to form the archipelago that exists today (Mulvaney 2015). There is, therefore, chronological variation within the engraved rock art of at least thousands of years, and possibly tens of thousands of years, with some geometric elements such as circles, arcs and ovals that are less well constrained chronologically (i.e. that appear to occur throughout the phases) (Mulvaney 2013, 2015). There are obvious implications for variation in the formation of patinas over the engraved surfaces and the mineral accretions, patinas and microbiome associated with rock

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[1] I note that the issues outlined herein may be partially or fully addressed by Part B of the MRAMP (Determination of Optimal Statistical Design of Study Site Locations and Selection of Locations for Sample Collection) which is yet to be provided for peer review. Nevertheless, clarification should be added to the Detailed Study Design as this document is the foundation for all aspects of the MRAMP that follow.

[2] Noting that a promising large-scale Australian Research Council funded project of this nature is about to begin.

surfaces of varying ages, as well as differences in how the degradation vectors and anthropogenic weathering acceleration will act on surface of different ages (i.e. some rock art may be more venerable than others).

Consideration should also be given to ensuring a representative sample of the diversity of engraving production techniques, i.e. hammered (pecking, pounding, bruising) and abraded (rubbing, incising, scratching) (Mulvaney 2015) and different rock types (Donaldson 2011) that art, accretions and patina are found on are included proportionally (gabbro, granophyre and dolerite, which Puliyapang explicitly state for off-art destructive sampling, p.56). The indicative numbers of samples for the non-invasive and laboratory programs, and the seasonal collection (wet and dry) of data under different climatic conditions biannually are all scientifically appropriate and I am pleased to see primacy for approval of sample locations being given to MAC.

2) **The modelling simulations and sample selection strategies do not appear to consider climate change impacts.** As the main source of, and catalysts for, rock art deterioration are environmental/atmospheric, projections and long-term strategies need to account for conservative increases in global temperatures and predictions for increasingly severe and frequent, extreme weather events. Global warming has already impacted natural and human systems to varying degrees of severity as **greenhouse gas emissions raise global temperatures an average of ~0.2°C** per decade. **Unabated, conservative predictions are for global warming** to 1.5°C above pre-industrial (>1750 AD) levels within decades (i.e. between 2030–2052), with areas of particular climate sensitivity, such as the tropics, set to experience up to 3x higher temperature increases. This trend in higher global temperature accompanies increased frequency and intensity of extreme weather events in the mid-latitudes (i.e. the tropics) where hot days have already increased by ~3°C (IPCC 2018). While I acknowledge that the initial contract awarded to Puliyapang is five years, the program they design needs to underpin much longer term monitoring over decades to come — the period in which global temperature increases, and variations in weather patterns and associated atmospheric conditions **will** occur.

3) **The five year term of Puliyapang commission is not stated in the document.** While it would be implicitly clear to DWER that the design and implementation of the phase of the MRAMP described herein is scheduled over five years, it is my understanding that the Detailed Study Design (and Conceptual Model) will be made publicly available. Clarity should be provided for all stakeholders, and as a matter of public record, that the study design relates to an initial five year period (specifying the start and end dates) with a view to underpinning a continual program of rock art monitoring while industrial development, infrastructure and urban settlement remain active on the Burrup Peninsula. It is important to make the five year term of this foundation program clear as the objective of the baseline rock art condition and monitoring design is the aspiration to hand over the data collection for the MRAMP to the MAC, implemented via the Murujuga Rangers.

I also provide the following specific feedback the Detailed Study Design to Puliyapang for **their consideration**. Where sections of the document are not addressed below, I have no further suggestions.

Section 1. Study Objectives

There is no map illustrating the area over which the MRAMP and detailed studies apply. The document would benefit greatly from clearly defining this at the outset. As with the Muruguga Rock Art Strategy (DWER2019b, their Fig.1) this should include land tenure types and show the location of potential industrial and residential sources of atmospheric pollutants. This would also help the reader to understand the relationship with detailed Figures 3-5 and 3-21.

Section 2. Evaluation of Previous Studies and Data

The evaluation of previous data is comprehensive and well supported. It identifies the limitations and utility of previous data that will be used by Puliyapang going forward. It is clear that they understand sources of variation and error and the inter-relationships between different analyses that will be deployed.

The textual surface data (Section 2.2.2) is an important addition by Puliyapang for the early identification of changes to rock surfaces, especially in petroglyphs. Also important is the fact that they clearly understanding that the use of 'control' sites within the MRAMP would be a misnomer (Section 3.1.4).

Section 3. Proposed Study Design

The local topography of Murujuga, especially the void spaces within hills composed of bedrock blocks, are likely to affect key detailed studies. I appreciate the practical sampling constraints that will be faced (Section 3.1.2). Row 4 in Table 3-1 shows that Puliyapang are aware of the differential exposure of rock surfaces to deterioration vectors and I presume this will be further elaborated on in PART B of the MRAMP. I note that the Laser Scanning outlined in Section 3.2.2 addresses this in part (referring specifically to gorge topography), but I wonder what the implantations might be for other detailed studies? For instance, could the void spaces in hills act as reservoirs for volatile organic compounds (VOCs)?

Data capture for spectral colour outside of the visible wave lengths (i.e. 300–900 nm) is excellent (Section 3.2.3i). Measuring colour and elemental composition (in situ XRF) on the same surfaces and across rock faces is an effective and informative means of disentangling the processes indicated by these methods. In situ elemental analyses (though much lower in resolution) will provide greater spatial coverage and can also be used to interpret the results of the detailed laboratory methods (Section 3.2.3ii). The detailed recording and quantification of micromorphological changes will be imperative for understanding agents of deterioration at a micro-scale. The capture of seasonal micromorphological data is an excellent mechanism for understanding and quantifying incremental erosion (Section 3.2.3iii).

Again, while I appreciate the practical sampling constraints that will be faced (Section 3.1.2), especially regarding the cultural sensitivity of the Murujuga cultural landscape, it will be critical that the comparability of environmental conditions for rock art and distant unmodified rock surfaces sampled for laboratory analyses is demonstrated in the detailed modelling conducted (Section 3.3.2).

The laboratory program described is exemplary (Section 3.3.3vii–x). The addition of extremely high resolution techniques such as ion mass spectroscopy, transmission electron microscopy and atom probe tomography are novel in Australian conservation science, particularly rock art studies, as are the thermodynamic calculations and synthesis studies, and the chamber experiments. These are likely to produce a new detailed understanding of the mechanisms of weathering (which will be of international interest and impact) and yield useful insights for early detection of impacts.

Rather than relying heavily on a single method of detection for rock surface change Puliyapang have built in complementary data and they clearly understand each of the change detection mechanisms they are measuring.

Figure 3-21 is very small and therefore difficult to interpret. I suggest enlarging it.

Separation of rock samples into strata for chemical preparations is imperative and I am glad to see Puliyapang will strive for this (patina, weathered rind and fresh rock, Section 3.3.4), and that they will deploy column chemistry to separate out organic compounds.

The air quality modelling, sampling strategy and source identification strategy outlined are also exemplary (Section 3.4). The collection of both wet and dry deposition, and gas samples should provide comprehensive coverage to ensure the emissions and pollutants present at Murujuga are characterised. I am pleased to see the team will design a bespoke deposition sampler in order to collect exactly what is required for the MRAMP. Again, I wonder if some topographic and micro-topography landscape features, including the void spaces in hills housing rock engravings, could act to trap emissions and pollutants, especially VOCs? I am therefore pleased to see that the sampling locations will be decided by the whole team so that the complexity encompassed in the Murujuga rock art system can be captured in the MRAMP. I wonder if the impacts of topography can be accounted for in the CFD modelling (Section 3.5)?

The practicalities of emplacing the air quality monitoring and weather station equipment are well thought through and I am satisfied that locations as close as practical to the sample sites identified in the computational fluid dynamic modelling will be used – giving primacy to not adversely impacting rock art (Section 3.4.1vii). Attention to detail in the sampling program, including the transport and chain of custody and sensor calibration, is impressive. The develop isotope "fingerprints" for key carbonaceous emissions through experimental work that will underpin the source apportionment studies is excellent. Constrains on the availability of the 'AirBox' are well managed by selectively deploying it at the height of the wet and dry seasons to capture maximum variation on weather conditions on Murujuga (Section 3.4.2ii).

While data from a dispersion modelling study of the Burrup Peninsula commissioned by DWER is planned to be used as the primary data for emissions used in the CFD simulations, I am pleased to see that Puliyapang have identified contingency data sources from recent air quality impact assessments required as part of industry compliance (Section 3.5.2.1). I am also relived to see that Puliyapang have requested 1 m resolution topographic data from Landgate released June 2020 and that this will be augmented by data the team collect during their own morphological study (Section 3.5.2.3).

The data hygiene, creation and archiving described in Section 4 (and Section 3.2.3v–viii) are comprehensive and appropriate. I was pleased to see mechanisms for data to be made available upon request are built into the framework.

I congratulate Puliyapang for producing comprehensive conceptual frameworks and detailed study designs that will yield critical information about the current condition of Murujuga's rock art, catalysts of environmental and anthropogenic deterioration and mechanisms for analysing and monitoring these. I look forward to receiving Puliyapang's response to this peer review.

Sincerely

Dr Jillian A. Huntley

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DWER 2019b Murujuga Rock Art: Environmental Quality Management Framework, Department of Water and Environmental Regulation: Perth, Western Australia.

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McDonald, J., W. Reynen, K. Ditchfield, J. Dortch, M. Leopold, B. Stephenson, T. Whitley, I. Ward and P. Veth 2018 Murujuga rockshelter: First evidence for Pleistocene occupation on the Burrup Peninsula. *Quaternary Science Reviews* 193:266–287.

Mulvaney, K. 2013 Iconic imagery: Pleistocene rock art development across northern Australia. *Quaternary International* 285:99–110.

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Puliyapang 2020b Murujuga Rock Art Project: Draft Detailed Study Design, Puliyapang Ref.: PYPP19001, Curtin Ref.: RES-HS-SPH-BM-62312. Unpublished confidential report prepared for DWER.

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet –
Huntley, Wallis Heritage Consulting

Reviewer: Dr Jillian Huntley with quality assurance/internal review by Associate Professor Lynley Wallis	
Document Title: Murujuga Rock Art Monitoring Project: Detailed Study Design and Conceptual Model – PART A	
Document Revision: Version 1 (July 2020); Version 1.1 Murujuga Rock Art Monitoring Program: Monitoring Studies Data Collection and Analysis Plan, Part A January 2021 (clarification provided 5 February 2021)	
Date of Review: 27 October 2020; Date of Close Out Report 17 February 2021	

Item No.	Section No.	Peer Reviewer Comment	Response	Peer Reviewer Close-out Comment
1	CM[1]	The team is to be congratulated for developing thoughtful, interconnected frameworks and for their approach of collective design, which will only serve to enhance collaborations by their individual specialists, benefiting the MRAMP going forward. The introduction to the conceptual modelling outlines clearly that these are adaptable and will be revised as new information about the Murujuga rock art system is acquired as a part of the detailed studies and data collection in the MRAMP.	Acknowledged.	No further comment in relation to this item.
2	CM Element One: Pressure-Response Model and Narrative	The model narrative does not specifically talk about human- accelerated climate change. While increased local pollution is mentioned, the specific consideration of increasing global temperatures, and more frequent and severe weather events from global green-house gas emissions have implications for the acceleration of rock art weathering. That is to say, that stress in the global scale environmental system **will change** 'natural' weather patterns and weathering catalysts, especially sunlight and moisture, in the local Murujuga rock art system, which is in turn being stressed by local anthropogenic activities (industry, tourism, shipping and associated pollution).	Agreed. This was outside the scope of the original contract, however it was agreed with DWER based on similar peer review comments to the Conceptual Model document that such interactions would be included. This has been added to the document. Unintentional or malicious impacts by tourists/direct human action on the rocks are not explicitly within the scope of the project, but may be observed if they occur at monitoring sites.	I have not been provided with a copy of the revised Conceptual Model document, but I am pleased that anthropogenic acceleration of climate change will be captured.
3	DSP	It is difficult to judge the efficacy of the sampling strategy with no information regarding the database of rock art sites/motifs that will underpin it. **The strategy for sample selection and monitoring locations should be strengthened to ensure a representative sample of the chronological variation in the Murujuga petroglyph assemblage.** At present, it is unclear how the modelling scenarios that will generate a randomised, statistically robust geographic sample (monitoring locations and laboratory sample sites) will account for temporal variation across the five identified chronological phases of art production. Consideration should also be give to ensuring a representative sample of the diversity of engraving production techniques, i.e. hammered (pecking, pounding, bruising) and abraded (rubbing, incising,	The approach to sampling design implied by this comment is called stratification or pre-stratification. It requires that the target population be sub-divided into sub-populations called strata (eg according to rock types, engraving types) in advance of the sampling process, and that 'representative' samples be taken from each stratum. We will be making some use of stratification techniques, but not at the level of subdivision which would be implied by this comment, because our assessment is that it would not be feasible to divide the entire population into such fine strata in advance.	This response seems to stem from a misunderstanding of my concern. My comment does not relate to the statistical approach to sampling the rock art assemblage. Rather, it goes to the root data from which the target monitoring population of rock art is drawn and how 'representativeness' of the rock art assemblage is defined and accounted for in the MRAMP. While Puliyapang assert that randomised sampling need not 'account' for any structure in the population; to meet the terms of their commission, Puliyapang need to include in the MRAMP rock art sites that are representative of the relative rock

[1] CM = Conceptual Model; DSP = Detailed Study Plan

Item No.	Section No.	Peer Reviewer Comment	Response	Peer Reviewer Close-out Comment
3	DSP	scratching) and different rock types that art, accretions and patina are found on are included proportionally (gabbro, granophyre and dolerite, which Puliyapang explicitly state for off- art destructive sampling, p.56).	The concerns raised in this comment will be addressed by the use of post-stratification techniques, which effectively divide the *sampled* rocks according to their strata membership and apply corrections for any under-representation of particular strata. As a matter of statistical principle, sampling inference from a randomised sampling design does not have to 'account' for any structure in the population, because its validity is derived from the randomness of the sampling design. Structure in the population may affect the efficiency and power of the statistical inference, but not its fundamental validity.	art sequence and archaeological features (DWER103118 Section 2.4.2), as Puliyapang state themselves in Section 3.1.3. The addition of an entirely new section (3.1.2 Variations in Murujuga Rock Art, pp. 21–22) goes some way to addressing my concerns here. There is now a description of the character of rock art assemblage in the document, that includes the relative rock art sequence as defined in a scholarly context. This is a significant improvement on the draft Detailed Study Design. This new section describes the different proportions of petroglyph production techniques by each of the types of stone upon which they have been recorded and outlines the proportion of subjects depicted. This new section appears to draw exclusively on Dr Mulvaney's published research (2015). My remaining concern is that the database of rock art sites to which Puliyapang will apply their sampling design, is as up-to-date and representative of the rock art assemblage as possible. For instance, the relative rock art sequence as described in the revised Part A document states that the reported characteristics are based on Mulvaney's (2015) sample of 5650 images – here I question, sample of what? How much of Murujuga (the Dampier Archipelago and the Burrup Peninsula—DWER and DBCA review Sept/Oct 2020) has been surveyed? Where are the gaps in the survey coverage? Will the root database for the MRAMP include data from the Cultural Heritage Management surveys conducted on Murujuga, especially within industrial zones? The addition of Section 3.1.2 is a good first step as there are now preliminary characteristics, including chronological variation of the rock art assemblage in the MRAMP against which the issue of 'representativeness' can begin to be evaluated. I acknowledge Puliyapang's sampling design is iterative and will include pre- and post-stratification techniques. I acknowledge also that the Traditional Owners via MAC Elders and staff, will (rightly) ultimately determine which rock art and associated archaeological features will be included in the MRAMP. I completely agree with MAC that "The issue of what constitutes the art-rocks on Murujuga is critical" (MAC peer review for Murujuga Rock Art Monitoring Program: Monitoring Studies Data Collection and Analysis Plan Part A, undated).

Item No.	Section No.	Peer Reviewer Comment	Response	Peer Reviewer Close-out Comment
4	DSP	**The modelling simulations and sample selection strategies do not appear to consider climate change impacts.** As the main source of, and catalysts for, rock art deterioration are environmental/atmospheric, projections and long-term strategies need to account for conservative increases in global temperatures and predictions for increasingly severe and frequent, extreme weather events.	As discussed above, this was outside the scope of the contract when this document was written. It has been agreed it will be included in the study design and will be explicitly addressed in the Monitoring Studies Data Collection and Analysis Plan - Part B document.	I look forward to seeing the trajectories for greenhouse gas accelerated climate change being incorporated into the detailed Monitoring Studies Data Collection and Analysis Plan - Part B.
5	DSP	**The five year term of Puliyapang commission is not stated up-front in the document.** While it would be implicitly clear to DWER that the design and implementation of the phase of the MRAMP described herein is scheduled over five years, it is my understanding that Detailed Study Design and Conceptual Model documents will be made publicly available.	The conceptual model document lists an overall/general timeline. The Monitoring Studies Data Collection and Analysis Plan - Part B document will include a Gantt chart with a more specific timeline for the study components. DWER have indicated that all documents will be made available.	The Gantt chart will be a welcome and succinct device to clarify not only the term of the Monitoring Program, but also to clearly outline the timing of key activities within the MRAMP.

2.2 Dr Jillian Huntley – Statement of Advice and Review comments sheet for Monitoring Studies Data Collection and Analysis Plan

Dr Jill Huntley
Specialist Archaeologist

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Government of Western Australia
Department of Water and Environment Regulation
Reference Number: DWERT5321

Attention: Naomi O'Hara
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Dear Ms O'Hara

RE: PART B, Peer Review of Monitoring Studies Data Collection and Analysis Plan (Part A and B) (Murujuga Rock Art Monitoring Program)

Consistent with the format of my peer review of the Part A Detailed Study Design and Conceptual Model, this *Statement of Advice* letter provides my detailed assessment of the Part B Monitoring Studies Data Collection and Analysis Plan and the finalisation of the first stage of the initial design phase of the five year program continuing the Murujuga Rock Art Monitoring Program (MRAMP). In the appended *Independent Peer Review Comment Sheet*, I succinctly outline those issues that I consider need to be addressed prior to the commencement of the field monitoring and laboratory characterisation programs.

It is my understanding that the MRAMP is being undertaken to determine if anthropogenic emissions are accelerating natural weathering processes affecting the petroglyphs (engraved and abraded rock art assemblage) and surrounding rock surfaces of Murujuga (the Burrup Peninsula), Western Australia. The initial five year program is being designed by the contractor to assess, monitor and manage uncertainties that remain over the levels of emissions that would accelerate weathering of the rock art; to consider how anthropogenic input could accelerate agents of deterioration acting on the petroglyphs (mechanisms and likely degradation vectors); and to measure the types, levels and locations of anthropogenic pollutants the Murujuga rock art is subjected to. Further, it is my understanding that the initial five year program undertake by the contractor will underpin a longer term monitoring campaign with the aspiration that the Traditional Owners of Murujuga will take carriage of the field data collection under the auspices of the Murujuga Aboriginal Corporation (MAC).

Calibre Ventures, with their partner technical experts from Curtin University, Artcare and ChemCentre (hereafter Calibre[1]), are to be congratulated as they have largely fulfilled their brief of designing a world-leading, scientifically rigorous approach to monitoring. Analysis of the results

[1] I note the Puliyapang joint venture arrangement between Calibre Ventures Pty Ltd and Tocomwall Pty Ltd that was in place at the beginning of the MRAMP has dissolved. For the purposes of peer reviewing the MRAMP, I will use the name Calibre when retrospectively talking about Part A of the project in recognition that the same team of experts remains in place despite the change in broader project management structure.

from the program will underpin the Environmental Quality Management Framework described by the Department of Water and Environment Regulation (DWER 2019), in turn informing the long-term management Murujuga's rock art. With some exciting, novel scientific approaches to analysis, the Monitoring Studies Data Collection and Analysis Plan has been thoughtfully conceived to capture the required complexity of different potential vectors for rock art deterioration. The selection of in field data collection techniques is also appropriate with an eye to the MAC Rangers who will work alongside the Artcare and Curtin teams and receive training to help MAC achieve its goal of ultimately taking responsibility for the long term monitoring program. The Part B document does a good job of identifying the major issues needing to be addressed: via what pathways the patina and mineral rinds on engraved boulders at Murujuga form, and by which mechanisms the same patina and mineral rinds decay/change, under natural and anthropogenic conditions. The need for an experimental program is clearly outlined (to establish levels for the Environmental Quality Criteria).

Overall, the study designs and analytical programs presented in the Part B document are outstanding, having requisite flexibility and contingency to be both rigorous and adaptive as the data collected in the field and laboratory programs is evaluated, and fed back into the MRAMP allowing adjustments to be made if required. My advice seeks to foster improvement of the scientific and technical methodology, and to clarify the evidence base and assumptions used by the contractor in the sampling design (both in-field and laboratory). These are important considerations as the modelling extrapolations, inferences and interpretations made by the contractor rest on the evidence base and assumptions that underpin the Monitoring Studies Data Collection and Analysis Plan, and ultimately the success of the MRAMP. The issues I raise here should be simple for the contractor to address and build into their comprehensive strategy, and/or clarify with the addition of explicit statements addressing how these issues have been considered, and/or will be considered, as the work program commences.

1) **Further clarity is required to establish the 'representativeness' of the petroglyphs and other 'non-culturally modified' rocks that will be analysed during both in the field and laboratory programs.**

Calibre acknowledge that they need to include in the MRAMP rock art sites that are representative of the relative rock sequence and archaeological features to meet the terms of their commission (DWER103118 MRAMP Tender Document Section 2.4.2). Calibre state in their summary of the overarching principles for the study design on page 26 that the proposed programs must have "Validity for the entire population of culturally modified rocks".

When I first raised concerns about this matter in the Part A peer review, Calibre's response was that the issue would "be addressed by the use of post-stratification techniques, which effectively divide the *sampled* rocks according to their strata membership and apply corrections for any under-representation of particular strata" in Part B of the study design.

In my option, the 'strata' — or attributes of the petroglyph assemblage — that require consideration to ensure that the data gathered in the MRAMP are representative of the Murujuga petroglyph assemblage, in hierarchical order, are:

- *Base geology upon which the petroglyphs were made*[2]
- Relative chronology of the motifs
- Engraving technique
- Petroglyph density

Only two 'strata' have been assigned to the Murujuga Rock Art assemblage via post-stratification in the statistical study design in Part B:

- Firstly, 'sites', being the 1.3 km discrete data 'tiles' overlayed over Murujuga in keeping with the Ramboll 2021 modelling, have been determined in consultation with Traditional Owners as being 'allowable' or culturally safe for use in the initial studies, see Section 3.7, Figure 3-21, pp.98–99, and Appendix 1, pp.5–6.
- Secondly, a classification for base geology has been assigned to each of the 1.3 km tiles, see Appendix 1, pp.6–12. Here, it seems the geology of the entire region has informed the strata imposed, rather than the geology proportionally to its use in the rock art assemblage.

Calibre's assertion (p.24) that "The study design includes a statistically representative sample of petroglyphs" requires further clarification and support in the Part B document. This could be done via minor revisions to include a statement addressing how the MRAMP will explicitly capture variation in the above attributes of the rock art representative of the entire Murujuga petroglyph assemblage, as explained below.

It is critical that the Monitoring Studies and Data Collection and Analysis Plan demonstrates a clear understanding of the geology of the petroglyph assemblage and the spatial location of the known distribution of engraved art in proximity to potential emission sources. I would remind Calibre that the aim of the MRAMP is not to understand the geology per se, but rather to understand the rock art assemblage. Despite the geological stratification appearing to have been assigned based on geological mapping of the region, rather than the proportion of recorded engravings per stone type, it seems that this variable will be captured adequately, **so long as Calibre ensure their field sampling program includes characterisation of some samples of the three potential additional geologies upon which Murujuga petroglyphs occur, that are discussed in Section 3.2.1 Variation in Murujuga rock art, but not accounted for in the statistical modelling or sampling strategies outlined.**

On p.26 of the Part B document Calibre state that:

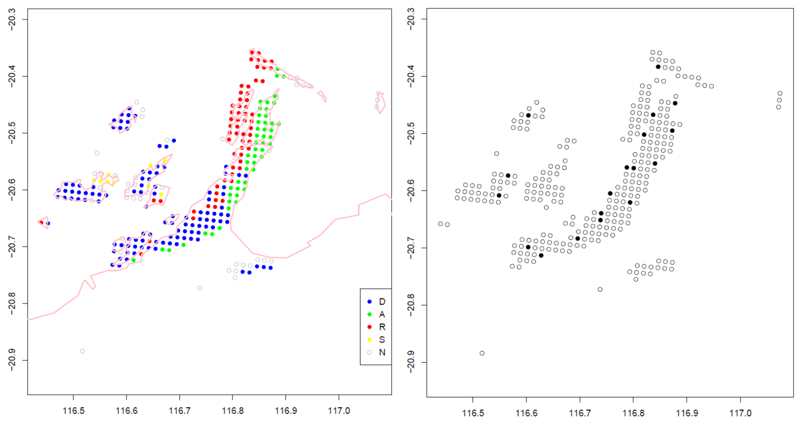
> "On Murujuga, the rock art occurs primarily on rock of fine-grained gabbro, granophyre or to a lesser extent dolerite. Some of the islands, like Legendre, comprise limestone, while on others, like Rosemary and Enderby, volcaniclastic sedimentary rocks and basalt are also present."

While it is difficult to be certain as the geological 'strata' and selected field sampling locations are presented in separate illustrations on separate pages from one another, the field sampling locations selected on Enderby Island should provide opportunities to characterise volcaniclastic sedimentary rocks and basalt as part of the 'other locations with petroglyphs' (yellow), in addition to the

[2] Italics indicate this has been addressed by Calibre in Part B

Dolerite (Blue) specified in the post-stratification, as should the Dolerite (Blue) location selected on Rosemary Island, as both the blue coloured locations with the Dolerite dyke are likely to also have basalt (see below).

At present the reader of the Part B document is required to work out for themselves the geological strata of the selected field sample location sites. I strongly recommend the current 'selected' field sampling location map be revised to colour code each selected field sampling site with their corresponding geological strata. This revision should also account for why the limestone geology of Legendre Island stated on p.26 of Part B is mapped as a mixture of "Granophyre present, Gabbro and Dolerite absent" (red) and "Gabbro present, Dolerite absent" (green) in the illustration in Appendix 1.



Geological units assigned to the potential sampling locations (left) and the location of statistically optimised sampling location (right). Reproduced from Section 4.2 of Appendix 1.

Nonetheless, the unique limestone geology of Legendre Island will be sampled because of the selected field sample location RS-18 (though Calibre needs to ensure that rock art is present in this field sampling site – see 1a below).

The three rock art characteristics that are critical to representatively characterising Murujuga's petroglyphs (i.e. relative chronology of the motifs, engraving technique and petroglyph density) are discussed by Calibre in the Part B document, but not accounted for in the statistical strategy for sample section nor in the field data acquisition methods. This might be addressed in several ways, but these attributes of the rock art assemblage need to be represented in the data collection and analysis program.

As I raised in comment 3 of my Part A review, **the strategy for sample selection and monitoring locations should ensure a representative sample of the chronological variation in the Murujuga petroglyph assemblage**. The relative chronology of motifs is discussed by Calibre based on the sequence proposed by Mulvaney (2015); however, they do not address how they will ensure the inclusion of at least one motif from each of the five chronological phases illustrated in Figure 3-1 (p.27). This is an important consideration as the older petroglyphs have been subjected to deterioration processes for the longest amount of time. Inclusion of at least one example of each stylistic rock art phase can therefore be used as a proxy for exposure to deterioration processes over time, which will be an important comparison to be able to make in the characterisation program.

I couldn't agree more with Calibre about the confounding factors for relative chronology (Section 2.2.7 Petroglyph age p.24) and am pleased to see that they will be able to access and incorporate the latest research as the results of the geochronology program to be conducted as part of the Australian Research Council Linkage project #LP190100724 become avalible.

A sample of at least one of each of the eight petroglyph production techniques recognised by Mulvaney (2015) should be included in the MRAMP (Table 3-1). As Calibre themselves explain on p.26, rock art "production techniques each … present different scenarios for motif preservation". In addition, "(r)ock surfaces which have been culturally altered may be physically different from the overall population of rock surfaces, for example because the engraving process may require the rock surface to be strong and homogeneous" (p.31).

It is critical to include the different attributes of the rock art assemblage in the data collection and analysis of MRAMP because the Old People (ancient Aboriginal populations) of Murujuga were making deliberate choices about the production of rock art that have resulted in a number of characteristics that influence its current preservation.

As Calibre explain:

> "Shallow scratching and abrading are more suited to, and more visible on, the finer grain and shallower weathered crusts of granophyre and dolerite. These techniques are also more likely to be amongst the more recent art as, being shallow, they are more prone to deterioration. The relative dominance of a technique is also reflective of the rock support on which the petroglyphs are produced; in areas where granophyre and gabbro are not dominant, the prevalence of scratched and abraded images reduces pecked images to around 60%" (p.26).

Finally, the location and known density of rock art is a critical consideration in the MRAMP. Locations with more rock art, and more stylistic and chronological variability in the rock art present, might well have functioned in a different way to other, lower density rock art sites in a region. For example, dense clusters of rock art may function as aggregation locales where large groups of people, and/or different cultural groups, came together (McDonald and Veth 2009). **Places with high petroglyph density in Murujuga may also present Calibre with remarkable opportunities to characterise (monitor and measure) multiple rock art motifs from different parts of the relative sequence, and/or different engraving techniques, and/or different engraved geologies, whilst only having to visit one field sampling location.** It should therefore be a priority for Calibre to include at least one high density cluster of rock art in their field campaign (assuming this is permissible by the Traditional Owners).

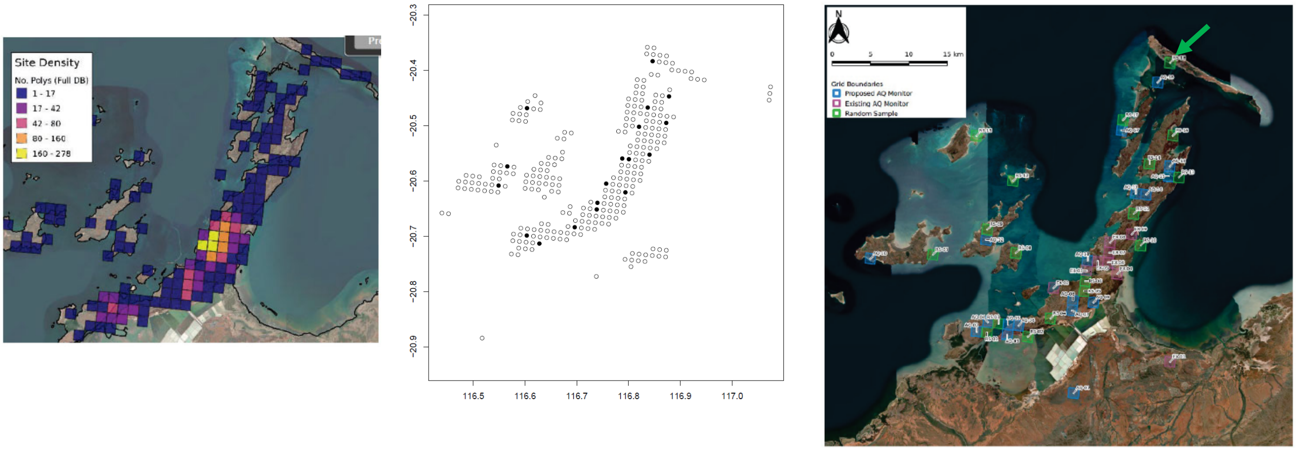
The data used to understand how many rock art sites have been recorded and the geographic distribution of Murujuga's rock art should be critically discussed as part of Section 3.1.2. The detailed Air Quality Monitoring Site Selection Report, Appendix 2 of the Part B document by co-author Andrew King, shows that Calibre has the means to easily clarify this issue. King's discussion of rock art location data in Section 3.5 of Appendix 2 is excellent, providing the sort of succinct detail required to clearly outline what the evidence base for the location of engravings is, and what characteristics of the petroglyph assemblage have been taken into consideration in this Monitoring Studies Data Collection and Analysis Plan. King's critical evaluation of the available rock art location data (his Part B Comparison of registered site databases, p.22 of Appendix 2) is important as it shows the need for Calibre to use the full, restricted register of Aboriginal sites.

I note also that a critical evaluation of the known rock art locations in terms of effective survey coverage is missing from the MRAMP. With all the other data that underpins the sampling strategies and models there is careful, critical evaluation of the datasets; this is lacking for the rock art data. It would be easy for Calibre to 'ground truth' relevant parts of the rock art database maintained by The WA Department of Planning, Lands and Heritage as part of their works, including confirming the absence of engravings in any of the field study locations where selected in tiles devoid of recorded rock art (as outlined below). This is important because understanding whether an absence of recorded rock art on Murujuga is genuinely the case, or merely a function of the fact that there has been no prior survey in an area, should feed into the Plume Modelling and other impact predictions, to be able to build in the need for further rock art recording later in the MRAMP program. For instance, if an emissions plume is modelled as depositing pollutants across an area where rock art is not recorded, or is recorded only in low density, will there be surveys to ground truth the absence/scarcity of rock art? This could be addressed in parallel with point 1a) below.

> **1a) Contingency should be added in the sampling methology in the event a selected field location does not contain rock art—e.g. in field petroglyph/climate monitoring and rock sample locations on Legendre Island.**

While it is difficult to tell (because the shoreline has been removed from the illustration of sites selected by the statistical model in Section 4.2), it appears that field sampling 'site' RS-18 on Legendre Island (top right of Figure E-O-1/5-1) is located in an area where there is no previously recorded rock art (Figure 3-20 in comparison to illustrations without figure numbers in Appendix Section 4.2 – reproduced in the centre of the figure below). Calibre should outline a contingency for opportunistic sampling of geological specimens and the subsequent reselection of a new field site should they be faced with a situation where there is no rock art within a field sampling location they have selected as illustrated in Figure 5-2.

Calibre should also produce a new figure that overlays the selected field sampling sites on the know rock art locations/petroglyph density (as interpolated onto the 1.3 km grid overlay—combining the information from Figures 3-2 and 5-1). This new figure would clarify if the proposed RS-18 field sampling site is on a part of Legendre Island with no previously recorded art.



Reporduction of Figure 3-20 (left), compared to the 'Selected' site location provided in Appendix 1, Section 4.2 (centre), and the location of 'optimised' site selction locations Figure E-O-1/5-1 with the location of RS-18 indicated by the arrow (right)

2) Climate change scenarios should be addressed in the Part B document.

In the peer review of Part A, I (and other experts) commented that the modelling simulations and sample selection strategies for the MRAMP did not appear to consider climate change trajectories and accelerating impacts. In response Calibre stated that "It has been agreed it will be included in the study design and will be explicitly addressed in the Monitoring Studies Data Collection and Analysis Plan – Part B document."

I note that the words climate change do not appear together anywhere in the Part B document.

Climate change impacts are already affecting rock art preservation on Murujuga and will continue to accelerate weathering processes in the region. While I acknowledge that the meteorological data from 2015–2019 used in the Computational Fluid Dynamics simulations (p.101) will incorporate some of the climate change impacts effecting the Murujuga at present, there is no discussion of how forward projections under different climate change scenarios will be considered. It is critical that the MRAMP consider climate change scenarios as these will directly affect through what pathways the patina on the engraved boulders at Murujuga form, and mechanisms of their decay/change under natural and anthropogenic atmospheric conditions. As a suggestion, I wonder, could the Computational Fluid Dynamics part of the MRAMP explicitly include climate change trajectories such as through the use of Representative Concentration Pathways—greenhouse gas concentration trajectory adopted by the United Nations Intergovernmental Panel on Climate Change?

As Calibre state on p.40, the current location/selection of the field sampling sites has been sufficiently "overdesigned" to allow for some error in the Ramboll modelling and/or future/changed emissions sources. The selection of field sampling sites should also take into account climate change impacts such as sea level rise and the increases in the frequency and intensity of heat extremes, marine heatwaves, heavy precipitation, droughts conditions and proportion of intense tropical cyclones (IPCC 2021; Sudmeyer 2021). That is, different geographic locations across Murujuga will be disproportionally impacted by sea level rises, heat retention from ambient temperature increases and the direct impacts of greater cyclonic activity. How this is captured or avoided in the location/selection of the field sampling sites should be explicitly discussed.

Increases in daily temperatures, the duration and intensity of drought conditions, higher humidity and evaporation rates, and more frequent and sever cyclonic activity will all impact the development and erosion of patina on the petroglyph assemblage. Calibre will already be collecting the data required to assess climate change impacts in real time (for example, the MRAMP will access the impacts of extreme weather events through their monthly condition assessments of the field sampling sites); the Part B document should make this explicitly clear.

3) **The language used in the Part B document regarding which monitoring/data collection/sampling points will be collected on petroglyphs and which will be collected on culturally unmodified materials (that will act as a proxy for the materiality of petroglyphs, vis-à-vis agents of deterioration) and their acceleration is unclear and inconsistent. The term 'sites' is also applied interchangeably and indiscriminately to a number of distinct concepts.**

The use of language matters here as the petroglyphs of Murujuga are much more than just 'rocks'. The Part B document should be revised to make clear throughout when the authors are talking about rock surface containing art versus when they are meaning to refer to other, non-culturally modified rocks, and soil surfaces. Similarly, the term 'sites' is used somewhat indiscriminately to describe not only cultural heritage sites but also the 1.3 km data 'tile' overlay used in the statistical modelling, as well as locations where air quality and/or in field data, monitoring and sampling for the laboratory program will occur. A clear and consistent distinction between petroglyphs/engravings and other stone/soil surfaces, and the use of the term 'site' to only refer to one concept (I suggest cultural heritage sites, given that it is the rock art of Murujuga which is fundamental to the monitoring program), would be simple to achieve and remove confusion regarding the context of the monitoring/data collection/sampling points.

One clear example of the confusion introduced by inconsistency applied terminology is seen in Section 2.1.2, Inorganic geochemistry, p.16, Paragraph 2. Here the language should be modified to reflect that it is not the 'rocks' that are the subject of the MRAMP, but the petroglyphs (engraved rocks) (as per my critique of Part A).

As another example, I found the Statistical Study Design (Appendix 1) confusing because the terms 'rock(s)' and 'rock surfaces' were applied without any distinction between stones containing petroglyphs and culturally unmodified stones. This makes the logic of the sampling program difficult to follow (and what will be measured on stone surfaces with petroglyphs and other stone surfaces will be used as a proxy for the petroglyphs). A summary table that sets out how many analytes/spectra/samples are anticipated to be collected and from what context (i.e. measured on the surface of a petroglyph, taken on/from a nearby culturally unmodified rock, or soil sample) would be helpful. Such a reference table could easily be added, perhaps at the back with the glossary and list of abbreviations.

Final comments for consideration by Calibre

Below I list some final comments and suggested revision for Calibre's consideration to enhance the otherwise generally excellent Part B document. I only tabulate points that are important to the success of the MRAMP and that require a specific response from Calibre in the appended *Independent Peer Review Comment Sheet*.

I would like to see a table outlining the roles of different specialists within the program. For example, in the document different teams of specialties are mentioned (e.g. statistical team p.58, inorganic geochemistry team p.75, etc.). In some instances a specialist is even named (e.g Marco Coolen and his team p.63, CI Grice p.91, and the naming of five project specialists in Section 4.3, p.106, etc.). This would make clear who is responsible for what component of the program.

It is my role to evaluate the technical content of the Part B documentation, not copy edit the Monitoring Studies Data Collection and Analysis Plan; however, I found inconsistencies in the naming conventions of 2.1.4 that switched between abbreviations for chemical elements (Fe and Mn), and their unabbreviated names (iron and manganese) and their inconsistent capitalisation (iron and Manganese) distracting. It would be helpful for Calibre to closely copy edit the document to ensure consistency in such matters throughout.

Section 1.1 Overarching Principles of the Murujuga Rock Art Monitoring Program, p.4:
Calibre state that "every effort will be made to verify no rock art is present" prior to destructive sampling of the base geologies that host the engravings, but a methodology for this is not provided. How will this be done? MAC Rangers and the Circle of Elders will be involved in the selection of sampling locations, but will MAC Rangers be present during the initial inspection and sampling? There is a rock art specialist (Dr Ben Gunn) on the Calibre team: will Dr Gunn lead ground survey within the 600 m radius field sampling sites depicted in Figure 5-2? This clarification would also address the accuracy or rock art distribution in the registered site database raised in point 1) above.

Section 2.1.5 Eh-pH-chloride Measurements, p.20, bottom of the third paragraph:
I would like quantification about what are considered "low" and "high" pH in relation to the dynamism of the rock surfaces (i.e. what are the lower and higher measurements).

Section 2.2.2 Inorganic geochemistry p.22 paragraph 2:
The opportunity to use Plutonium as an anthropogenic marker is very exciting. I would like to see the short (~two sentence) explanation of why Plutonium might be used as a proxy for the onset of the Anthropocene moved up to the initial discussion of the topic from 3.3.2 Inorganic Geochemistry on p.67.

Section 2.2.3 Microbiome p.23:
The proposed molecular characterisation program is very exciting and will address the knowledge gap outlined with regards the pathways to patina/rind formation and subsequent degradation, especially the vectors involved in each. This section would be a good opportunity to discuss how MRAMP will take into account climate change trajectories as flagged in point 2) above.

Section 3.2.3 Colour change:
Using raw spectral data for measurements that are outside human visual colour perception is exciting and I am looking forward to seeing what this produces.

In response to my Comment 5 in the Part A review Calibre stated that they would include a Gant Chart of the staged works program to make clear the initial five year term of the Monitoring Program, and clearly outline the timing of key activities within the MRAMP. While there is no Gant Chart included in Part B, I note that the schematic illustration provided as Figure 5-3 serves the same function. I recommend that the indictive timing (years) be added at the top of the Phase 2 “studies” and Transition to Monitoring phases of the schematic illustration provided as Figure 5-3.

In closing, the evaluation of previous monitoring studies, and the design, collection and analyses plans described in this Part B document are of a very high standard. Calibre are to be congratulated for their rigor, and also for not ‘throwing the baby out with the bathwater’ by ensuring they incorporate legacy data into the MRAMP program wherever possible.

I would like to again endorse the underlying principle of the MRAMP, taken from Section 3A of the *Environment Protection and Biodiversity Conservation Act 1999*, that ‘if there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation’, and in the specific case of MRAMP, to take action to halt and prevent rock art deterioration.

I commend DWER’s implementation of rigorous oversight of the MRAMP through expert peer review by MAC, the Murujuga Rock Art Stakeholder Reference Group and expert external specialists such as myself, and look forward to receiving Calibre’s response to this peer review of the Part B document.

Sincerely

Dr Jillian A. Huntley
Wallis Heritage Consulting

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MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: Dr Jillian Huntley with quality assurance/internal review by Associate Professor Lynley Wallis		
Document Title: Murujuga Rock Art Monitoring Program: Monitoring Studies Data Collection and Analysis Plan – PART B		
Document Revision:	Version 2.1 (September 2021)	Close out comments on Version 2.2 (November 2021)
Date of Review:	5 October 2021	Close out comments 6 December 2021

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
1	Executive SummaryFig. E-O-1 & 5 Locationsand ScheduleFig. 5-1 **and** 3.1.2 Variationsin Murujuga rock art	RS-18 in field monitoring/sampling location appears to be on a part of Legendre Island that has no previously recorded rock art (see details in the Statement of Advice letter provided). The in field sampling methodology should explicitly address how each field sampling location will be surveyed for rock art and how the rock art included in the MRAMP is representative of the Murujuga rock art assemblage. In addition, the unique limestone geology of Legendre Island outlinedby Calibre in 3.1.2 Variations in Murujuga rock art, seems not to be considered in the post-stratification of the statistical modelling or sample strategy rationale of the Monitoring Studies Data Collection and Analysis Plan (see also items 6b, 11 and 12 below).	The draft design did not specify detailed protocols for sampling in the field as (in keeping with standard statistical practice) it was first necessary to undertake field visits to identify the sampling constraints and practical exigencies. This has now been done and a field protocol included. The reviewer is correct, Legendre island is indeed limestone, it was accidentally selected as the geological maps show granophyre underneath the limestone. It was moved as per protocol and is now located on Collier Rocks (see revised map).	Noted I acknowledge that the Murujuga Rock Art Monitoring Program has been disrupted by the global pandemic and there were many unforeseen restrictions to the staging planned for fieldwork that underpins the Monitoring Studies Data Collection and Analysis Plan. Further, I acknowledge that many of Calibre/Curtin's responses to the reviewer comments are that the final format of methods is undergoing validation at present, and/or will be tested and validated as the first part of implementing the Monitoring Program. To some extent this 'living document' effect was always going to be a necessary part of the of Monitoring Program. While it was unavoidable, it is regrettable that the location of sample locations was chosen after peer review of the Monitoring Studies Data Collection and Analysis Plan – PART B.
2	Executive Summary	The schematic representations of the works program given in Figure 5-2 and the work schedule in Figure 5-3 are excellent. I suggest adding them to the Executive Summary.	Noted. We were asked to shorten and simplify the executive summary, however will discuss with DWER prior to publication.	Noted.
3	Throughoutthe Part B document	The language throughout the document should be 'tightened up'. It is unclear which monitoring/data collection/sampling points will be collected on petroglyphs and which will be collected on culturally unmodified materials (that will act as a proxy for the materiality of petroglyphs, vis-à-vis agents of deterioration and their acceleration). The current interchangeable use of terms rock, rock surfaces and petroglyphs makes the study design and rational difficult to follow (andevaluate) at times. Of course, petroglyphs were made on rocks that have surfaces, but delineating which parts of the characterisation program derive from rock art contexts and which have been sourced from unmodified lithologies is important (and easily done). Similarly, the term 'sites' is used for cultural heritage items, field sampling locations, air quality monitoring stations, etc., leading to confusion overwhich type of site is actually being referred to. Terminology used in the document must be consistent and clearly delineate petroglyphs from other surfaces/samples, and the term sites should be applied thoughtfully with synonyms used for concepts other than "cultural heritage sites" so there is internal consistency throughoutand no confusion can arise as to exactly	The document has been revised for internal consistency and edited for language.	Noted.

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
		what is being referred to.		
4	Any	I would like to see a summary reference table, perhaps at the back with the glossary and list of abbreviations, which sets out how many analytes/spectra/samples are anticipated to be collected and from what context (measured on the surface of a petroglyph, taken on/froma nearby culturally unmodified rock, or soil sample) and specifying forwhat invasive and non-invasive techniques that will be used.	Measurements on or near petroglyphs will be confined to non-invasive approaches (pXRF, pH, spectral/colour). The number of each replicate sample is currently undergoing further statistical design and validation. Rock samples have been twinned/matched (similar location, dip, strike patina) to each petroglyph panel in the AQ and EX and AS squares (selected randomly in other squares) and these will be sampled for microbiome analysis, then sectioned between all the analyses discussed in the study design. The sample size and number of replicates for each analysis is also currently undergoing validation using preliminary sample rocks.	As noted above, there is an inherent impediment to the peer review process here as we have been asked to evaluate a 'living document'. There are obvious limitations to being able to assess the adequacy, and likely efficacy, of the data collection and analytic strategies as they are ongoing (as explained in Calibre/Curtin's response to this comment). It seems implicit in Calibre/Curtin's response that the Monitoring Studies Data Collection and Analysis Plan will be finalised with the sample sizes and number of analytes decided upon completion of the analysis of preliminary samples and additional statistical design and validation that is currently ongoing. Will there be a further round of peer review prior to this finalisation? This seems to be important, especially by reviewers Dr John Henstridge, A/Prof. Ron Watkins and Prof. Geoffrey Michael Gadd. Again, I acknowledge that there have been unanticipated impacts to the staging of the overall Murujuga Rock Art Monitoring Program arising from the covid pandemic restricting on Country work with the Murujuga Aboriginal Corporation (including their Circle of Elders).
5	Any	I would like to see a table outlining the roles of different specialists within the program. For example, in the document different teams of specialties are mentioned (e.g. statistical team p.58, inorganic geochemistry team p.75, etc.). In some instances a specialist is evennamed (e.g. Marco Coolen and his team p.63, Cl Grice p.91, and the naming of five project specialists in Section 4.3, p.106, etc.). A table that explains who is doing what within the study would be useful to identify (for the benefit of the public and their peers), the specialists with primary responsibility for particular areas of the research. This would also have the benefit of clearly delineating the team members contributions to the project (acknowledging that the multidisciplinary nature of the overall team means that there is collaboration between the specialists).	This is something, which can be considered, but may need to be approved by DWER and is unlikely to form part of the published document. In short: • Andrew Thorn is leading the Petroglyph monitoring/imaging • Marco Coolen is the lead (geo)microbiologist • Katy Evans is the lead Geologist • Kliti Grice is the lead Organic Geochemist • Adrian Baddeley (with Noel Cressie) are the lead statisticians • Ben Mullins is the overall scientific lead and is leading the air quality design and modelling work, together with Ryan Mead-Hunter and Andrew King. Other members of the team are working under the above people or in project coordination/management roles	I am satisfied that this response has provided a public record of Calibre/Curtin' project expertise and accountabilities.
6	Section3.2.1 Variation in Murujuga rock art and Appendix 1	Further clarity is required to establish the 'representativeness' of thepetroglyphs and other 'non culturally modified' rocks that will be analysed during both in the field and laboratory programs (refer to point 1) in the attached Statement of Advice for further details). In response to the Part A peer review Calibre stated that the issue ofrepresentativeness of the rock art included in the MRAMP would "be addressed by the use of post-stratification techniques, which effectively divide the *sampled* rocks according to their strata membership and apply corrections for any under-representation of particular strata" in Part B of the study design. The part B document only identifies two parameters for post-stratification (safety and geology). Below (6a-d) I outline the attributes of the Murujuga Rock Artassemblage that need to be accounted for in order for the MRMP to beconsidered representative.	We disagree with some parts of this, as we are concerned that any attempt to preference particular rock types, would undermine the statistical rigour of the study design. The sample survey rocks (petroglyphs and destructive samples) are selected according to the principles of random design-target based sampling (see Thompson, 2012) which prescribed the probability of selection of each item in the population regardless of its characteristics. Attempting to modify this process by stipulating quotas or balance in the sample, would violate this basic principle and render statistical inference difficult. However, such considerations may be useful in selecting the petroglyphs and destructive sample rocks for the air quality sites. The data from these air quality sites will be analysed using regression/modelling principles rather than sampling inference.	I think we are at cross purposes here. I am not suggesting that a preference be given to the sampling probabilities of individual rocks, nor that there should be a change to the sampling protocol. The use of a statistically robust random design-target based sampling strategy need not be mutually exclusive to also achieving a sample population that is representative of the rock art assemblage. As I have outlined in my detailed advice statement that accompanies this peer review table, Calibre/Curtin acknowledge that they need to include in the MRAMP rock art sites that are representative of the relative rock sequence and archaeological features in order to meet the terms of their commission (DWER103118 MRAMP Tender Document Section 2.4.2). Calibre/Curtin state in the study's overarching principles in Section 3.1.1 (page 24) that the proposed programs must have "Validity for the entire population of culturally modified rocks". In response to my comment 1, the (green tile) sample survey site previously on

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
				Legendre Island "was moved as per protocol and is now located on Collier Rocks (see revised map)". Similarly, in response to comment 6d below Calibre/Curtain state "If no appropriate rock types are present above ground (e.g. Legendre Is) then the square is moved according to protocol." The monitoring site selection protocol can therefore respond to having to select new locations without undermining the random design-target based sampling strategy. I am therefore not suggesting any modification to the sampling strategy, only that it be applied until such time that Calibre/Curtin can demonstrate that the required representative characteristics of the rock art assemblage have been captured in the sample populations. Even though the field campaign to select monitoring locations has now been completed, the notes supplied in the table in Section 11 make no mention of the rock art recorded during monitoring location selection, nor how this represents what is known about the rock art assemblages characteristics (which, as I outlined in my detailed statement of advice, includes not only the base geology upon which the petroglyphs were made, but also the relative chronology of the motifs, engraving technique and petroglyph density). This may be a mute point as the select monitoring locations that have now been chosen may contain a representative sample of Murujuga rock art assemblage. However, this is unclear from the Monitoring Studies Data Collection and Analysis Plan as presented in November 2021 and needs to be demonstrated.
6a	Section3.2.1 Variation in Murujuga rock art and Appendix 1	The strategy for sample selection and monitoring locations should ensure a representative sample of the **relative chronological variation** in the Murujuga petroglyph assemblage. The relative chronology of motifs is discussed by Calibre based on the sequence proposed by Mulvaney (2015); however, Calibre do not address how they will ensure the inclusion of at least one motif from each of the fivechronological phases illustrated in Figure 3-1 (page 27) in the MRAMP. This need not be factored into the statistical approach driving random field sample location selection. Indeed, the optimised statistical approach to the field sampling and air quality monitoring location couldbe deployed to generate prospective locations until a sample of at least one of each of the chronological phase is captured in the program.	We agree that consideration of chronological ages of the rocks at the air quality sites is merited. The approach proposed here would alter the sampling probabilities of individual rocks, violating the conditions for statistical inference from the sample.	See above.
6b	Section3.2.1 Variation in Murujuga rock art and Appendix 1	Calibre should ensure their field sampling program includes **characterisation of all the geologies upon which Murujuga petroglyphs occur**. Three additional geologies are discussed inSection 3.2.1 Variation in Murujuga rock art, but these are not accounted for in the statistical modelling or sampling strategies outlined (Appendix 1). Given the complexities of recognising geological units in the field, thisneed not be factored into the statistical approach driving random fieldsample location selection. Rather, I recommend that the MRAMP usethe monthly field sampling over the initial program to harness the analytic techniques outlined (pXRF, XRD and thin section analyses inparticular) to ensure that over time the program accumulates samplesof all the geological units upon which the rock art has been previouslyrecorded. The current 'selected' field sampling location map should be revised tocolour each selected field sampling site to their corresponding geological strata (Appendix 1).	Recent fieldwork has shown that the geology of Murujuga is extremely complex. A thorough investigation is beyond the scope of the current project, though we agree that such a study should be undertaken.	Noted. My request (at the bottom of the comment) that the current 'selected' field sampling location map be revised to colour each selected field sampling site to their corresponding geological strata (Appendix 1, page 7) has not been addressed. This could be easily remedied by adding a cross or drawing a box around the cells to indicate the location of selected air quality field sites to the geology figure on page 10 of Appendix 1. As I stated in my detailed comments, the reader of the Part B document is required to work out for themselves the geological strata of the selected field sample location sites.

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
6c	Section3.2.1 Variation in Murujuga rock art and Appendix 1	A sample of at least one of each of the eight **petroglyph production techniques** recognised by Mulvaney (2015) should be included in theMRAMP (Table 3-1).	We disagree with this based on the discussion in response to comments 6 and 6a.	As per my close-out comment to comment 6 above, I was not suggesting that the approach to sampling locations change – I understand that this would invalidate the statistical basis for the sample selection methodology. I am also aware of how critical a statistically valid sampling methodology is, especially in the historical context of the previous CSIRO program. Rather, I am drawing attention to Calibre/Curtin's requirement to include in the MRAMP rock art sites that are representative of the relative rock sequence and archaeological features to meet the terms of their commission (DWER103118 MRAMP Tender Document Section 2.4.2). In addition, this response by Calibre/Curtin seems to contradict their response to Dr António Batarda Fernandes' comment 13 above. When Dr Batarda Fernandes suggested the inclusion of diverse engraving techniques his advice was described as an "excellent point" – yet here it is disagreed with.
6d	Section3.2.1 Variation in Murujuga rock art and Appendix 1	It should be a priority for **Calibre to include at least one high densitycluster of rock art in their field campaign** (assuming this is permissible by the Traditional Owners). The data used to understand how many rock art sites have been recorded and the geographic distribution of Murujuga's rock art shouldbe critically discussed as part of Section 3.1.2. **It is important to understanding whether an absence of recorded rock art on Murujuga in the registered sites database is reflective of reality, or is merely a function of the fact that there has been no prior survey in an area.** It appears that field sampling 'site' RS-18 on Legendre Island (top rightof Figure E-O-1/5-1) is located in an area where there is no previously recorded rock art (Figure 3-20 in comparison to illustrations without figure numbers in Appendix Section 4.2). **Contingency should be added in the sampling methodology in the event a selected field location does not contain rock art**—e.g. in field petroglyph/climate monitoring and rock sample location on Legendre Island. Furthermore, the Part B document would benefit from a new figure thatoverlays the selected field sampling sites on the known rock art locations/petroglyph density (as interpolated onto the 1.3 km grid overlay—combining the information from Figures 3-2 and 5-1). This new figure would clarify if the proposed RS-18 field sampling site is on a part of Legendre Island with no previously recorded art.	We disagree with this based on the discussion in response to comments 6 and 6a. EX and AQ squares were selected based on known rock art site boundaries. RS sites were not, however the field protocol specifies action when a square contains no rock art. In the case that rock types exist within the square that are rock types known to have art, then a rock sample only is taken. If no appropriate rock types are present above ground (e.g. Legendre Is) then the square is moved according to protocol.	See above. Acknowledged regarding the selection of EX and AQ squares. My request for a new figure that overlaysthe selected field sampling sites on the known rock art locations/petroglyph density (as interpolated onto the 1.3 km grid overlay—combining the information from Figures 3-2 and 5-1), has not been addressed. Also see close out comment to 9 below.
7	Throughout	Climate change scenarios should be addressed in the Part B document. In response to this suggestion in the peer review of Part A of the program, Calibre stated that "It has been agreed it will be included inthe study design and will be explicitly addressed in the Monitoring Studies Data Collection and Analysis Plan – Part B document." However, the words "climate change" do not appear together anywhere in the Part B document. Climate change impacts are relevant in relation to both the selection ofthe field sampling sites for the MRAMP and the measurement and interpretation of data relating to the deposition and degradation of the patina and mineral rind layers of the various engraved lithologies present in the rock art assemblage.	Climate change scenarios have now been mentioned in 3.32 and will be addressed as part of the project. However, we believe it may be premature to address it in detail at this stage, as we must first establish relationships involving relevant parameters (temperature, UV, CO2, weather patterns, etc.). that will be clearly influenced by climate).	I could not find any mention of climate change scenarios. A search of the supplied final draft for the words 'climate change' and 'scenarios' retrieved no results. There is no section 3.32 in the document. I assume this response refers to section 3.3.2. Section 3.3.2 i: "…representing the three rock types that host rock art (gabbro, granophyre, dolerite, basalt and granite)" I suggest editing the number of host rock types to five instead of three in the text to reflect the listed host rock types (also in the first paragraph of this section changing three to five). I acknowledge that many climate variables impacted by climate change should be implicitly captured in the thermodynamic modelling (outlined in section 3.3.2ix). I suggest adding a research question to "Section 3.3.2 xi Synthesis" that explicitly addresses the observed/predicted impacts of climate change on Murujuga rock art

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
				weathering and how these may feed into (and potentially amplify) any detected impacts from industry.
8	3.7 Detailed description of the proposed data collection program	The legend of the site density map shown as Figure 3-20 of the "Detailed description of the proposed data collection program", obscures Rosemary Island. The legends of both maps in the figure should be moved so that they do not cover any parts of the landmassin the illustration (perhaps they could be moved to sit in Nickol Bay).	Revised.	Acknowledged. The legend in right hand image of Figure 3-19 *DPLH registered site data, original data and resampled for weighting,* p.91 obscures Rosemary Island.
9	5 Locationand Schedule	Calibre should produce a new figure that overlays the selected field sampling sites on the known rock art locations/petroglyph density (as interpolated onto the 1.3 km grid overlay—combining the information from Figures 3-2 and 5-1). This new figure would clarify if the proposedRS-18 field sampling site is on a part of Legendre Island with no previously recorded art.	Addressed above	This comment has not been addressed. No response to a request for this new figure was provided in comment 6d. The does not contain a figure that overlays the selected field sampling sites on the known rock art locations/petroglyph density. Figure 3-19 in the final Monitoring Studies Data Collection and Analysis Plan illustrates the location of known rock art sites and rock art densities. It is not clear how these relate to the selected monitoring locations selected for the MRAMP.
10	5 Locationand Schedule	In response to my Comment 5 in the Part A peer review Calibre statedthat they would include a Gant Chart of the staged works program to make clear the initial five year term of the Monitoring Program, and clearly outline the timing of key activities within the MRAMP. While there is no Gant Chart in the Part B document, I note that the schematic illustration provided as Figure 5-3 serves the same function.I recommend that the indictive timing (years) be added at the top of thePhase 2 "studies" and Transition to Monitoring phases on the right of the illustration.	Indicative timing has been added.	Noted.
11	Section3.2.1 Variation in Murujuga rock art and Appendix 1	Calibre should ensure their field sampling program includes characterisation of some samples of the three additional geologies upon which Murujuga petroglyphs occur, that are discussed in Section 3.2.1 Variation in Murujuga rock art, but not accounted for in thestatistical modelling or sampling strategies outlined. On page 26 of the Part B document Calibre state that, "On Murujuga,the rock art occurs primarily on rock of fine-grained gabbro, granophyre or to a lesser extent dolerite. Some of the islands, like Legendre, comprise limestone, while on others, like Rosemary and Enderby, volcaniclastic sedimentary rocks and basalt are also present."	A virtue of design-based sampling is that is it not necessary to describe or account for the population structure in advance. However, sampled geology will be carefully studied.	I understand and acknowledge that the virtue of design-based sampling is that it is not necessary to describe or account for the population structure in advance. I would simply remind Calibre/Curtin, again, that the mechanics of how the representativeness of the rock art assemblage is accounted for is not in question (as per above comments). As they outline to Dr John Henstridge's comment 7 below, petroglyphs included in the MRAMP that have now been selected were chosen by a randomized procedure and arbitrarily. This does not preclude a representative sample of rock art being included in the study. Monitoring locations have indeed been 'reselected' a number of times already (see response to Dr António Batarda Fernandes' comment 28). It is therefore possible that sample locations could have been selected, 'ground truthed' and selected/reselected until such time as the requirement for a population of rock art that is representative of its known characteristics has been included in the MRAMP. I draw attention to the requirement of the MRAMP that the program include rock art sites that are representative of the relative rock sequence and archaeological features (DWER103118 MRAMP Tender Document Section 2.4.2). The characteristics of the rock art sites included in monitoring locations that have now been selected for the MRAMP remain unclear as the details of the selected rock art sites are not provided in the Monitoring Studies Data Collection and Analysis Plan.
12, but related also to6b	Appendix 1	The illustration of statistically selected 'Sample survey sites' (map labeled 'Selected' on Appendix 1 page 11) does not make clear whichgeological unit the survey sites belong to (map labeled 'strata on Appendix 1 page 10). The infilled circles in the former illustration that show the sample survey site 'Selected' via the statistical modeling should be coloured by their respective geological 'strata'.	A table has now been provided.	Noted.

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		As part of the revisions of this Appendix, Calibre should account for why the limestone geology of Legendre Island stated on page 26 is mapped as a mixture of “Granophyre present, Gabbro and Dolerite absent” (red) and “Gabbro present, Dolerite absent” (green) in the ‘Selected’ illustration in Appendix 1.		

2.3 Dr Antonio Batarda Fernandes – Review comments sheet for Detailed Study Design (Part A)

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: António Batarda Fernandes	
Document Title: Murujuga Rock Art Monitoring Project: Detailed Study Design (Part A)	
Document Revision: Version 1 (July 2020)	**Revised version**: Version 1.1 (January 2021)
Date of Review: 2 November 2020	**Date of Close out Report**: 6 February 2021

I believe that on-point general comments and notes will more appropriately set the tone for the review. This is an ambitious project and should be commended for attempting to tackle variable, undisclosed to great extent, sets of circumstances affecting the conservation of the Murujuga rock art complex. Focus is on the identification of anthropogenic sources of damage, arising from different forms of pollution, to the stability of the cultural rapport between patinated/unpatinated (or less patinated) rock surface areas, i.e. petroglyphs. Methodological approaches certainly considered a range of knowledge areas, and their recognized/anticipated interplays, to endeavor determining the real nature of damage effected on the petroglyphs by industrial activity at the Burrup Peninsula. Suitably, as the Study Design has benefited from the input of several researchers from diverse fields, so the peer review process will also benefit from the expertise that have been included in the review panel. Hence, I will keep my comments below within the realms of rock art conservation, management, and conservation management.

As overarching points regarding premises, structure, and content of the proposal document, the following are noted:

- Characterizing the fashion in which activities related to heavy industry at the Burrup effect the conservation of the Murujuga rock art has been identified as a sufficiently significant issue to be the subject of present and past efforts to scientifically address it. If such a goal is indeed praiseworthy, and full of promise regarding pioneering research domains, it should also be noted that natural change to the petroglyphs is also occurring. Hence, there is an opportunity made available by deploying resources that could also be taken advantage to identify, characterize, and attempt to mitigate natural threats to the survival of the rock art. If indeed the data that the project expects to acquire can also be of use in that regard, it is also acknowledged that it is the specific context of the Murujuga rock art conservation that in the first place motivated the creation of the research questions. Hence, if successful, it can be expected that the project major outcome, an effective Environmental Quality Management Framework (EMQF), will set the standard for future similar situations;
- I believe that a description of the Murujuga rock art complex should be included in the Introduction. Even if there are available various publications, including scientific papers, on the matter, and the draft Conceptual Model comprises a quite brief thus insufficient characterization of the how the Murujuga rock art was made, a broader audience consulting this document, reviewer included, would benefit from an account of the main facets of this rock art complex. For instance, questions such as “How old is it believed to be?”, “How many sites/motifs are known?”, “Were different styles/chronologies of the rock art identified?”, “Were all petroglyphs achieved resorting to the same engraving technique?”, etc. other relevant issues, should be concisely addressed and included in the proposal. Photos and other documentation materials, such as drawings, of the rock art should also be included to further illustrate the said characterization;
- The former point made me ponder if an archaeologist/anthropologist that could also act as an expert in liaising with the aboriginal community was included in the research team that prepared the document. If that was not the case, such an inclusion should be contemplated, not only to prepare the aforementioned addition to the text, but mostly to assure that the team counts with specific rock art knowledge expertise. I understand that the Murujuga Aboriginal Corporation (MAC) will closely monitor the unfolding of the project, and veto choosing a site not culturally suited to undergo sampling procedures. Therefore, ideally, the said archaeologist/anthropologist should be recruited from within the MAC, or, if not possible, be someone with an expertise in rock art studies, wide-ranging communication skills, and an already established rapport, or potential and willingness to do so, with MAC, or other aboriginal communities. This expert would also be of use in understanding and perhaps detailing the issues related to cultural constraints in site sample selection, as in giving a final family look to the text’s writing style and inconsistencies identified below, namely when considering the sample’s representativity issues;
- I understand that this is an ongoing process and at this stage it may be difficult to determine and envision for how long the project will run and, more importantly, how long before acquired data will effectively inform the EMQF. The straightforward answer to this question will note that the more time, the better. It is recognized that the proposal perhaps did not suggest any time frame out of reserve regarding the number of variables involved and yearly, decadal weather variability. Hence, from the offset it is advisable to consider if there is and will be a continuous commitment to carry the project through within multiannual and multidecadal time scales, notably regarding the future deployment of the EMQF. If that is not be the case, there wouldn’t be any point in launching the project under review;
- A methodology issue identified throughout the proposal is the non-consideration of aspect as one of the possible general variables, such as terrain slope (that nonetheless is only mentioned once, on p. 34), that may influence the behavior of identified systems that may affect the conservation of the rock art such as Microbiome, Organic, and Inorganic Chemistry. Indeed, it seems reasonable to assume that different solar orientation, as position in the slope, and consequent daily/seasonal oscillation of shaded areas would have an impact in growth/depletion of different organisms. Aspect may also have an effect in dissimilar receptivity of differently oriented surfaces to the deposition of pollution derived elements. Hence, aspect should also be considered in sampling methodology. On aspect and rock art conservation see Fernandes (2014).

- Again on methodology, it is a source of concern the lack of consideration for Biodeterioration, besides on the Microbiome scale, and a brief mention to bird droppings. Yet, are there different species of insects, or arachnids, etc., colonizing the rock surfaces? Lichens, liverworts, or bryophytes? Snakes, rodents, and so forth? *Existing* organisms are certainly part of the set of interplays that can affect both the patina *and* instrument's measurements at (sampling) sites. I acknowledge the range of expertise gathered towards this proposal, in a global context were projects of this breadth are quite rare, but I strongly advise considering the role in Biodeterioration, and resulting constraints to overall goals, of visible to the eye organisms under the scope of this proposal.

- It should be noted that although this is mainly a review of the methodological approaches the to issue at stake, some inconsistencies in writing style, references formatting, use of acronyms, and a few typos were identified, reasonable to expect when a text is written by several hands, as it appears to have been the case. Even if this is not a scientific paper for publication, care should be placed in reviewing those issues. If I will not signal (the few identified) typos, I will point, for each case, the first occurrences of inconsistent bibliographic referencing in the text. Linking references in the text to the correspondent entry in References list is suggested in order to make the full document easier to navigate and read;
- Finally, I note the availability of my PhD thesis, as I believe that it might help to inform an updated version of the proposal, even if my approach was on natural issues affecting the conservation of the Coa rock art complex in Portugal, and I will point to work I undertook in comments below: http://eprints.bournemouth.ac.uk/20995/1/Fernades_A-2012-compressed.pdf

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1	1.1, p. 4	"Once the microbiome has been characterised, it may no longer need to be monitored so closely as part of the ongoing monitoring programme, if a more accessible indicator of change has been identified." I have a few issues with this passage such as: will it be possible to completely characterize the microbiome, at each sampled site? How confidently can we expect that a more accessible (because it is easier to obtain/characterize?) indicator of change can be identified? Can this indicator be applied/valid in/for all sites?	The microbiome is expected to be substantially different during wet and dry seasons. For statistical reasons we would need to sample and analyse the microbiomes at least during mid winter and mid summer in years 1 and 3. This "initial monitoring" will result in an overview of locations and samples where the microbiomes differ significantly. In years 2-4, the unique samples will be investigated in in more detail to elucidate their activities and functional roles in forming biofilms, virulence, energy metabolisms incl. nitrogen cycling, ability to degrade aromatic compounds and PAH, organic acid production, and processes involved in biomineralisation processes, metal redox cycles, metal resistance, and metal acquisition. This is more costly and labor intensive and will therefore be performed on a smaller selected set of samples. Yes, we can sequence the entire microbiome (bacteria, archaea, microeukaryotes incl. fungi) nowadays and check if we reached full sequence depth from rarefraction curves. This can easily be done for all samples. Over 200 samples can be pooled and sequenced simultaneously in one run to obtain at least 40,000 sequence reads per sample.	Ok, I'm satisfied.
2	1.5, p.6	"(…) metal acquisition (varnish formation) vs. acidic biofilm formation (varnish dissolution) to the key microbial players associated with rock varnish." Does aspect, as noted in general comments, influence varnish formation/dissolution dynamics?	Yes, aspect affects patina formation. we have added new text to cover this: "We will use advanced genomic ordination techniques and advanced statistical methods to identify the effects of environmental parameters, such as aspect, on the microbiome, with particular reference to their effect on the varnish."	Ok, I'm satisfied.
3	1.6.1, p. 8	"(…) life of this project (…)". Which is? See general comment above.	The total project/contract duration is 5 years, which will consist of approximately 12 months of preliminary studies, followed by 3 years of ongoing monitoring. Upon completion, the ongoing monitoring will be handed over to DWER/MAC and/or subcontractors.	I believe this needs further clarification: duration is 5 years (12 months + 3 years). So, what will happen in year 5?
4	1.6.1, p. 8	"In an industrially-influenced scenario, the process of change is less well understood, but has been anticipated in recent studies to be an erosion of the manganese/iron mineralization crust. This would result in a lighter surface as the dark mineralization gives way to the lighter weathered rind beneath." It is assumed that pollutants indeed affect the patina, when it may not be so or the extent of that affection unmeasurable. In any case, the mentioned recent studies mentioned here should be quoted, and their insights summarized.	The quoted paragraph (beginning "In an industrially influenced scenario..") serves only as a guideline for the type and magnitude of changes which the study must be capable of detecting. The study design and the data analysis do not assume that pollutants affect the patina, and do not assume that anthropogenic sources affect the patina in any particular fashion. The sample size and other aspects of the study are chosen so that the study has adequate power to detect changes of a specified size and sign, predicted by one possible model of degradation. "..erosion of the manganese/iron mineralization crust" is one possible scenario suggested by Black et al. (year) and Dorn (2020), however addition and/or degradation through geomicrobial action (see recent review by Favero-Longo and Viles., 2020) is also a possibility, which will be investigated for the rock surfaces at Murujuga.	I suggest making this explanation/discussion available in the final text.
5	1.6.3, p. 9	"(…) but a quantum loss of surface through delamination can vastly alter the spectrometric measurement of a surface."	Agreed. Such loss through delamination is easy to detect through spectrometry via a "step change" in spectral values. This would prompt	I suggest making this explanation/discussion available in the final text.

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		This is a major uncertainty and the proposed morphological studies should be effective in determining quantum loss of surface.	further examination to determine if delamination or some other major event has occurred (animal droppings, etc.). However determining the factors which influence this phenomenon are more complex. The inorganic studies will investigate this phenomenon and develop a validated methodology to quantify surface adhesion.	
6	2, p. 10	No entry for Lau et al 2008 in references.	The citation should be Markley *et al*. (2014). All Lau *et al.* (2008) have been updated and Markley *at el.* added to the reference list.	Ok, I'm satisfied.
7	2.1.1, p. 10	"(…), the results are not available to us." Why? Can this situation be reverted?	This statement has been rephrased for clarity in the Part A document. Note, all CSIRO generated data is in our hands. There are a vast number of important details about the measurement protocol that have not been described in CSIRO reports.	Ok, I'm satisfied.
8	2.1.1, p. 11	No entry for Bednarik 2004 in references.	Reference to Bednarik 2004 has been removed from the text.	Ok, I'm satisfied.
9	2.1.1 i, p. 11	"These selected sites are not "representative" (…)" As pointed out just below in the text proposal, selection of representative sites to be included in a sample is a major concern in such a study. Evidence regarding this matter from previous studies should thus be taken as a cautionary tale, moreover considering that cultural constraints may hinder a completely random selection of sites, to an (yet) unknown extent. Check also comment #31.	Noted and agreed.	Ok.
10	2.1.1 ii, p. 12	"(…) it presents the risk that scientific findings that are partially based on these instruments may not be accepted by the scientific community." As I understand, the proposal attempts to address this concern in Table 3.1 (2). However, it would be beneficial to expand here (or in section 3.1.3 on the fashion the project will endeavor to counter instrumental operational limitations.	The quote is from Section 2.1.1. paragraph ii, and states that some of the published commentary on previous research drew attention to the fact that the instrument manufacturers' disclaimers discourage the use of their instruments in field work. In our view, this criticism can only be conclusively eliminated by finding a suitable instrument that is endorsed for field work. However, we agree with the reviewer that, by adopting careful technique, we may be able to achieve the desired level of reproducibility, and thereby gain the confidence of a majority in the scientific community.	Ok, I'm satisfied.
11	2.1.2, p. 16	"Ramanaidou et al., 2019" Check et al referencing throughout the text as this should read "Ramanaidou and Fonteneau	Noted and corrected.	Ok, I'm satisfied.
12	2.1.3, p. 18	"In addition, various microcolonial fungi (MCF) have been characterized in rock varnish coatings on andesitic volcanic rock of the semi-arid Chihuahuan desert (New Mexico, USA) using a combination of scanning electron microscopic (SEM), cultivation, and molecular (18S rDNA profiling). Many of these MCFs were found to be related to fungi known to perform Mn- and Fe- oxidation (Parchert et al., 2012)." As these teams investigated microbiomes in similar environments to the Burrup, with petroglyphs also made by erasing varnish in the case of the Negev Desert, I suggest checking both Nir's papers, specially the one on seasonal diversity, as well as Wu's, all noted in References below.	We thank the reviewer for this comment. Please note that we already mentioned that we will study the fungal diversity using ITS and 18S barcoding. 18S profiling will e.g. reveal algae that may live in symbiosis with fungi if endolithic lichens are present. We will now perform cultivation experiments from rock varnish and underlying weathered rock samples in media supplemented with and without reduced forms of manganese and/or iron plus low amount of carbon to enrich for bacteria and fungi capable of precipitating iron and/or manganese oxides (Northup et al., 2010; Parchert et al., 2012). The enriched microbiomes will be sequenced and compared with enrichments without reduced forms of manganese and iron present as well as with the original 16S rRNA community to verify their capability to form the patina. The parallel sequencing of (reverse transcribed) short-lived transcripts of bacterial 16S, fungal ITS and 18S of the Domain Eukarya will confirm which fraction of the patina microbiome was alive at the time of sampling. This has now been added to the proposal. We also cited the relevant papers from Irit et al., 2019 and Wu et al., 2020 plus a recent review article from Fabveor-Long and Viles, 2020 among others in Evaluation of Previous Studies section 2.1.3.	Ok, I'm satisfied.
13	2.2.3, p. 20	"Coolen and Orsi, 2015" not in the References section.	Reference added	Ok, I'm satisfied.
14	3.1.2, p. 21	"Representative sampling under constraints" This is potentially one of the major challenges to overcome.	We see no need to edit the existing text in section 3.1.2 (Key Considerations and Constraints). The paragraph headed 'Representative sampling under constraints' begins with the statement that 'The selection of sites ... must reconcile many competing	Ok, I'm satisfied.

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		"Analysis should focus greatest attention on culturally important areas. All observation and sampling activities require approval for cultural and safety reasons. Approval will not be granted for sampling or observation at some sites --- especially those sites which are the most culturally important." I recommend rephrasing to avoid redundancy/contradiction: "focus greatest attention on culturally important areas"/"Approval will not be granted for sampling (…) at some sites --- especially (…) the most culturally important".	requirements.' The subsequent text represents those requirements and constraints, which are indeed somewhat contradictory. This text accurately represents the design challenges.	
15	3.1.2, p. 21	"Complex inter-relationships" Indeed the multidisciplinary approach wisely comprising the most relevant scientific fields to tackle research questions (namely, the overriding "How does industrial pollution impact the petroglyphs?"), as proposed methodologies, are on the right track to obtain relevant data regarding the query. Nevertheless, it remains uncertain that the mustered knowledge disciplines alone can adequately characterize the full extent of these "Complex inter-relationships". As noted above, at least two fields of expertise were identified as valid additions to the research team: Rock Art studies and non-microscopic Biodeterioration. Also, Geology, Desert Ecology, …?	In addition to and supporting the scientific studies, the sites will be condition surveyed by Murujuga Rangers under the leadership of one of the research team, a specialist in rock art condition surveys. It is purely an observational process but one that notes all relevant bio-, geo- and other features, including the extent of delamination, presence of bird droppings and other transient and incidental changes to the rocks.	Ok, I'm satisfied.
16	3.1.2, p. 22	"rock composition" And of the patina?	"Rock composition" has been replaced by "rock and patina composition"	Ok, I'm satisfied.
17	3.1.2, p. 22	"chemical composition of the industrial output (…) is needed" Will such information be available?	Some compositional information is available or has been obtained (Reportable emissions). Further analysis of high volume/mass air samples will be undertaken.	Ok, I'm satisfied.
18	3.1.2, p. 22	"(…) in an effort to artificially age and degrade the rock." Again, and the patina?	"and patina" has been added.	Ok, I'm satisfied.
19	3.1.2, p. 22	"Rock strength" Perhaps it is convenient to look at different methods to measure rock strength. A classic one can be found in Summerfield (see below in References).	Strength might not have been the best term to use here, because the preparation method will depend on a range of rheological properties that will determine the optimal preparation technique. This has been clarified in the new text in this section, which now reads "The rock's rheological properties will affect preparation methods. Petrographic technique involves cutting a very thin slice of rock, polishing the cut surface, and observing it under an optical microscope (in transmitted light). Typical section thickness is 30 microns (0.03 millimetres), and if the rock is too fine-grained and breakable then it might need to be impregnated with epoxy. The alternative would be to use a 'billet' (a chip of rock about 25 x 15 x 15 mm, about the size of the top joint of a person's thumb). These considerations affect the study design."	Ok, I'm satisfied.
21	3.1.3, p. 23	"(...) (Andersen, 1980)." Year does not coincide with that given in References.	This has been corrected to Andersen (1990).	Ok, I'm satisfied.
22	3.1.3 i, p. 23	"(…) angle to the prevailing wind directions." I.e., aspect…	Andrew Thorn suggests the conventional use of the term "aspect" in the rock art research community encompasses a broad range of features including 3 dimensional orientation. This has been clarified in the glossary.	Ok, I'm satisfied.
23	3.1.3 ii, p. 25	"Differences between rocks" Again, check aspect.	See above response.	Ok, I'm satisfied.

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24	3.1.3 ii, p. 25	"Rock surfaces which have been culturally altered may be physically different from the overall population of rock surfaces, for example because the engraving process may require the rock surface to be strong and homogeneous." This is an extremely important point, moreover considering that some "culturally important sites" may not be available to be included in the sample chosen to implement the proposal. The proposed methodology ahead in the text to tackle potential sampling sites selection limitations is believed to have the potential to counter this constraint. However, considering all the latent constrictions, perhaps a totally random ("culturally important sites" exempt) selection is not the most suited to counter these. Do check Fernandes (link in general comments, namely pp. 53-56).	It would be incorrect to describe the sampling regime as 'totally random'. A much more sophisticated randomised sampling design is envisaged. We are confident that the sampling design will be well-suited to the application.	Ok, I'm satisfied. I look forward on what the project results can offer as evidence of deliberate choice of stronger rock surfaces to be object of artistic attention.
25	Table 3.1, p. 26	"Instrument will be stabilized in two ways. Air temperatures will be recorded for each measuring session at each target. Instruments will be insulated and peltier cooled to the nominated operating range. Readings only take within defined air temperature range." I suggest revisiting this passage; it is hard to entirely comprehend the fashion in which instruments, and their readings, will be stabilized.	This passage has been rephrased to clarify this.	Ok
26	Table 3.1, p. 27	"Undocumented change to the surface, bird droppings tourist impact etc" See general comment above on Biodeterioration.	Unclear what the reviewer means. This is a reference to Table 3-1 (Table 3-2 in revised Part A document) on sources of variability. The entry in the table acknowledges that undocumented changes to the rock, including tourist impacts, constitute a potential source of variation in the color measurements. This affects the study design but does not oblige us to call on additional branches of science.	Agreed, but bird droppings, and I suppose tourist impact, are all Biodeterioration issues… Yet, are there different species of insects, or arachnids, etc., colonizing the rock surfaces? Lichens, liverworts, or bryophytes? Snakes, rodents, and so forth?
27	Table 3.2, p. 29	"(…) which would take it a 100 microns or more." I suggest revisiting this passage; it is hard to entirely comprehend what is meant.	In the document, this has been clarified as: " The thickness also varies from almost undetectable to opaque. Opacity indicates thicknesses above 100 micrometers. "	Ok, I'm satisfied.
28	Table 3.2, p. 29	"Impact might be proportional to the degree of sheltering, but then again, it might not. I am not aware that this factor has been studied." Again, check my PhD, also for reference list. Also, check pronouns regarding writing style: we/I.	Phrasing has been revised to remove first person pronouns.	Ok, I'm satisfied.
29	Table 3.2, p. 30	"We are not aware of a study of the effects of this factor" Although not precisely on the effects of water flow on rock surfaces, and its consequences for the goals of this project, perhaps Mol and Viles paper in References below can provide useful insights on this matter. I also recommend browsing Helen Viles scientific output as other relevant data relevant to this project may be found.	Noted; we will incorporate this work in the Part B document.	Ok, I'm satisfied.
30	3.1.4 b, p. 35	"For the Murujuga study there is still insufficient information about space-time correlation to confidently predict accuracy, or to determine the optimal locations for additional monitoring stations. An initial priority for the project is to obtain better information about the space-time behaviour of the pollution field on the peninsula." Won't space-time correlations interpolated/extrapolated/inferred from limited sampling/available data, on both dimensions, influence/determine obtaining "better information" regarding that behavior? Please expand further.	At this stage of the document we are discussing only the principles of study design. The statement is that there is insufficient information about the space time correlation of weather variables and gas species concentrations across the peninsula, and that it is a priority to obtain more information. The statistical methodology for obtaining detailed information about the space time correlation structure is complex and will be described in Part B of the study design document.	Ok.

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31	3.2.1 i, p. 36	"'representative'" I suggest considering the use of apostrophes and/or quotation marks throughout the text and with this particular word. On the one hand, consistency in using one or another is recommended. On the other, more importantly, considering the importance of choosing a representative sample has for research goals, I believe that noting in this fashion that the sample may not be representative, if that is the point in using one or the other, or non-use at all in other passages, casts doubt on what is really meant, as on the possibility of arriving to a representative sample.	The term 'representative' is popular in vernacular writing and in many branches of science, but is not a recognised technical term in statistical science. In statistical science, more precise terms are used to specify the exact sense in which a sample may be considered representative. Rather than delving into this technical detail at a stage when we are merely describing the overall principles of study design, we have chosen to use the word 'representative' with quotes.	Ok
32	3.2.1 i, p. 36	"This second set of sites will be the basis for statistical inference about the entire population of rocks, while the combined set of old and new sites will allow spatial interpolation." Why use old sites in one (spatial interpolation) and not the other (statistical inference)?	Different statistical principles are used to draw inferences about a population from a sample (of rocks) and to interpolate spatial observations (of air quality). The principles of sampling theory which apply to the first problem do not permit the use of non-representative samples.	Ok.
33	3.2.1 ii, p. 37	"Areas which are deemed unsafe for any reason, or for which permission will not be granted under any circumstances, will be designated as such, and removed from consideration." The major question here in selecting a representative sample is the proportion of areas that will be removed from consideration within the total universe of *sites/rocks/surfaces* with petroglyphs.	Our randomised sampling design will obtain a sample which is representative of the population of rocks in the areas which have not been excluded from consideration. Estimates of population quantities based on this randomised sample will be based on standard principles of randomised-design-based sampling. For the areas which are excluded, we will use completely different methods, based on prediction from available data, to obtain estimates for the population in these excluded areas. The concept of a representative sample will not be applicable or relevant to the excluded areas. However, we agree in broad terms that the task would become more difficult if a large proportion of area were to be excluded.	I suggest making this explanation/discussion available in the final text.
34	3.2.1 iii, p. 39	"In summary the desired sampling procedure should select 10 to 20 individual rocks, which determines the sampling fraction for the site selection protocol. Each rock site should be examined at 10 to 20 fixed spots, and each observation replicated 10 times." It is not clear if this figure ("10 to 20 individual rocks") is proposed to be the sample size for *all* monitoring procedures or *only* for color measurements as just above you only discuss CIE coordinates a and b. I suggest revising all the passages in which sample size is mentioned, to assure consistency throughout the text, namely of suggested sample size to be considered in each monitoring activity.	This refers only to the spectrophotometry work. (Sample sizes are tentative in Part A of the document, and will be revised in Part B using rigorous statistical design procedures)	Ok, I'm satisfied.
35	Figure 3-6, p. 46	"Ambient temperature" How was this value calculated? Or is this Figure just an example?	The temperature data have been taken from half-hourly readings from the nearest weather station, Karratha. The days were random but typical whereas the hourly variations within each day followed a set pattern. The purpose of the diagram is to show that a 5-degree measurement window can be achieved on almost any day, simply by choosing the time of day to start measurements, provided the months are reasonably consistent each year.	Ok, I'm satisfied.
36	3.2.3 i, p. 47	"while the project is ongoing" Again, for how long will it be ongoing? See general comment and comment # 3 above.	As above, The total project/contract duration is 5 years, which will consist of approximately 12 months of preliminary studies, followed by 3 years of ongoing monitoring. Upon completion, the ongoing monitoring will be handed over to DWER/MAC and/or subcontractors.	See above.
37	3.2.3 i, p. 47	"known age sequence" What is meant by this? Age of petroglyphs, exposure, geologic sequence?	The age sequence has been determined by archaeologists studying these engraved surfaces. A combination of contrast between engraving and background with stylistic changes has allowed for a reasonable sequence to be developed. This will be used as the basis of this study but is not an attempt to confirm the sequence, simply a means of matching loss of contrast with known age trends.	I suggest making this explanation/discussion available in the final text.

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38	3.2.3 iii, p. 49	“sandstones identified by the author” Which author?	By the researcher undertaking the in-situ colorimetric and elemental studies (Andrew Thorn)	Ok, I’m satisfied.
39	3.2.3 iii, p. 49	“Pillans and co- authored” Check referencing.	Corrected to Pillans and Fifield (2013)	Ok, I’m satisfied.
40	3.2.3 vi, p. 54	“45 elements” Relates to p. 48?	The Skyray instrument is factory set to analyse 45 elements. This covers all of the relevant elements from Magnesium and heavier. Of the elements that can be measured only 15 or so should be of relevance in studying element ratios, used to monitor alteration.	Ok, I’m satisfied.
41	3.2.3 viii, p. 54	“Condition surveying” Comprising which parameters/indicators of change?	The proposed Condition surveys have been developed by the researcher over several decades to record observable non-contact features of a rock surface. In a full survey up to 80 features are recorded. In the Murujuga context a specific database has been constructed that records about 30 attributes ranging from surface slope and solar orientation through to rock type, biota, accretions, delamination’s, salt efflorescence, water flow patterns, and all other observable features that affect the long term stability of the rock.	Ok, I’m satisfied.
42	3.2.3 ix, p. 55	“As discussed in Section 3.2.1 the design involves the 9 sites used in previous studies, augmented by approximately 10 additional sites selected by a randomised sampling design. At each site there will be 20 replicate measurements taken at each of 10 spot targets.” 10 or 20 additional sites? See comment 34.	See response to comment 34.	Ok, I’m satisfied.
43	3.2.3 x, p. 55	“This technique has been developed by the researcher and published” Which researcher? Reference please.	Developed by the researcher undertaking the colorimetric measurements (Andrew Thorn, Thorn, 2021).	Ok, I’m satisfied.
44	3.3.1, p. 56	“As there is significant evidence that the bio/geo/physico-chemical processes which occur on the rock patina are comparable on both culturally altered (petroglyphs) and unaltered rocks of all types (Dorn, 2020).” Even if this assertion is correct, just one reference, tough from a leading researcher in the field, I believe doesn’t constitute “significant evidence”. Dorn focuses his studies in the Southwestern USA area; different environment conditions at the Burrup may cause variations (pace, etc.) on the fashion these processes unfold on engraved and non-engraved patinas. Moreover, patina was removed to achieve a petroglyph, exposing, at some time in the past, non-patina covered fresh rock. This fact, even considering subsequent (steady-paced?) repatination dynamics, may also determine differences in the way the said processes occur in both types of surfaces.	Black et al., 2017 shows an image of a petroglyph in Murujuga that is overgrown with patina. We are not allowed to sample patina and exposed weathered rocks directly from the petroglyphs. However, there is no reason to assume that the microbiome associated with this patina is substantially different from the patina-associated microbiome on similar unaltered rock types if exposed to similar environmental conditions. It is now more clearly described in the proposal that we will also subsample the weathered rock located immediately below the patina to confirm if endolithic fungi/lichens have penetrated the patina and started to colonise the underlying weathered rock. This may have also served as a vehicle to transport bacteria to the weathered rock below the patina. This is now better described in 2.1.3.The presence of fungal hyphen of endolithic fungi will also be confirmed through scanning electron microscopy at the John de Laeter Centre at Curtin University. We added the recent Dorn, 2020 reference among others.	Ok, I’m satisfied.
45	3.3.1, p. 56	“are consistent across the whole of Murujuga (subject to environmental gradients).” Are they? Aspect, slope, petrography, etc. may cause environmental gradients to be more than ‘just’ gradients. I look forward for the project results on this matter.	Agreed. This may be the case. The study design will ensure all of these features (aspect, slope, petrography, exposure to precipitation/moisture and direct sunlight/UV etc...) are captured with appropriate statistical power to answer these questions.	Ok, I’m satisfied and looking forward to resulting answers.
46	3.3.1, p. 56	“Rocks showing variation in surface coloration and mineral composition will be investigated for organic composition” Why? Please expand.	The organic composition needs to be determined because VOCs and other petrochemical-derived compounds vs. natural organic compounds such as terpenes from plants may cover these rocks. These organic films are not per se visible to the eye, but may serve as energy and carbon sources to (have) support(ed) microbial growth, which then could (have) impact(ed) the minerology and subsequent color changes.	Ok, I’m satisfied.

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47	3.3.1 i, p. 66	"(in)organic" I find this formulation lacking clarity; wouldn't be more appropriate to say "organic and/or inorganic"?	Noted and corrected in the document.	Ok, I'm satisfied.
48	3.3.3 i, p. 66	"If this is the case, it is to be expected that microbially formed dark varnish will start to overgrow the lighter coloured weathered rock underneath." It will be interesting to assess if there are spikes (or drops) in microbial growth that can be (directly) linked with shifting abundance of different pollutants.	This is indeed our main hypothesis. As mentioned in the proposal we will perform multivariate statistical analysis to compare changes in the microbiome (relative abundance of the members of the communities, gene copy numbers, changes in gene expression) with quantitative differences in the various organic and inorganic pollutants. The drops in growth will be mainly observed by comparing wet vs. dry conditions/seasons. Furthermore we added a paragraph in the detailed approach section 3.3.3. where we propose to install sterile slabs in year 1 that will be subsampled during the second sampling expedition in year 3 which will allow us to determine the communities and functions that developed within a time frame of 2 years. This will also serve to eliminate variability in rock fabric and orientation.	Ok, I'm satisfied.
49	3.3.3 ii, p. 67	"north to south and east to west environmental gradients" This is the sole reference on how aspect will influence sample selection, though only in the case of obtaining "rock varnish and underlying weathered rock" samples. See comments above on aspect.	Details of the sampling design will be elucidated in Part B. The quoted text indicates that it will be important for the sampling design to capture the expected geographical gradients, including but not limited to the 3 dimensional aspect, elevation, sheltering effects and mineralogical gradients.	Ok, I'm satisfied.
50	3.3.3 ii, p. 67	"(...) in years 1 and 2 of the project. The locations will be chosen in agreement with the original owners of the land, the rest of the research team, and to ensure that they differ significantly in the level of petrochemical and fertiliser pollutant exposure, which will be analysed by the team in parallel." Enough time to determine how petrochemical and fertilizer pollutant exposure differs? Or other data will be used to determine how "they differ significantly in the level of petrochemical and fertiliser pollutant exposure"?	Since this document was finalised, we have received the results of a separately commissioned (2020) study by Ramboll, which used plume dispersion modelling to conduct coarse resolution (1.33 km) modelling of air quality and deposition on rocks from local and distal sources (including the industry mentioned). These data are being used for the initial site selection, with refinement to be provided by the (finer scale) CFD modelling. We therefore will have predicted exposure for all study sites, allowing us to select an appropriate, statistically rigorous exposure gradient for the study. These predictions will be validated against measured data at co-located air/deposition monitoring stations.	Ok, I'm satisfied.
51	3.3.3 ii, p. 67	"(…) paintings" Are there rock art paintings at the Burrup or this is just an inaccuracy? If there are, which would add another layer of complexity to the project, due to painted rock art specific conservation constraints, these present proposal does not consider them.	This was an inconsistency and has been changed to "rock engravings" or "rock art engravings" in the document.	Ok, I'm satisfied.
52	3.3.4, p. 72	"3.3.4 Organic Geochemistry" Follow section 2 order?	The section numbering and titles have been made consistent.	Ok, I'm satisfied.
53	3.3.4 ii, p. 72	"(see 3.2.4.3)" Which section?	This has been changed to 3.3.4 iii	Ok, I'm satisfied.
54	3.4, p. 76	"at a number of rock art," sites, surfaces?	Sites; corrected in the document.	Ok, I'm satisfied.
55	3.4.1, p. 77	"viii Deposition Sampling" Check subheading numbering.	Noted and corrected.	Ok, I'm satisfied.

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56	3.4.1, p. 77	"The samplers utilise humidity and/or precipitation sensors which are linked to a mechanism which will rotate the cover to open the appropriate collection bucket. In a rain event the wet deposition collection bucket will be opened and the others covered. When the humidity drops the cover will again rotate and the dry deposition bucket will open, and the other buckets will remain covered. When the humidity is high but the weather station is not reporting rain (sampler and weather stations to be co- located) the third bucket will be uncovered. Thereby allowing us to collect both wet and dry deposition samples, and a third set of samples for mist events, without needing to continuously be onsite." Attention should be given to 'odd' recorded events as indication of samplers/weather station malfunction.	Noted and Agreed	Ok, I'm satisfied.
57	3.4.1, p. 78	"VOCs"?	Volatile Organic Compounds - now defined when first used	Ok, I'm satisfied.
58	3.4.1, p. 79	"To help ensure reliability of the results and to account for any failure, or damage of the passive sampling tubes there will be duplicates of each tube at each location (i.e. they will be deployed in pairs)." And will the data from these duplicates be also compiled and analyzed? If yes, interesting to check if data collected by duplicates strictly concurs with the one gathered by 'originals'.	Yes - we plan to analyse all samples.	Ok, I'm satisfied.
59	3.4.1, p. 79	"The weather station and NO monitor measure continuously so will be set up to log data every 5 minutes, resulting in 288 measurements per day, per location." This will generate vast amounts of data! As stated below in the proposal, supercomputing resources need to be deployed to process and analyze this wealth of information.	Yes - agreed.	Ok, I'm satisfied.
60	3.4.1, p. 79-80	"Departures from Best Practice" Mention should be given here to monitoring devices malfunction and maintenance in harsh and remote locations.	Mention of this issue has been expanded in the revised document.	Ok, I'm satisfied.
61	3.4.1, p. 80	"These stations have both on board data-logging and a range of communication options." Resorting to antennas? How high? Consider visual impact at rock art sites, even if the sites are not open to public visitation. Moreover, mention should be given to apparatus reliability constraints.	Our preliminary studies to date indicates that most of the sites have adequate 3G/4G GSM coverage to enable communications to be performed using short antennas (<200 mm) - which will be no more obtrusive than the monitoring stations.	Ok, I'm satisfied.
62	3.4.1, p. 81	"The passive sampling tubes will be prepared by analysed by the supplier." ?	It is a requirement of the project that analysis be undertaken by a NATA certified (or equivalent) laboratory where possible. For this reason we have selected a supplier which can provide sampling tubes for all species required and analyse them using appropriately validated methods.	Ok, I'm satisfied.
63	3.4.1, p. 83	"Data logging" Consider that data from sites/samplers/loggers can corrupt and state how available/collected data will be used to interpolate/extrapolate missing data.	Data will be logged locally as well as transmitted via 4G GSM to a central base station. Locally stored data will be downloaded monthly and cross checked withy transmitted data as part of QA/QC procedures.	Ok, but will available/collected data will be used to interpolate/extrapolate missing data impossible to retrieve?
64	3.4.1, p. 83	"This will be similar to the power supply utilised by the weather station, which will also utilise a solar panel and a rechargeable battery." A reliable supply of batteries will be needed.	Agreed.	Ok, I'm satisfied.

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65	3.4.1, p. 85	"Damaged or faulty sensors will be replaced, with repairs and recalibration of any faulty sensors to be completed by the supplier." So, it is advisable to have a vast supply of spares to substitute faulty sensors in-between completion of repairs.	Agreed and this will be undertaken.	Ok, I'm satisfied.
66	p. 93	"3.5.2 Detailed description of the proposed data collection program" Check subheadings ordering in this section.	Corrected in the document.	Ok, I'm satisfied.
67	2. Emissions Inventory, p. 97	"(…) as long as the availability of this data is compatible with Rock Art Monitoring project timeline." What is meant in this passage? That the data may not be available? Under which circumstances?	At the time of writing, the authors were unsure of the timeline for obtaining these data. It has now been obtained.	Ok, I'm satisfied.
68	2. Emissions Inventory, p. 97	"Better data is likely to be found in past environmental impact studies and/or directly from the industries operating on the Burrup Peninsula." Will it be available?	As above	Ok, I'm satisfied.
69	4. Site Topography, p.97	"This data has been requested from Landgate, in addition to the point cloud used to create the smoothed DEM." Will it be available?	As above	Ok, I'm satisfied.
70	Fitness criteria for assessing the monitoring network, p. 100	"An example would be where MAC deems a site to be of particular cultural importance." I recognize this is a delicate topic, but, as already discussed throughout comments, more should be said regarding sites of particular cultural importance. For instance, what is the criteria for establishing significance? Or aren't all sites bearing petroglyphs culturally significant? As this constraint has the potential to thwart, to an unknown extent, a completely unrestricted selection of sites, I believe efforts should be placed in trying to understand criteria for establishing cultural significance. Understandably, it may be the case that MAC is not comfortable in divulging/sharing the reasoning that shapes such criteria. It is at this juncture that including a rock art expert in the overall project, as mentioned in general comments, may prove to be instrumental to its success. If on the one hand it is acknowledged that MAC has all legitimacy to veto site selection, and to not detail the reasons to do so, on the other, inappropriate choice of sampling sites may render results of the whole project less conclusive, hampering the overarching goal of determining the role pollutants play in petrogplyph degradation…	Technically it is not necessary to know why a particular area has been excluded from consideration in the sampling design. There exist many well-developed statistical methods for accommodating stratification, non-response and variable response in surveys. Some of these techniques will be deployed in the study. We also wish to emphasize that MAC and DWER have jointly commissioned this research, and jointly determine the objectives and ground rules. There is a spirit of partnership between MAC, DWER and the research contractors, who all have an interest in the success of the research project. We are confident that any substantial difficulties which might arise will be addressed in a cooperative fashion by all parties.	Ok, I'm satisfied.
71	4.3, p. 102	"Dr. Andrew Thorne" Thorne or Thorn?	This has been corrected to Thorn.	Ok, I'm satisfied.
72	References, p. 111	"Ramanaidou E.R., Fonteneau L.C., 2019. Rocky relationships: the petroglyphs of the Murujuga (Burrup Peninsula and Dampier Archipelago) in Western Australia. Australian Journal of Earth Sciences 66, 671- 698." Repeated entry.	Noted and repeated entry has been removed.	Ok, I'm satisfied.

Item No.	Section No.	Peer Reviewer Comment	Response	Peer Reviewer Close-out Comment
73	References, p. 112	"Sessions A.L., 2006. Isotope-ratio detection for gas chromatography. Journal of Separation Science 29, pp. 1946-1961." Check formatting.	Corrected.	Ok, I'm satisfied.
74	References, p. 112	"Thompson, S.K., Seber, G. 1996. Adaptive Sampling. Wiley, New York." Not cited in the text.	Noted; removed from document.	Ok, I'm satisfied.

References:

Fernandes, A. B. (2014) Aspect and rock-art conservation: Preliminary meteorological data regarding the Côa Valley, Portugal, open-air rock-art complex. In Darvill, T. & Fernandes, A. B. *Open-Air Rock-Art Conservation and Management: State of the Art and Future Perspectives.* New York: Routledge, pp. 125-141.

L. Mol, H.A. Viles, Geoelectric investigations into sandstone moisture regimes: Implications for rock weathering and the deterioration of San Rock Art in the Golden Gate Reserve, South Africa, *Geomorphology*, Volume 118, Issues 3–4, 2010, Pages 280-287, https://doi.org/10.1016/j.geomorph.2010.01.008.

Nir, I., Barak, H., Kramarsky-Winter, E. *et al.* Seasonal diversity of the bacterial communities associated with petroglyphs sites from the Negev Desert, Israel. *Ann Microbiol* **69,** 1079–1086 (2019). https://doi.org/10.1007/s13213-019-01509-z

Nir, I.; Hana, B.; Yifat, B.; Esti, K.-W.; Ariel, K. Insights into bacterial communities associated with petroglyph sites from the Negev Desert, Israel. *J. Arid. Environ.* **2019**, *166*, 79–82.

Summerfield, M., 1991. *Global geomorphology: An introduction to the study of landforms*. Harlow: Longman. (p. 166)

Wu, Y.-L.; Villa, F.; Mugnai, G.; Gallinaro, M.; Spinapolice, E.E.; Zerboni, A. Geomicrobial Investigations of Colored Outer Coatings from an Ethiopian Rock Art Gallery. *Coatings* **2020**, *10*, 536.

2.4 Dr Antonio Batarda Fernandes – Review comments sheet for Monitoring Studies Data Collection and Analysis Plan

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: António Batarda Fernandes		
Document Title: Murujuga Rock Art Monitoring Program: Monitoring Studies Data Collection and Analysis Plan		
Document Revision:	Version 2.1 (September 2021)	Close out comments on Version 2.2 (November 2021)
Date of Review:	29 September 2021	Close-out comments 2 December 2021

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
1	All	Further proofreading is required: there are typos and wording or format issues throughout the text. I did not check in text references or reference list.		
2	Executive Summary	“which will be revisited for studies where preliminary data is yet to be obtained.” Does this mean that sample choice as presented in the whole document isn’t yet final?	The sampling sites have now been confirmed and visited and are considered final. Refer section 11 in the revised document.	Ok. Be sure to be prepared to choose, following the same method, ‘secondary’ sample sites in case any of the chosen became unavailable for any unforeseen reason.
3	Executive Summary	“It is important to note that the rangers and staff of the Murujuga Aboriginal Corporation (MAC) will be involved in (and trained in) all aspects of the field data and sample collection, as well as the laboratory techniques and analysis/interpretation of data if desired. It is envisaged that all field monitoring will be able to be wholly handed over to the MAC rangers during the life of the Program.” Apart if it is desired or not (but if it isn’t?), it seems quite challenging to wholly hand over field monitoring to MAC rangers because of a major constraint, the complexity of instrumentation and measurements. If some will be quite straightforward to master (weather stations, for instance), equipment such as the JAZ spectrometer will be more difficult to operate by non-specialists. I understand that one of the goals is also to hand over monitoring and respective app-like platforms for straightforward MAC use. To make *all* variables measured in the field user-friendly to be monitored is, I believe, one of the greatest challenges of the project and indeed of the ‘after-project’. Case in point, if the project length is of 5 years, perhaps fully handing over monitoring to MAC rangers may require and extension of the project’s length.	Agreed. The MAC rangers have been undertaking some similar monitoring and will be trained in all aspects over the following years if capacity exists among the ranger cohort. It will be up to MAC and DWER to decide at the end of the current study if the ongoing monitoring is to be performed directly by MAC or instead by consultants supervised by MAC. These issues will no doubt be explored further in the coming years.	Ok. I reiterate the need to consider that the end of the current evaluated project must not be the end of monitoring the condition of the Murujuga petroglyphs.
4	1	"https://www.wa.gov.au/government/publications/murujuga-rock-art- monitoring-program-conceptual-models” Link not working.	Link is now fixed.	Ok
5	1.2	“fungi and endolithic lichens are present on and in the rock surface” “Rock surface” with or without petroglyphs?	Lichens have not been recorded on petroglyphs. However, they could easily overgrow a petroglyph. Microfungi have been found to be abundant in preliminary works.	Ok. This reviewer prior work/experience indicates that petroglyphs grooves tend to be ‘preferred’ by lichens for recolonization purposes due to the shelter and easier to attach to areas these provide. https://eprints.bournemouth.ac.uk/20995/1/Fernades_A-2012-compressed.pdf (see page 382)
6	1.4	“organics present in the host rocks” Host to what? I’m guessing petroglyphs but it is unclear.	Revised. This was intended to be “fresh” rock.	Ok

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
7	1.7.1	“It is considered likely that, within the life of this Monitoring Program, colour change will not be of sufficient magnitude to provide meaningful interpretation in its own right.” Hence the importance of extending length but also of the ‘after’ project. Check comment #3.	There are certain aspects of the project, which it would be beneficial to continue after the scheduled end of the project. This is certainly the intended for the air quality monitoring, but would certainly be beneficial for colour change measurements and the like. Ultimately, decisions around continuation of the project rests with DWER.	Ok
8	1.7.1	“The rate of this convergence has been estimated to take millennia.” Please add reference.	Revised and reference added.	Did not find reference in the final document sent on 22/11.
9	1.7.1	“In an industrially-influenced scenario, the process of change is less well understood, but has been anticipated in recent studies.” Please add reference.	Reference added	As previous.
10	1.7.3	“available using the laboratory-based techniques” It is not clear what will be done in the lab and to what.	All measurements of petroglyphs will be performed in the field. However, in the AQ sites, rock art panels have been “twinned” with rock samples of similar patina and orientation, which can be studied in the laboratory using higher resolution methods.	Ok.
11	2.1.1.i	“Overcoming this weakness should be a priority for the Program. Otherwise, the study will need to deploy alternative, less- satisfactory methods of extrapolation based on model assumptions.” Overall, the randomized sampling methods applied to the study design did a good job in trying to assure, all constraints considered, that the resulting sample will be representative, in all studied dimensions. Nevertheless, caution suggests that the Program should be prepared for the need of extrapolating data.	We anticipate the need to extrapolate data and are prepared.	Ok.
12	2.2.7	Don't, all, as apparent in previous sections (ie, p.20, line 1), petroglyphs at Murujuga result from a negative that was made in previously existing patina? Or just a few have been accomplished in such a fashion? Please clarify as mention to different engraving techniques is given below, not akin to the act of “just” removing patina to create a rock art motif. What is noted in this section is somewhat at odds with what is detailed in section 3.1.2	All petroglyphs are a negative of some description, however several different methods of production have been recorded. Some are pecked (i.e. as a series of divots removed from the surface, while others are cut or scraped to various depths. The first paragraph has been revised to aid clarity.	Ok, but do see reply to next comment
13	3.1.2	Not sufficiently detailed and tied with what was mentioned earlier about petroglyphs (see previous comment). For instance, how will different engraving styles affect patina formation? It can be argued that pecking or pounding leaves more profoundly incised marks, or negatives in the rock, or at least deeper that the ‘shallower’ scratched or abraded motifs. Won’t, and how, these differences in precise engraving technique, but mainly, and more importantly to the scope and objectives of this study, in rock art groove, or negative, depth affect patina growth? Hence, I believe that a further discussion of how (even if final results of the project can provide more definite information regarding this issue) diverse engraving techniques may affect not only patina regrowth but also if these different techniques may pose field measurements constraints.	These are excellent points and we plan to collaborate with Prof Jo McDonald who has a project dating petroglyphs to answer some of these questions. She has found (presumably older) petroglyphs where “desert varnish” has either re-formed in the engraved area or perhaps formed entirely on the rock surface post engraving. The influence of texture and face orientation on patina growth and microbiome colonization will	While I’m quite happy that the project secured the collaboration of such an experienced and preeminent scholar and look forward to the results of future cooperative work, the term “bruised” is still used in the in the final document sent on 22/11. Moreover, no clarification on the terms used (noticeably “pecking” and “pounded”) is offered.

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
		Moreover, even if understanding that there are differences in writing and characterization styles according to different authors, this reviewer, while familiar with all others, has never heard before the term "bruised" to describe rock art engraving techniques. Furthermore, isn't "pecking" (direct or indirect) the same as "pounding"? So, perhaps it is convenient to further, if briefly, characterize engraving techniques, exemplifying each with a photo.	additionally be investigated using the fresh rock tiles/cubes.	
14	3.1.3	Shouldn't short-term, ie. within the time span of the, possibly extended (see comment #3), project, expectable climate change impacts in the region be considered here?	We will consider the impacts of climate change where possible.	As these impacts are overreaching, can what is meant by "where possible" be concisely detailed?
15	Table 3.2-1	"relocation method" Which is?	The relocation method will be finalised and validated in a blind/controlled trial using samples at the WA museum prior to commencement of this phase of the fieldwork. However, Andrew Thorn has been unable, as yet, to visit WA to undertake this. The method involve triangulation of position from successively zoomed images. The target is located between readily identifiable stable features, such as protrusions, whereby the spectrometer light beam is aligned precisely between these features. The light beam will illuminate the surface with a fixed 8-10 mm diameter light beam. This circle of light will be aligned to the reference features via a macroscope mounted to the casing of the light exclusion shield. This system give sub-millimetre alignment for a sensor beam of 6 mm diameter. The spectrometer has also been assembled to be able to take scanned readings of a surface at as low as 5 microns. It is proposed in the pilot phase to scan the surface at 1 mm increments over a nominally 10 mm square surface.	Ok
16	Table 3.2-2	Can this be done with a cell phone? See comment #3. Or is it a case that the methodology for this, and/or other measurements, will be difficult or even impossible to be transformed into user-friendly cell phone apps?	A cell phone is used to assist relocation/position of the measurement head however cannot be used to undertake colour recording as the appropriate data cannot be accessed from the camera. The project will be evaluating a Pico spectrometer in parallel wit the main instrument. The Pico is a small device linked to an Android app. Repeatability trials have shown it to be more reliable than at least two of the previous instruments used.	Ok.
17	3.2.1.ii	"A map of the entire Murujuga region (including islands) has been partitioned into discrete subsets ("areas") in consultation with the traditional owners (Circle of Elders) and MAC, utilising the 1.3 km grid cells used in the Ramboll (2021) modelling. As explained by Thompson (2012), the partition can be drawn in any arbitrary fashion, and can be based on any relevant information. Areas may be delimited by cultural boundaries, by physical markers such as the crest of a hill, by a road or fence, or any other kind of boundary or criterion. As explained by Thompson (2012), use of this information affects the efficiency but not the fundamental validity of the method. The partition may be "nested" (each area may be divided into sub-areas) or "stratified" (areas may be organised into groups which have the same cultural permissions, for example)." So these areas can be not equal in size? Does that matter?	The areas can be of different sizes, and explanation is provided in Thanjen (2012). This does not impact the work.	Ok.

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
18	3.2.1.ii	“Due to COVID/project restrictions, the partitioning step has not yet taken place, as it requires close collaboration of key personnel and MAC elders/rangers on-site. Accordingly, N is not yet determined, but this is not a major consideration.” Has this been done yet? The impression one gets after reading Appendixes 1 and 2 is that this has been already accomplished. But agreed that it is not a major concern, although it has to be completed, if it hasn’t been yet, asap, before the project initiates.	This has now been completed.	Ok
19	Figure 3.6	Many restricted flight areas!	Yes.	Did it affect a ‘representative’ sample choice?
20	3.2.3.i	Is rock art “held at the Western Australian Museum”? How come?	Rock art samples were historically removed from Murujuga and nearby regions and located in the museum warehouse. We believe discussions are underway to repatriate them, however have no information to comment further.	Ok. This matter is of no primary concern for the project.
21	3.2.3.viii	OK, partially answers instrument complexity (see comment #3) but strengths the overall question of for how long the project will run, using the methodologies, instrumentation, human resources present in this proposal. Also, MAC rangers will monitor in the future a suite of variables included in the present study design, but not all?	It is not envisaged that all aspects of the project would continue, rather just the parts that are required for ongoing monitoring. i.e. the initial comprehensive studies will be reduced to a more simplified and smaller suite of measurements.	Ok
22	3.3.2.x	See above (comment #13) on petroglyph engraving styles.	The style of engraving will be noted and treated as a variable in the analysis. Question added in 3.3.2.xi “How do these reactions relate to the style of engraving (pecking or scratching)?”	Did not find the sentence in the final document sent on 22/11.
23	Figure 3.18	Incorrect referencing in the text: order and color of dots.	Corrected.	Did not find it corrected in the final document sent on 22/11.
24	Figure 5.3	Will transition to monitoring start after 18 months, as noted in the figure, or at the end of the 5 years of the project? Unclear throughout the text, check comment #3 and related ones.	After 18 months.	Ok
25	Glossary	Aspect (or orientation) is not defined in the Glossary, in spite of authors having acknowledged to this reviewer when Part A was reviewed when answering comment #22: “Andrew Thorn suggests the conventional use of the term "aspect" in the rock art research community encompasses a broad range of features including 3 dimensional orientation. This has been clarified in the glossary.”	The geologists have preferred to use measurements of dip and strike in the field, which are well defined concepts. These have been recorded for all rock art and sample rock panels being studied.	Ok
25	Glossary “Petroglyph”	Terms differing from supplied above, see comment #13.	Revised	Ok
26	Appendix 1, 1.2-1	See comment #3 and related above		
27	Appendix 1, 4.2	“those which are excluded for some reason” Cultural or other reason?	Any legitimate reason. These could be cultural or practical. Exclusions during fieldwork were either for cultural regions or safety constraints (steep terrain etc) imposed by the land tenure holder.	Ok

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
28	Appendix 2, 7.1	But if it is not possible, although being relatively large areas, to place in one of the chosen cells for cultural reasons? Proceed to the next one?	The sites have now been visited and suitable locations identified within the identified grid squares. One of the RS squares was moved according to protocol (Appendix 1) for cultural reasons, and another for inappropriate geology (limestone).	Ok

3 Statistical analysis and study design

3.1 Data Analysis Australia – Statement of Advice and Response to Review comments for Detailed Study Design (Part A)

Comments on Detailed Design Study

1. These comments relate to the document *Murujuga Rock Art Monitoring Project: Detailed Study Design* draft report prepared by Puliyapang and Curtin University dated July 2020 (the "Study Design").

   (a) The comments have been prepared by Dr John Henstridge with assistance from Brett Andrijich and Graeme Ward, both of Data Analysis Australia.

   (b) The focus of our review is the statistical aspects of the Study Design. References to pages or sections of this document are given in brackets […].

   (c) We have also read the *Murujuga Rock Art Monitoring Project: Conceptual Model* also dated July 2020 (the Conceptual Model).

2. At this stage we are reviewing Part A of the Study Design. It is not clear whether our comments on Part A will change when Part B becomes available.

General Comments

3. The Conceptual Model represents a clear view of how the team sees the issues affecting the petroglyphs as seen by the study team.

   (a) In particular it presents a causal path for changes, both natural and anthropogenic (explicit in the figure on page 13 of the Conceptual Model and implicit in other parts).

   (b) Whilst this model is likely to encompass most of what is occurring, good practice dictates ensuring that ongoing monitoring is also capable of detecting the unexpected.

4. The Study Design had as stated research objectives which are in line with the Conceptual Model [1.2]:

   (a) Accurately measure the colour and surface texture of rocks across the Murujuga Peninsula, establish baseline values for a long-term monitoring program, identify important differences in colour or surface texture which may be associated with degradation, and develop criteria for assessing 'degradation';

   (b) Identify and characterise the minerals, inorganic and organic chemicals, and microbes present on the rock surface and in the sub-layers, which are relevant to the appearance and integrity of the petroglyphs, or may be involved in accelerating or preventing the degradation of the petroglyphs;

   (c) Determine which atmospheric pollutants are present in industrial and natural emissions on Murujuga, and which are capable of causing degradation or change of the petroglyphs;

   (d) Under controlled laboratory conditions with small samples of rock, measure the effect of a known amount of pollutant chemical on the constituents of the rock surface and sub-layers;

(e) Measure the concentration of atmospheric pollutants to which rocks are exposed across the Peninsula;

(f) Identify the weather conditions, environmental conditions and industrial output conditions which are likely to pose the greatest risk of degradation to petroglyphs;

(g) Calculate the timescales over which changes are predicted to occur, and thresholds of pollutants giving rise to accelerated change;

(h) Identify sentinel variables ("canary in the coal mine") which can be observed in the field and which can serve as indicators of increased *risk* of degradation; and

(i) Link all of the evidence in the studies above to reach rigorous scientific conclusions and provide a rigorous evidence base for the Conceptual Model and the EQMF.

5. However the Study Design does not *clearly* present how the various components of the study might support these objectives. I believe there is a plan that connects the components but it tends to be implicit rather than explicit. This creates the risk of some components not being as well directed as others.

(a) Ideally it should be clear how every component of the study contributes to research objectives, demonstrating the logic of the design and the appropriate use of resources.

(b) It is clear that some steps are preparatory and some are to confirm that suggested methods will indeed work. That is, there is an implicit dependence between components. This dependence and possible sequencing of the work is not clearly presented.

(c) It is also not clear how various components may relate to each other. For example, it is less than clear whether the sampling sites referenced in variation sections are the same or different. (We would generally recommend the former.)

(d) This suggests that the Study Design needs to include a proper description of how the various components go together, both logically and temporally. This description might include diagrams for the knowledge flow and a Gantt chart.

6. In the absence of a systematic overview in the Study Design, our understanding of the overall plan to achieve these objectives is summarised as:

(a) Use a computational fluid dynamics approach to better understand where various pollutants might impact upon the rock art;

(b) On the basis of this understanding plan, a spatial sampling approach that will ensure that rock art can be monitored across a range of possible pollutant levels, overcoming the problem of no strict "control" sites;

(c) Develop means of measuring the rock surfaces, considering the appearance (colour) and geometry of the surface, inorganic and organic chemistry and the microbiome;

(d) Establish baseline measurements and a means of ongoing monitoring the rock art. This represents the 'field studies";

(e) Develop an analysis approach that will determine relationships between observed changes and modelled pollutant

(f) Through gaining an understanding the science involved, develop a means of indirectly understanding the effects of pollutants on the rock art, possibly using indirect measures of the effect; and

7. The last two steps in this represent the dual approach of the Study Design.

(a) It is stated [page 1 of the Study Design] that the field studies might not be of sufficient size and statistical power to be conclusive, and hence the fall back of the indirect monitoring.

(b) By necessity indirect modelling is likely to consider a limited number of causal pathways. While these will be the ones considered most likely to occur, there remains a possibility of a mechanism not currently considered is at play.

(c) In contrast the field measurements aim to directly measure changes of concern, *independent of mechanisms*. It could also be argued that the field measurements should be the fall back for indirectly modelling.

(d) We regard this asymmetry as potentially a major concern, creating a risk that the statistical power in monitoring actual changes in the petroglyphs is not sufficient to detect real change. At the very least we believe that the Study Design should explain why this risk should be accepted.

Previous Studies

8. Most emphasis in the discussion of previous studies relates to the spectrophotometry. It points out the considerable issues with the spectrophotometric data.

(a) It correctly points out the non-scientific site selection process for this work [2.1.1.i].

(b) It correctly points out the inconsistencies with the original BYK instrument, as originally highlighted by Data Analysis Australia. This implies (but does not completely rule out) that the historical BYK data should not be used [2.1.1].

(c) It references the Konica-Minolta (KM) instrument but does not comment on the usefulness of its data or the possibility of its future use.

(d) It refers to the ASD spectrometer data but only in terms of its possible use for geochemical information, for which it is considered to give inadequate detail [2.1.2]. No reference is made to the use of this instrument for giving colour values (L^*, a^*, b^*) even though a key recommendation of the Data Analysis Australia reports was that this probably provides the only consistent long term record of colour. If there are good reasons for not building part of the historical record, they are not given.

9. Some discussion is presented on the more recent inorganic chemistry and microbiome studies but with no reference as to how they might influence future designs.

Proposed Study Design

10. The statistical principles of the proposed study design reflect good practice.

    (a) Representative sampling, considering the petroglyphs, the rock population and the area of the peninsula. The need to have a sample that spans these different dimensions in the population of possible sites suggests a moderately large sample size.

    (b) Closely located observations in the component studies so that findings using different methods can be interrelated. (This is the only statement in the Study Design that implies that when various sections refer to sampling at about 10 locations, they might all be referring to the same locations.) Co-location of samples will mean that correlations can be established independent of spatial modelling, giving a more robust result.

    (c) Consideration of detection limits at an early stage. This is seen in the Study Design as a need to develop methods with suitably low levels of detection, but we would also suggest that it needs a statistical approach to ensure that data is not unnecessarily truncated.

    (d) Identifying that the overall aim is to produce a dose-response type relationship between pollution and the art. This should provide a predictive function and the possibility of modelling the effect of strategies to ameliorate the effects of pollution.

    (e) Recognition that there will be difficulties in using previously collected data.

11. It adopts an important position that there can be no control sites in the traditional sense of that term. Rather there will be a gradation of exposure to pollutants. This is a key aspect of the Study Design that is likely to resolve many of the past criticisms.

12. The Study Design proposes [3.2.1.i] to *extend* the existing set of sites by adding a number that selected by a procedure that ensures that they are representative.

    (a) It is not clear whether the intention is for the new sites by themselves to be representative or the full set of old and new sites. (It is unlikely both can be.) If the latter, it is not clear how this would be achieved. If the former, it is not clear how the old sites will be used in the analysis.

    (b) A nested cluster sample is proposed. While this is a well-established statistical technique, its purpose here appears to be more driven by the need to consider practical issues of access and the cultural requirements. No indication is given as to the size of the clusters, a critical aspect since too few clusters could seriously affect the statistical properties of the design. (In general the statistical ideal is clusters of size one and where the data collection costs are high, small clusters are usually optimal.)

(c) A simple sample size calculation is presented using historical colour data. While this is of some value as a "back of the envelope" calculation, it is very simplistic:

(i) It appears to use the standard errors obtained for the ASD instrument, even though it is not intended to continue to use that instrument. It is not clear whether the new instruments and methods proposed will be as accurate as this.

(ii) It only considers a very simple statistical test for a linear trend, not a more complex one where there is an interest in comparisons in trends between sites and relationships with several pollutant fields.

(iii) The sample size is based upon a single sided alternative hypothesis even though changes are acknowledged as possibly occurring is either direction.

(iv) The sample size discussed should ideally be the number of new sites since it is not clear whether any of the existing sites are of real scientific value.

(v) These considerations suggest that the proposed sample size of about 10 may be substantially inadequate and that a value of 30 to 40 might be more appropriate.

(d) The Study Design is silent on whether all sites should be sampled every year.

(i) It seems to be implied that all sites will be visited every year.

(ii) A fractional design would potentially give the possibility of greatly improved spatial sampling with minimal loss in the statistical power in measuring trends and little change to the ongoing effort required.

(iii) We recognise that effort is required in establishing new sites (and indeed to bring up old sites to the new standard with methods such as laser scanning). Hence this suggests that a fractional design should not be too sparse.

13. The discussion on laser scanning [3.2.2] is mixed with a discussion of other scanning and optical methods. This is somewhat confusing and makes it unclear what method is applied where.

(a) It seems that the laser scanning is intended to give information for an area of perhaps 100 to 200 metres diameter around a sampling site. The size of the region scanned and the resolution suggest that this is well adapted to the needs of modelling air flow around the petroglyphs and perhaps shadowing effects.

(b) The macro photogrammetry appears to be at the scale of several metres. This might be of a scale to give information on a whole petroglyph and its immediate surround.

(c) The micro photogrammetry is of a scale of up to 100 millimetres, and presumably refers to a spot on a sampled petroglyph. This suggests that it might be performed at 10-20 spots at each site.

(d) It is not clear what scale the Reflectance Transformation Imaging will be implemented. It is not clear what essential purpose the RTI method is intended to serve – it is not quantitative and more of a discovery technique rather than a monitoring one.

Surface Change Analysis

14. In some respects the measurement of colour change is critical since the appearance of the petroglyphs is why they were created by the original artists. Detrimental changes to the appearance such as a reduction in contrast are a major concern.

15. The measurement of colour change [3.2.3.i] proposes to use a JAZ Spectrophotometer and a Pico colorimeter.

    (a) It appears that the Pico is a very low cost instrument (<$200) intended in this case to be one for use by rangers.

    (b) Neither of these instruments is similar to the instruments of the previous studies (the BYK, KM and ASD) and the data they produce would not be compatible. Reference is made to cross calibrate ASD data to the new instruments, but it is not clear that this is even possible and no details of the cross calibration are presented. (The cross calibration method used by the CSIRO to model the relationship between the BYK and KM data was faulty and may have given a false impression on how accurate such cross calibrations can be.)

    (c) No plan is presented for cross calibration between the JAZ and Pico instruments.

    (d) Hence it is possible (perhaps likely) that the new data will be essentially from the JAZ instrument and will not be compatible with existing data. This would severely limit how the new data can be analysed together with existing data in an attempt to obtain a longer time series.

    (e) If this is the case, it is natural to ask why it has been proposed that existing (poorly chosen) sites be retained as part of the design.

16. Previous studies have had significant difficulty in returning to the precisely same spots at a site for colour measurement. The Study Design attempts to address this by measuring both as a single spot and over a broader area of 20mm by 20mm.

    (a) It is disturbing that it is proposed to measure an area "chosen for its apparent chromatic homogeneity" [page 48]. This is a potential source of bias (are homogeneous areas representative or even typical) and subjectivity (the criteria for homogeneity being unclear).

    (b) There appears to be some belief that this subjective choice of spot selection was done in the past. In general it is not feasible to be consistent in subjective choices and hence it cannot be recommended for the future.

17. Surface elemental distribution will be measured using portable XRF [3.2.3.ii], presumably at the same spots as the colour analysis.

(a) This is seen as somewhat exploratory, but the intention is that this will give some understanding of the JAZ colour spectra.

18. Morphological change measurement is also proposed [3.2.3.iii], using a microscope and a scanning frame, presumably computer controlled.

(a) It is not clear how many spots at each site are proposed to be sampled. It appears that it will take 20-30 minutes to scale a single spot and that the same scanning frame is used for some of the colourimetry. Allowing for set up, this suggests a rate of one spot per hour.

(b) Given that each location may need to consider both engraving and background spots, this suggests that not all colourimetry spots may be sampled.

(c) The approach with both focus stacking and camera movement is data intensive – up to 1000 images each of perhaps 25 MB would be acquired at each spot, not allowing for replication.

(d) RTI is also proposed for morphological change measurement. In this regard we note with concern the statement that "Murujuga provides an abundance of suitably flat cultural surfaces" [page 51], suggesting that this technique will be limited to only certain spots. It is not clear whether it is suggested that spots be selected on some such subjective criterion.

(e) This raises a question concerning various other measurement methods, whether they also have constraints on what types of surface they can be used on. (For example, the photogrammetry technique has a limited depth of field and hence may also require a reasonably flat surface.)

19. Beyond the above, no protocol or guidelines are provided for selecting spots to be sampled.

(a) This is a major omission. We appreciate that measurement methods may impose constraints but it is important that they be documented so any potential biases are understood. It is also important that to the greatest extent possible any subjective inputs to spot sampling are minimised.

(b) A related issue is how spots will be returned to in subsequent years.

Destructive Analysis

20. As a general comment, it appears that the destructive analysis [3.3], perhaps better described as laboratory based analysis, has fewer statistical issues – it is aimed at understanding processes rather than measuring the status of the rock art in the field.

(a) It is important to ensure that the laboratory work consider all possible conditions encountered in the field, but it is not necessary for it to be representative in itself. For example, the sampling discussion refers to the need to examine all three major rock types.

(b) The exception is where the laboratory work aims to provide measures of the rock status directly. For that the same sampling requirements as for the surface change measurements apply. Co-located sampling is strongly recommended.

(c) Since it is not ideal for destructive testing to be carried out too close to petroglyphs, to get the full benefit of co-located sampling it will be necessary to carry out some more intense sampling at a limited number of sites to ensure that small scale spatial effects are understood and what, for sampling purposes, can constitute a local area around a site.

21. This section is correspondingly short of detail on actual sampling processes.

(a) Some indication on numbers of samples for the microbiome work [3.3.3.ii and iii, page 67] but not on how these samples are chosen.

(b) The reference to ten sites [3.3.3.ii] suggests a site selection process but does not indicate whether this is co-located with other site selections.

22. It is apparent that some methods will only be available for limited samples or sites. This is understandable when using demanding methods but it must be done consciously with an understanding of potential biases.

(a) The statement that "CSIA will therefore only be done on select samples where these requirements are able to be met" [3.3.4.iv] is therefore read with some (hopefully misplaced) concern.

Air quality modelling

23. The collection of air quality and meteorological data will use automated stations. The critical statistical aspect of these is their siting. It is notable that the approach is one of combining measurement in the field and modelling (CFD and spatial statistical methods) to complement each other and maximise the information.

24. It is not clear just how many sites will be sampled for this purpose and how they relate to the sites used for other measurements.

(a) Our understanding from the workshop earlier in 2020 was that the number of sites might be relatively small – perhaps 3.

(b) We also note that there is only one Airbox available for some of the more complex monitoring [3.4, page 77] and that this might only be available for limited times, it "is likely we could only deploy facility for approximately 1 month at the peak of the wet season and 1 month at the peak of the dry season" [3.4.2.ii].

(c) This suggests that at best a subset of the sites used for other measurements might be monitored for air quality. How these are chosen is not clear.

(d) Some measurements will be essentially continuous while others will be periodic. How these choices are made is also not clear.

Computational Fluid Dynamics Modelling

25. It is perhaps unfortunate that such a key component of the study is placed towards the end of the Study Design [3.5].

(a) The computational fluid dynamics (CFD) models are key to understanding what pollutants travel where and how they interact with the ground surface including the petroglyphs. That is, they provide an understanding of possible the exposure of the petroglyphs to pollution.

(b) The CFD models also assist the spatial interpolation of direct measurements of deposition of pollutants.

(c) For these reasons the CFD models are to be used to directly drive the statistical site sampling process [3.5.2.iii].

26. We commend the approach taken here as it provides the only way of overcoming the problem of no true control sites. As such it is critical and it would be useful is more detail was provided.

(a) This section of the Design Study also appears to be the source of the reference made in many places to sampling at 10 sites [3.5.2.iii].

(b) It would be useful to know how the value of 10 sites was derived.

(c) More importantly, it would be comforting to know what strategy would be adopted if the CFD study suggests that 10 sites is not enough.

Summary

27. The sampling of sites and petroglyphs within sites is one of the most important steps at the beginning of the monitoring study. Inappropriate sampling can result in wasted effort in collecting data that is not of full value. Efficient sampling optimises the amount of information obtained for the effort applied.

28. Similarly, the scale of sampling, essentially the sample size, is also critical in ensuring that the sample is able to answer the critical questions. Sampling below a certain level can be wasted effort if, no matter how well the science is done, it cannot answer the questions.

29. Whilst the Design Study covers a range of scientific work which is intended to be conducted to a high standard, it is not clear at this stage whether the sampling issues have been sufficiently described. In particular, if further consideration of sampling suggests that more sites are required, this may have major implications for the budget or the range of scientific methods that can be used.

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: Data Analysis Australia	
Document Title: Murujuga Rock Art Monitoring Project: Monitoring Studies Data Collection and Analysis Plan (*Part A*) "Detailed Study Design"	
Document Version: Version 1 (July 2020);	**Revised Version:** Version 1.1 (January 2021)
Date of Review: 2/11/2020;	**Close out comments:** 11/2/2021

Item No.	Peer Reviewer Comment	Response	Peer Reviewer Close-out Comment
1	**Comments on Detailed Design Study** These comments relate to the document Murujuga Rock Art Monitoring Project: Detailed Study Design draft report prepared by Puliyapang and Curtin University dated July 2020 (the "Study Design"). The comments have been prepared by Dr John Henstridge with assistance from Brett Andrijich and Graeme Ward, both of Data Analysis Australia. The focus of our review is the statistical aspects of the Study Design. References to pages or sections of this document are given in brackets […]. We have also read the Murujuga Rock Art Monitoring Project: Conceptual Model also dated July 2020 (the Conceptual Model). At this stage we are reviewing Part A of the Study Design. It is not clear whether our comments on Part A will change when Part B becomes available	No response required.	We have reviewed the responses, the new version of the Part A document and the Ramboll report. We note that the changes to the Part A report are primarily some minor additions – the structure is essentially unchanged.
2	**General Comments** The Conceptual Model represents a clear view of how the team sees the issues affecting the petroglyphs as seen by the study team. In particular it presents a causal path for changes, both natural and anthropogenic (explicit in the figure on page 13 of the Conceptual Model and implicit in other parts). Whilst this model is likely to encompass most of what is occurring, good practice dictates ensuring that ongoing monitoring is also capable of detecting the unexpected. The Study Design had as stated research objectives which are in line with the Conceptual Model [1.2]:	Noted. A clearer overview of the connections between the component studies, the sequencing of work, and the analysis pipeline, will be presented in Part B of the Detailed Study Design.	We look forward to reading Part B.

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	Accurately measure the colour and surface texture of rocks across the Murujuga Peninsula, establish baseline values for a long-term monitoring program, identify important differences in colour or surface texture which may be associated with degradation, and develop criteria for assessing 'degradation'; Identify and characterise the minerals, inorganic and organic chemicals, and microbes present on the rock surface and in the sub-layers, which are relevant to the appearance and integrity of the petroglyphs, or may be involved in accelerating or preventing the degradation of the petroglyphs Determine which atmospheric pollutants are present in industrial and natural emissions on Murujuga, and which are capable of causing degradation or change of the petroglyphs; Under controlled laboratory conditions with small samples of rock, measure the effect of a known amount of pollutant chemical on the constituents of the rock surface and sub-layers; Measure the concentration of atmospheric pollutants to which rocks are exposed across the Peninsula; Identify the weather conditions, environmental conditions and industrial output conditions which are likely to pose the greatest risk of degradation to petroglyphs; Calculate the timescales over which changes are predicted to occur, and thresholds of pollutants giving rise to accelerated change; Identify sentinel variables ("canary in the coal mine") which can be observed in the field and which can serve as indicators of increased risk of degradation; and Link all of the evidence in the studies above to reach rigorous scientific conclusions and provide a rigorous evidence base for the Conceptual Model and the EQMF. However the Study Design does not clearly present how the various components of the study might support these objectives. I believe there is a plan that connects the components but it tends to be implicit rather than explicit. This creates the risk of some components not being as well directed as others.		

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	Ideally it should be clear how every component of the study contributes to research objectives, demonstrating the logic of the design and the appropriate use of resources. It is clear that some steps are preparatory and some are to confirm that suggested methods will indeed work. That is, there is an implicit dependence between components. This dependence and possible sequencing of the work is not clearly presented. It is also not clear how various components may relate to each other. For example, it is less than clear whether the sampling sites referenced in variation sections are the same or different. (We would generally recommend the former.) This suggests that the Study Design needs to include a proper description of how the various components go together, both logically and temporally. This description might include diagrams for the knowledge flow and a Gantt chart. In the absence of a systematic overview in the Study Design, our understanding of the overall plan to achieve these objectives is summarised as: Use a computational fluid dynamics approach to better understand where various pollutants might impact upon the rock art; On the basis of this understanding plan, a spatial sampling approach that will ensure that rock art can be monitored across a range of possible pollutant levels, overcoming the problem of no strict “control” sites; Develop means of measuring the rock surfaces, considering the appearance (colour) and geometry of the surface, inorganic and organic chemistry and the microbiome; Establish baseline measurements and a means of ongoing monitoring the rock art. This represents the ‘field studies”; Develop an analysis approach that will determine relationships between observed changes and modelled pollutant Through gaining an understanding the science involved, develop		

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	a means of indirectly understanding the effects of pollutants on the rock art, possibly using indirect measures of the effect; and The last two steps in this represent the dual approach of the Study Design. It is stated [page 1 of the Study Design] that the field studies might not be of sufficient size and statistical power to be conclusive, and hence the fall back of the indirect monitoring. By necessity indirect modelling is likely to consider a limited number of causal pathways. While these will be the ones considered most likely to occur, there remains a possibility of a mechanism not currently considered is at play. In contrast the field measurements aim to directly measure changes of concern, independent of mechanisms. It could also be argued that the field measurements should be the fall back for indirectly modelling. We regard this asymmetry as potentially a major concern, creating a risk that the statistical power in monitoring actual changes in the petroglyphs is not sufficient to detect real change. At the very least we believe that the Study Design should explain why this risk should be accepted		
3	**Previous Studies** Most emphasis in the discussion of previous studies relates to the spectrophotometry. It points out the considerable issues with the spectrophotometric data. It correctly points out the non-scientific site selection process for this work [2.1.1.i]. It correctly points out the inconsistencies with the original BYK instrument, as originally highlighted by Data Analysis Australia. This implies (but does not completely rule out) that the historical BYK data should not be used [2.1.1]. It references the Konica-Minolta (KM) instrument but does not comment on the usefulness of its data or the possibility of its future use. It refers to the ASD spectrometer data but only in terms of its possible use for geochemical information, for which it is considered to give inadequate detail [2.1.2]. No reference is	(1) our main concern about the previous colour monitoring studies is not the instrumentation itself but the non-repeatable placement of the sensor, the uncontrolled natural lighting, and undocumented changes of technique from time to time. Discrepancies between results obtained from different instruments may be partly attributable to differences in use (for example, incorrect or omitted calibration of one instrument; undocumented changes to the instrument such as bulb replacement). (2) We have indicated that some of the prior observations will be included in the final analysis using techniques of meta-analysis. (3) The ASD instrument is very expensive and we understand that CSIRO has purchased only a few of these instruments. Successive models of the ASD instrument may have different characteristics.(Incidentally it is unclear whether all the CSIRO observations attributed to ASD were made using exactly the same individual instrument, or whether there may have been a change from one individual instrument to another at some date.) If we purchase an ASD instrument, there is no guarantee that this will be compatible with the ASD instrument or instruments used by CSIRO a decade ago. The replacement cycle for the instrument would require further investment, and cross-calibration of the new and old instruments.	(1) We can understand this comment while not being as certain as to the relative contributions of instrument variability and relocation variability. It is evident from reading the CSIRO studies that they struggled (largely unsuccessfully) with the placement of the sensor. It was apparent that they were unsure whether to concentrate on more precise placement or increasing the area of measurement by spreading the placement and hence making the resulting averages less dependent on the precise of the centre of the measurements. This meant that practice may have changed with change in instruments. However, in moving forward it is clear that the relocation problem needs to be addressed. (2) The meta-analysis is likely to be problematic due to the poor quality of the existing data. If it is decided that the existing data is largely incompatible with the new data, then meta-analysis will not be possible. **Our strong opinion is that the BYK data is totally flawed and should not be used, partly because of the instrument but mainly because it is not possible with any certainty to identify the original data.** (3) We appreciate the issues with the ASD instrument. (We

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	made to the use of this instrument for giving colour values ($L*$, $a*$, $b*$) even though a key recommendation of the Data Analysis Australia reports was that this probably provides the only consistent long term record of colour. If there are good reasons for not building part of the historical record, they are not given. Some discussion is presented on the more recent inorganic chemistry and microbiome studies but with no reference as to how they might influence future designs.	Thus, we see cross-calibration as an inevitable component of the study. There is also the contractual requirement to transfer technology to the MAC for ongoing monitoring of rock condition, and this may require a relatively inexpensive hand-held instrument. Our study will evaluate, as a matter of urgency, the reliability of cross-calibration between the JAZ and Pico instruments. If this is found to be unacceptably inaccurate, then we will investigate options involving the ASD instrument. Data from previous instruments has been evaluated. It was found that the BYK has a very poor repeatability, the KM had moderate repeatability and the ASD has very good repeatability. As mentioned above, we will suggest a contract variation to purchase one or more ASD instruments unless we can conclusively demonstrate that the JAZ (and Pico) instruments can provide equivalent performance.	were *verbally* given conflicting stories as to whether it was one or several instruments.) It did however provide the closest to consistent measurements in the historical data, and was far better than the BYK and KM instruments. However, changing to a fourth and fifth type of instrument must be done with care if there is to be any hope of making comparisons with the historical data. Having multiple instruments does introduce the need for cross-calibration and this needs to be done with care, ideally using a designed experiment approach to ensure that the calibration works across a range of conditions. Such work should be done at an early stage to ensure that whatever is adopted with work in the long term. **It would be helpful for this purpose if it was clearer what the criteria would be for accepting the use of the JAZ and Pico instruments.** This may be a particular issue for the Pico instrument which does not seem to be "research grade". If there is an intention to include the ASD data in the meta-analysis, it would be ideal if the instrument could be included in the cross-calibration work.
4	**Proposed Study Design** The statistical principles of the proposed study design reflect good practice. Representative sampling, considering the petroglyphs, the rock population and the area of the peninsula. The need to have a sample that spans these different dimensions in the population of possible sites suggests a moderately large sample size. Closely located observations in the component studies so that findings using different methods can be interrelated. (This is the only statement in the Study Design that implies that when various sections refer to sampling at about 10 locations, they might all be referring to the same locations.) Co-location of samples will mean that correlations can be established independent of spatial modelling, giving a more robust result. Consideration of detection limits at an early stage. This is seen in the Study Design as a need to develop methods with suitably low levels of detection, but we would also suggest that it needs a statistical approach to ensure that data is not unnecessarily truncated. Identifying that the overall aim is to produce a dose-response type relationship between pollution and the art. This should provide a predictive function and the possibility of modelling the effect of strategies to ameliorate the effects of pollution.	(1) The existing rock sites (where previous researchers conducted rock surface colour measurement and monitoring) will be revisited but will not be treated as part of a representative sample. That is, statistical sampling inference about the rock population, using the principles of randomised-design-based inference, will be based solely on the 'new' rock sites that are to be selected by a randomised sampling procedure. It is desirable to revisit the existing rock sites because it is likely that access permission will be granted quickly. The existing rock site locations are inaccurately specified, and difficulties with the previous studies have been noted, so future observations at these existing sites will not constitute a continuation of previous observation series in any sense. However, as foreshadowed in Section 3.1.4 (d) of the Study Design Part A, we shall use hybrid model-assisted inference to borrow strength from these new observations at existing sites (essentially to fit regression models supporting spatial interpolation and other kinds of prediction). (2) Nested cluster sampling will be performed using systematic sampling as the sub-selection mechanism, rather than the more usual independent random sampling. See Section 10.6 of A. Baddeley and E.B. Vedel Jensen, Stereology for Statisticians, Chapman and Hall/CRC, 2005. The sampling design is characterised by the sampling fractions (inverse sampling periods) rather than sample size or cluster size. However we agree in general that the ideal design for such a structured population is one in which each sub-cluster typically consists of only one or only a few units. (3) We concur with the comments about spatial co-location of samples. (4) We acknowledge that Part A of the Study Design omits many details of sample sizes and sampling processes.	(1) It is reassuring that the existing sites will not be considered as part of the new representative sample. Their use for pilot purposes may be sensible since access is likely to be least problematic. **However we would be concerned if this diverted resources away from the new sites.** (2) Cluster sampling that should reduce access costs should enable an increase in the number of sites. This is strongly supported. (3) Good. (4) We look forward to Part B. (5) Good. (6) It is particularly good to see acknowledgement of the possible need to substantially larger sample sizes.

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	Recognition that there will be difficulties in using previously collected data. It adopts an important position that there can be no control sites in the traditional sense of that term. Rather there will be a gradation of exposure to pollutants. This is a key aspect of the Study Design that is likely to resolve many of the past criticisms. The Study Design proposes [3.2.1.i] to extend the existing set of sites by adding a number that selected by a procedure that ensures that they are representative. It is not clear whether the intention is for the new sites by themselves to be representative or the full set of old and new sites. (It is unlikely both can be.) If the latter, it is not clear how this would be achieved. If the former, it is not clear how the old sites will be used in the analysis. A nested cluster sample is proposed. While this is a well-established statistical technique, its purpose here appears to be more driven by the need to consider practical issues of access and the cultural requirements. No indication is given as to the size of the clusters, a critical aspect since too few clusters could seriously affect the statistical properties of the design. (In general the statistical ideal is clusters of size one and where the data collection costs are high, small clusters are usually optimal.) A simple sample size calculation is presented using historical colour data. While this is of some value as a “back of the envelope” calculation, it is very simplistic: It appears to use the standard errors obtained for the ASD instrument, even though it is not intended to continue to use that instrument. It is not clear whether the new instruments and methods proposed will be as accurate as this. It only considers a very simple statistical test for a linear trend, not a more complex one where there is an interest in comparisons in trends between sites and relationships with several pollutant fields. The sample size is based upon a single sided alternative hypothesis even though changes are acknowledged as possibly occurring is either direction.	The standard procedure is to determine optimal sample size after performing a pilot experiment. Sample sizes for a pilot experiment are usually determined from available prior background knowledge and initial expert assessment. In the case of this study, COVID-19 restrictions prevented us from visiting Murujuga to acquire the necessary information. Nevertheless we expect to be able to specify sample sizes and sampling procedures in Part B. (5) We agree that it is necessary to be extremely careful to avoid sources of bias in the selection of samples. Statisticians will be closely involved in the development and documentation of the practical procedures for sample selection. (6) An overly simple calculation of sample size was performed because we consider that the available information about sources of variability is inadequate (mostly because several sources of variability are conflated) or is not trustworthy (mostly because of potential bias). We agree that the optimal sample sizes could be inflated by a factor of 2 to 3.	

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	The sample size discussed should ideally be the number of new sites since it is not clear whether any of the existing sites are of real scientific value. These considerations suggest that the proposed sample size of about 10 may be substantially inadequate and that a value of 30 to 40 might be more appropriate. The discussion on laser scanning [3.2.2] is mixed with a discussion of other scanning and optical methods. This is somewhat confusing and makes it unclear what method is applied where. It seems that the laser scanning is intended to give information for an area of perhaps 100 to 200 metres diameter around a sampling site. The size of the region scanned and the resolution suggest that this is well adapted to the needs of modelling air flow around the petroglyphs and perhaps shadowing effects. The macro photogrammetry appears to be at the scale of several metres. This might be of a scale to give information on a whole petroglyph and its immediate surround. The micro photogrammetry is of a scale of up to 100 millimetres, and presumably refers to a spot on a sampled petroglyph. This suggests that it might be performed at 10-20 spots at each site.		
5	**Surface Change Analysis** In some respects the measurement of colour change is critical since the appearance of the petroglyphs is why they were created by the original artists. Detrimental changes to the appearance such as a reduction in contrast are a major concern. The measurement of colour change [3.2.3.i] proposes to use a JAZ Spectrophotometer and a Pico colorimeter. It appears that the Pico is a very low cost instrument (<$200) intended in this case to be one for use by rangers. Neither of these instruments is similar to the instruments of the previous studies (the BYK, KM and ASD) and the data they produce would not be compatible. Reference is made to cross calibrate ASD data to the new instruments, but it is not clear that this is even possible and no details of the cross calibration are presented. (The cross calibration method used by the CSIRO	(A) Due to an editing error, the text of the Study Design in Section 3.2.3 (i), second-last paragraph, appeared to say that target locations would be selected for their 'apparent chromatic homogeneity'. This is incorrect. Rather, it is believed that *previous* targets were selected for their apparent chromatic heterogeneity, as indicated in the last sentence of the paragraph. (B) We have concluded that the previous colour monitoring studies cannot be used to form a longer time series of observations, even if we were to use the ASD instrument in the coming years, because of the non-repeatable placement of sensor heads, the uncontrolled natural lighting, and other sources of variability and bias. We suspect that these sources of variability are greater than the discrepancies between the instruments themselves under controlled conditions (this will be evaluated during our study). (C) We have chosen to re-visit the previous sites, despite the fact that they were poorly chosen, because permission to revisit these sites is	(A) We note that the current draft of Part A still states in Section 3.2.3 that "The micrometre *will* be progressed in 2 or 3 mm increments in a grid to provide 49 or 100 readings over the grid, chosen for its apparent chromatic homogeneity. An homogenous (sic) surface, while suggesting bias in a statistical sense, is important to ensure that the target avoids potential error through undue roughness or chromatic heterogeneity. The bias is towards error reduction rather than a subjective preference for a given type of surface appearance." From a statistical perspective, we can understand the desire to reduce variability at the individual measurement level, but the suggested approach creates a potentially serious bias in what is being measured. It is not clear how the homogeneous areas are to be objectively chosen. **This needs to be addressed as it seemingly contradicts the principle of randomised objective sampling.**

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	to model the relationship between the BYK and KM data was faulty and may have given a false impression on how accurate such cross calibrations can be.) No plan is presented for cross calibration between the JAZ and Pico instruments. Hence it is possible (perhaps likely) that the new data will be essentially from the JAZ instrument and will not be compatible with existing data. This would severely limit how the new data can be analysed together with existing data in an attempt to obtain a longer time series. If this is the case, it is natural to ask why it has been proposed that existing (poorly chosen) sites be retained as part of the design. Previous studies have had significant difficulty in returning to the precisely same spots at a site for colour measurement. The Study Design attempts to address this by measuring both as a single spot and over a broader area of 20mm by 20mm. It is disturbing that it is proposed to measure an area “chosen for its apparent chromatic homogeneity” [page 48]. This is a potential source of bias (are homogeneous areas representative or even typical) and subjectivity (the criteria for homogeneity being unclear). There appears to be some belief that this subjective choice of spot selection was done in the past. In general it is not feasible to be consistent in subjective choices and hence it cannot be recommended for the future. Surface elemental distribution will be measured using portable XRF [3.2.3.ii], presumably at the same spots as the colour analysis. This is seen as somewhat exploratory, but the intention is that this will give some understanding of the JAZ colour spectra Morphological change measurement is also proposed [3.2.3.iii], using a microscope and a scanning frame, presumably computer controlled. It is not clear how many spots at each site are proposed to be sampled. It appears that it will take 20-30 minutes to scale a	likely to be granted promptly, and much groundwork has already been done for these sites. These previously-selected sites will not be treated as representative in any statistical sense. Previous observations will only contribute to the overall analysis using a meta-analysis technique. (D) The references to 'sufficiently flat' and 'sufficiently homogeneous' surfaces need to be clarified. The photogrammetry instruments will scan a field that is only a few millimetres across. This small segment of rock surface should not be very rough or pockmarked. This requirement is unlikely to cause a large sampling bias.	**(B)** Irrespective of this bias, it is still not clear how the relocation problem is to be solved. Measuring over a 20×20 mm grid is more systematic than the previous somewhat fuzzy CSIRO approach of multiple measurements over a larger area, but the location of the grid remains a challenge that is not addressed in Part A. If, as is stated, the relocation problem was at the core of previous problems of consistency, it needs to be spelt out how it is to be addressed. (C) It is appropriate to exclude the historical data from the main analysis as it is likely to be incomparable. However it appears that the intention is to continue measurements at the old sites. **If there was spare capacity after collecting data at the properly sampled new sites this may be useful, but it should not be allowed to divert resources from the new sites.** (D) This aspect is discussed above and remains of concern. In general, measuring what is easy to measure is a poor substitute for measuring what should be measured. If, for example, rougher surfaces were more prone to degradation, the proposed approach would give severely biased measures of degradation.

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	single spot and that the same scanning frame is used for some of the colourimetry. Allowing for set up, this suggests a rate of one spot per hour. Given that each location may need to consider both engraving and background spots, this suggests that not all colourimetry spots may be sampled. The approach with both focus stacking and camera movement is data intensive – up to 1000 images each of perhaps 25 MB would be acquired at each spot, not allowing for replication. RTI is also proposed for morphological change measurement. In this regard we note with concern the statement that "Murujuga provides an abundance of suitably flat cultural surfaces" [page 51], suggesting that this technique will be limited to only certain spots. It is not clear whether it is suggested that spots be selected on some such subjective criterion. This raises a question concerning various other measurement methods, whether they also have constraints on what types of surface they can be used on. (For example, the photogrammetry technique has a limited depth of field and hence may also require a reasonably flat surface.) Beyond the above, no protocol or guidelines are provided for selecting spots to be sampled. This is a major omission. We appreciate that measurement methods may impose constraints but it is important that they be documented so any potential biases are understood. It is also important that to the greatest extent possible any subjective inputs to spot sampling are minimised. A related issue is how spots will be returned to in subsequent years.		
6	**Destructive Analysis** As a general comment, it appears that the destructive analysis [3.3], perhaps better described as laboratory based analysis, has fewer statistical issues – it is aimed at understanding processes rather than measuring the status of the rock art in the field. It is important to ensure that the laboratory work consider all possible conditions encountered in the field, but it is not necessary for it to be representative in itself. For example, the sampling discussion refers to the need to examine all three	Agreed; this will be discussed in detail in Part B of the document.	We look forward to Part B

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	major rock types. The exception is where the laboratory work aims to provide measures of the rock status directly. For that the same sampling requirements as for the surface change measurements apply. Co-located sampling is strongly recommended. Since it is not ideal for destructive testing to be carried out too close to petroglyphs, to get the full benefit of co-located sampling it will be necessary to carry out some more intense sampling at a limited number of sites to ensure that small scale spatial effects are understood and what, for sampling purposes, can constitute a local area around a site. This section is correspondingly short of detail on actual sampling processes. Some indication on numbers of samples for the microbiome work [3.3.3.ii and iii, page 67] but not on how these samples are chosen. The reference to ten sites [3.3.3.ii] suggests a site selection process but does not indicate whether this is co-located with other site selections. It is apparent that some methods will only be available for limited samples or sites. This is understandable when using demanding methods but it must be done consciously with an understanding of potential biases. The statement that "CSIA will therefore only be done on select samples where these requirements are able to be met" [3.3.4.iv] is therefore read with some (hopefully misplaced) concern.		
7	**Air quality modelling** The collection of air quality and meteorological data will use automated stations. The critical statistical aspect of these is their siting. It is notable that the approach is one of combining measurement in the field and modelling (CFD and spatial statistical methods) to complement each other and maximise the information. It is not clear just how many sites will be sampled for this purpose and how they relate to the sites used for other measurements.	The choice of sampling equipment is based in part on practical considerations, recognising that sites are likely to be unpowered, remote and there may be the need to carry the equipment from a vehicle to a site. We also need to ensure we measure all species specified in the tender document. Where power is available (for example the AIRBOX site) we would look to employ more continuous methods. This would be the NO sensor, FT-IR and some additional direct reading instruments for SOx and Ammonia. Where power is unavailable (likely for most sites) we will rely primarily on diffusive samplers. The exception here is the NO sensor, where a non-direct reading instrument is required (the NO sensor). This sensor has a fairly significant power requirement so would need an associated solar-	We look forward to reading Part B but make the following comments based on the replies contained here. Constraints on where sampling can be done due to issues such as vehicle access and electrical power are not unexpected but always to be avoided where possible. In the case of the AIRBOX, interpolation between the extremes proposed is fraught with implicit assumptions unless done carefully. At the very least, some effort should be made to correlate measurements made with the AIRBOX with others that are more readily made at lower cost and without the same constraints. **Since air quality provides the connection between the**

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	Our understanding from the workshop earlier in 2020 was that the number of sites might be relatively small – perhaps 3. We also note that there is only one Airbox available for some of the more complex monitoring [3.4, page 77] and that this might only be available for limited times, it "is likely we could only deploy facility for approximately 1 month at the peak of the wet season and 1 month at the peak of the dry season" [3.4.2.ii]. This suggests that at best a subset of the sites used for other measurements might be monitored for air quality. How these are chosen is not clear. Some measurements will be essentially continuous while others will be periodic. How these choices are made is also not clear	battery based power supply, we may also have to consider non-continuous monitoring or monitoring for NO at a reduced number of sites. See additional comment above re the considerations between passive and active monitors, as well as power and intrusiveness considerations. Plans have been revised based on the above comments to consider permanent realtime monitors. The proposal to deploy the AIRBOX for 1 month at the peak of the wet season and 1 month at the peak of the dry season was tentative and subject to review by the statistical design team. There are also constraints on the AIRBOX's availability, however it was felt that capture of full speciation and compositional data for the two extremes of the annual climate would provide sufficient data to interpolate throughout the year, and permit follow-up studies if later determined to be necessary. All components of the research will undergo full statistical design under the Part B component of this report. It is however envisaged that each sub component will be designed around the most appropriate time scale for the component. E.g much of the monitoring will be ongoing (e.g. monthly), some geological and microbial work will occur once or twice within the first 12 months of studies and then transition to ongoing (simplified/streamlined) studies.	**emission sites and the rock art sites, and air quality measurements are amongst the best means of validating the various CFD models, it is important that the statistical design team is involved in this.**
8	**Computational Fluid Dynamics Modelling** It is perhaps unfortunate that such a key component of the study is placed towards the end of the Study Design [3.5]. The computational fluid dynamics (CFD) models are key to understanding what pollutants travel where and how they interact with the ground surface The CFD models also assist the spatial interpolation of direct measurements of deposition of pollutants. For these reasons the CFD models are to be used to directly drive the statistical site sampling process [3.5.2.iii]. We commend the approach taken here as it provides the only way of overcoming the problem of no true control sites. As such it is critical and it would be useful is more detail was provided. This section of the Design Study also appears to be the source of the reference made in many places to sampling at 10 sites [3.5.2.iii]. It would be useful to know how the value of 10 sites was	The 10 sites was an initial placeholder for calculating the proposed budget. The actual number of sites will be determined by statistical design incorporating the RAMBOLL modelling data and all relevant spatial and cultural datasets and constraints. This will be included in the Part B document.	We remain concerned that the CFD component of the work appears to be given secondary status. Its proposed use to drive the placement of measuring sites was one of the most innovative and important aspects of the study. It is not clear how the RAMBOLL report addresses this. When we re-read the CFD section of the revised Part A, we note that only 16 simulations are proposed. As one of the aims is to understand variability and hence sensitivity to meteorological conditions, this seems to be a very small number of simulations. We suggest that a number in the order of 100 to 500 would be more appropriate.

Item No.	Peer Reviewer Comment	Response	Peer Reviewer Close-out Comment
	derived. More importantly, it would be comforting to know what strategy would be adopted if the CFD study suggests that 10 sites is not enough.		
9	**Summary** The sampling of sites and petroglyphs within sites is one of the most important steps at the beginning of the monitoring study. Inappropriate sampling can result in wasted effort in collecting data that is not of full value. Efficient sampling optimises the amount of information obtained for the effort applied. Similarly, the scale of sampling, essentially the sample size, is also critical in ensuring that the sample is able to answer the critical questions. Sampling below a certain level can be wasted effort if, no matter how well the science is done, it cannot answer the questions. Whilst the Design Study covers a range of scientific work which is intended to be conducted to a high standard, it is not clear at this stage whether the sampling issues have been sufficiently described. In particular, if further consideration of sampling suggests that more sites are required, this may have major implications for the budget or the range of scientific methods that can be used.	Full detail will be given in Part B. We will also take into consideration suggestions from reviewers that a larger number of continuous (permanent) monitoring stations would be more desirable, replacing many of the proposed passive monitoring stations.	It is good to see that sampling of sites is to be given more in depth thought. We look forward to reading Part B. In this context we note that the revised Part A introduces a classification of the rock art, by period and motif.

3.2 Data Analysis Australia – Statement of Advice and Response to Review comments for Monitoring Studies Data Collection and Analysis Plan

General comments

1. This is a summary of my review of the statistical aspects of the *Monitoring Studies Data Collection and Analysis Plan Draft Report* (hereinafter "the Report") dated September 2021 to consider whether it provides a solid scientific basis for ongoing monitoring of the Murujuga Rock Art.

2. Overall the document is a **much more polished and complete description of the proposed methodology than previously provided**. Hence my comments are somewhat briefer than those on the previous version as generally the Report now describes a largely reasonable plan of action.

3. Appendix I of the Report titled *Study design methodology* is new, covering in detail many issues that were only alluded to in the previous version.

   (a) This appendix states that "the Appendix prevails on matters of study design and methodology", whilst on other issues the main text prevails.

   (b) For that reason my review has given priority to the Appendix and I have essentially ignored comments that might suggest sample sizes etc in the main text.

   (c) Clearly any contradictions between the main text and the Appendix should be resolved early on. If this or budget constraints lead to a substantial change to the design and in particular sample sizes then my positive conclusions may need revision.

4. I have also given attention to the rock colour and condition monitoring, in part because of my familiarity with the previous studies in this area and because it has the most complex sampling issues.

Comments on main text

5. The main part of the Report is largely concerned with measurement methods which are outside of my scope. The issues of sampling are essentially covered by Appendix I.

6. The colour measurement or surface change (section 3.2.3) is significantly revised from earlier versions and contains a number of unique sampling issues.

   (a) It is now acknowledged that compatibility with previous studies is no longer possible. **I agree with this decision.**

   (b) Hence it is proposed to use new instruments, particularly the JAZ spectrophotometer, and the new random Sample Survey Sites for the major part of the study.

7. It now proposes that the monitoring of petroglyphs be done at the Sample Survey Sites (which it terms the "Representative Sites"). The measurements at these Sample Survey Sites will endeavour to detect changes to actual petroglyphs.

8. At the Air Quality Sites it proposes a separate program of measuring specially chosen rock surfaces (chosen on the basis of their homogeneity). Presumably these surfaces are expected to provide a more sensitive indicator of change that may be able to be related to the directly adjacent air quality measurements.

   (a) As such this links through to other aspects of the study design that look at causal links between airborne pollutants and the rock surfaces rather than monitoring the petroglyphs themselves.

   (b) Such a sample will not be representative in any statistical way, but may not need to be.

9. Reference is made to the problems in reliably locating the Konica Minolta spectrophotometer (used by the CSIRO in their later stages) on measurement points on the rock surface so that longitudinal measurements can be made.

   (a) This is a problem that almost definitely bedevilled all the instruments previously used and led to several ad hoc changes to the manner of using them, resulting in inconsistent data from one year to the next.

   (b) It is proposed to use a microscope stage to take a grid of observations instead. It is not clear how this microscope stage (or whatever equipment is used) will itself be reliably located. If it cannot be properly located then it might not be an improvement over previous studies.

   (c) As described, it appears that the microscope stage is simply a method of collecting data over a larger area, to some extent compensating for the smaller head on the JAZ instrument. This reduces but does not eliminate the effects of poor location.

   (d) A key step in the early development of this methodology should be to better understand the small scale spatial variation and hence the degree of improvement that might be obtained by this method.

   (e) It is possible, but not stated, that the intention is to register the scans from one year to the next to ensure that the location problem is solved. (This is related to the commonly used image stacking method.) It would be nice if the answer was yes.

Comments on Appendix I

10. The Appendix takes a systematic approach to the design issues, using modern standard methods.

   (a) It focuses on calculating required sample sizes through identifying the size effect that might be considered necessary to detect, quantifying the size and understanding the structure of uncertainties in the measurement process and then deriving a sample size that will have a prescribed probability (power) of detecting such an effect.

   (b) This approach is standard although it is carried out here with a degree of sophistication that is better than what is frequently seen.

11. The division into Air Quality Sites and Sample Survey Sites (presumably the same as the Representative Sites on page 50) gives a certain flexibility in the design which will permit the artwork sites to be truly representative.

    (a) The assumption here is that the placement of the Air Quality Sites will enable through a geostatistical interpolation method the prediction of air quality anywhere, including the Sample Survey Sites.

    (b) It is not clear how the accuracy of this prediction will be tested. Since this is central to the whole project – it directly addresses the question of whether the petroglyphs at site with poor air quality degrade faster than those at other sites – this seems to be a relevant omission. **We recommend that a modest program of monitoring air quality at some Sample Survey Sites be considered.**

    (c) The Appendix (page 6) states the number of Air Quality Sites is optimised at 18 and this is given in Section 3.7 of the Report. I believe this reference is incorrect and the correct reference is to Appendix II, that covers site selection

    (d) As is indicated by Figure 5 of that Appendix, over the range studied from 5 to 20 monotonic improvement in fitness as the number of sites increases, with the perturbations in the figure simply due to the randomised algorithm used. **Hence it is not clear what logic was used to choose 18** – there is no reference to a threshold that suggests that 18 is "good enough" and the "best" was clearly 20. **However it is a distinct improvement on the 10 earlier suggested.**

12. The subsequent calculations in Appendix I use this figure of 18 and in a sense use it as a constraint. It is also applied to the Sample Survey Sites.

    (a) Having a similar number of sites for the two samples does make sense statistically as an allocation of resources.

    (b) The subsequent calculations of sample size within sites worked within this constraint. This implicitly assumes that replication within sites can to some extent compensate for fewer sites. This can be true to the extent to which variation with sites is of a similar magnitude to variation between sites. Appendix I makes reference to the need to better understand such issues.

13. The sampling process for Sample Survey Sites follows a standard two stage process, the first stage sampling "cells" and the second regions within cells.

    (a) This method avoids needing to define regions across the entire study region while still providing proper sampling. Hence it is cost effective and adaptable.

    (b) The use of systematic sampling (with a random start point) ensures that the coverage is geographically reasonably complete.

    (c) Overall we are satisfied with the site sampling procedure.

14. For the colour monitoring it is proposed to select three rocks (presumably rocks with petroglyphs) at each site.

    (a) It is not clear where the number three came from, although it does seem reasonable. The number of sites will constitute a total of 54 petroglyphs, a considerable increase over previous studies. **A written protocol will need to be developed for this rock sampling.**

(b) A number of spots on each rock "will be selected as targets". It is not clear how they are selected. It is not clear whether each "spot" might be a pair of points (as in the terminology of the CSIRO), one on the engraved area and one adjacent but on the background rock.

15. The statement (page 13 off Appendix I) that "the number of spots on a given site should be roughly commensurate with the number of sites" is unclear since it is based on a table of variance components from previous work where a "site" and a "rock" were essential the same.

(a) Information is essentially lacking on how rocks within a site (current definition) may vary from each other – it is not known whether two rocks from within the same site are more likely to be similar to each other than two rocks from different sites.

(b) Data will become available to resolve this and better optimise the sampling but in the meanwhile some decisions may need to be made. The suggestion (Section 5.2.3) of 10 fixed spots on each rock (each being a pair of points to cover on and off the engraving) seems reasonable.

16. The Appendix considers the power when using the scanning grid. It is not clear what assumptions are behind this.

17. It is also proposed to conduct at least some analyses with the full reflectance spectrum rather than just the three co=ordinates in (L,a,b) space. This will also increase the statistical power as well as potentially giving greater insights.

(a) The use of an improved spectrophotometer (JAZ compared with the BYK at least) will also increase power through a reduction in noise.

18. The proposed analysis will consider linear trends, typically over time. This provides a good way of increasing statistical power Appendix I rightly points out the dramatic increase in power as more years are observed. (This is an underappreciated fact of statistical life.)

(a) One consequence of this will be that after the first four or five years that are the scope of the initial study, the monitoring program will increase substantially in statistical power up to a time when it is no longer reasonable to consider just linear trends. However this is contingent on the monitoring processes being kept consistent.

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: Dr John Henstridge; Data Analysis Australia	
Document Title: Murujuga Rock Art Monitoring Program: Monitoring Studies Data Collection and Analysis Plan	
Document Revision: Version 2.1 (September 2021)	**Revised Version:** Version 2.2 (November 2021)
Date of Review: 30 September 2021	**Close out Comments:** 2 December 2021

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
1	All	This is a summary of my review of the statistical aspects of the *Monitoring Studies Data Collection and Analysis Plan Draft Report* (hereinafter "the Report") dated September 2021 to consider whether it provides a solid scientific basis for ongoing monitoring of the Murujuga Rock Art.	Noted	Noted
2	All	Overall the document is a **much more polished and complete description of the proposed methodology than previously provided**. Hence my comments are somewhat briefer than those on the previous version as generally the Report now describes a largely reasonable plan of action.	Acknowledged	Noted
3		Appendix I of the Report titled *Study design methodology* is new, covering in detail many issues that were only alluded to in the previous version. (a) This appendix states that "the Appendix prevails on matters of study design and methodology", whilst on other issues the main text prevails. (b) For that reason my review has given priority to the Appendix and I have essentially ignored comments that might suggest sample sizes etc in the main text. (c) Clearly any contradictions between the main text and the Appendix should be resolved early on. If this or budget constraints lead to a substantial change to the design and in particular sample sizes then my positive conclusions may need revision.	Noted.	Noted
4		I have also given attention to the rock colour and condition monitoring, in part because of my familiarity with the previous studies in this area and because it has the most complex sampling issues.	Noted	Noted
5		**Comments on main text** The main part of the Report is largely concerned with measurement methods which are outside of my scope. The issues of sampling are essentially covered by Appendix I.		
6	3.2.3	The colour measurement or surface change (section 3.2.3) is significantly revised from earlier versions and contains a number of unique sampling issues. (a) It is now acknowledged that compatibility with previous studies is no longer possible. **I agree with this decision.**	Note – we plan to conduct a detailed cross-validation study of all available instruments once A. Thorn has travel approval. This will likely be undertaken at the WA museum using their collection.	It is good that a cross validation study is to be conducted early on as instrument differences have plagued earlier studies. Ideally this study should endeavor to understand why instruments are different and hence should be designed with different rock types and different settings etc with a proper statistical balance. **I strongly recommend that the cross-validation study be independently reviewed.**

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
		(b) Hence it is proposed to use new instruments, particularly the JAZ spectrophotometer, and the new random Sample Survey Sites for the major part of the study.		
7	3.2.3	It now proposes that the monitoring of petroglyphs be done at the Sample Survey Sites (which it terms the "Representative Sites"). The measurements at these Sample Survey Sites will endeavour to detect changes to actual petroglyphs.	Petroglyph colour monitoring will occur at all sites in the study design where petroglyphs are present. At Sample Survey (RS) Sites, the petroglyphs to be monitored have been chosen by a randomised procedure. It is intended that these observations would permit design-based statistical inference about the entire population of petroglyphs. At Air Quality (AQ) Sites and Existing Monitor (EX) Sites,the petroglyphs to be monitored are chosen arbitrarily to satisfy numerous constraints, including closeness to the Air Quality monitoring station, apparent homogeneity of surface colour, and availability of a `matched pair' with a non-petroglyph rock. It is intended that these observations would support dose-response modelling of the effect of emissions and other explanatory variables on colour and condition of petroglyph surfaces.	Noted, although it is important that the "numerous constraints" be properly documented so that potential biases can be identified.
8	3.2.3	At the Air Quality Sites it proposes a separate program of measuring specially chosen rock surfaces (chosen on the basis of their homogeneity). Presumably these surfaces are expected to provide a more sensitive indicator of change that may be able to be related to the directly adjacent air quality measurements. (a) As such this links through to other aspects of the study design that look at causal links between airborne pollutants and the rock surfaces rather than monitoring the petroglyphs themselves. (b) Such a sample will not be representative in any statistical way, but may not need to be.	See comments regarding #7. We confirm (a) and (b) are the intention.	Noted
9	3.2.3	Reference is made to the problems in reliably locating the Konica Minolta spectrophotometer (used by the CSIRO in their later stages) on measurement points on the rock surface so that longitudinal measurements can be made. (a) This is a problem that almost definitely bedevilled all the instruments previously used and led to several ad hoc changes to the manner of using them, resulting in inconsistent data from one year to the next. (b) It is proposed to use a microscope stage to take a grid of observations instead. It is not clear how this microscope stage (or whatever equipment is used) will itself be reliably located. If it cannot be properly located then it might not be an improvement over previous studies. (c) As described, it appears that the microscope stage is simply a method of collecting data over a larger area, to some extent compensating for the smaller head on the JAZ instrument. This reduces but does not eliminate the effects of poor location. (d) A key step in the early development of this methodology should be to better understand the small scale spatial variation and hence the degree of improvement that might be obtained by this method. (e) It is possible, but not stated, that the intention is to register the scans from one year to the next to ensure that the location problem is solved. (This is related to the commonly used image stacking method.) It would be nice if the answer was yes.	Again, this phase of the work will undergo detailed validation in the coming months. Together with the spatial scientists on the project we have devised a method to determine the accuracy of instrument positioning that is blind to the operator (A Thorn). Thereby we will obtain and publish a method validation study prior to commencing in the field. The influence of small-scale variations as mentioned has now been explored. (a) We concur. This is an important consideration of our study. (b) A scanning frame of sub-milimetre increments.The stage micrometer is simply to maintain constant distance between the probe and the surface, thereby maintaining a constant target diameter. The sensing area can be programmed to any diameter and reliability with distance has been verified. This means we can provide a target diameter of any dimension up to c. 8mm (c) The stage micrometer ensures constant distance of the probe to surface, hence target area dimensions. (d) This study has been completed on a grid of 20 x 20 mm with 2 mm increments. The data has been presented in deltaE units. (e) Image registration is being entertained as one possible strategy to be tested and validated.	The Calibre response provides additional information and clarifies some of the equipment but does not directly address the issue of how the same spot on a rock surface will be measured year upon year. If a grid of 25 or 81 points (presumably 5×5 or 9×9points) is recorded every year, how are these to be placed and aligned on the rock surface? Not being able to overcome this challenge will increase year to year random variation and hence affect statistical power. In (d) it is suggested a study has already been done along these lines – is this available? Has registration already been trialed? We note that Appendix 1, Section 5.2.2 addresses some of the issues of analyzing the gridded data but by our reading not the registration issue.

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
10	Appendix I	**Comments on Appendix I** The Appendix takes a systematic approach to the design issues, using modern standard methods. (a) It focuses on calculating required sample sizes through identifying the size effect that might be considered necessary to detect, quantifying the size and understanding the structure of uncertainties in the measurement process and then deriving a sample size that will have a prescribed probability (power) of detecting such an effect. **(b) This approach is standard although it is carried out here with a degree of sophistication that is better than what is frequently seen.**	Acknowledged.	Noted
11	Appendix I	The division into Air Quality Sites and Sample Survey Sites (presumably the same as the Representative Sites on page 50) gives a certain flexibility in the design which will permit the artwork sites to be truly representative. (a) The assumption here is that the placement of the Air Quality Sites will enable through a geostatistical interpolation method the prediction of air quality anywhere, including the Sample Survey Sites. (b) It is not clear how the accuracy of this prediction will be tested. Since this is central to the whole project – it directly addresses the question of whether the petroglyphs at site with poor air quality degrade faster than those at other sites – this seems to be a relevant omission. **We recommend that a modest program of monitoring air quality at some Sample Survey Sites be considered.** (c) The Appendix (page 6) states the number of Air Quality Sites is optimised at 18 and this is given in Section 3.7 of the Report. I believe this reference is incorrect and the correct reference is to Appendix II, that covers site selection (d) As is indicated by Figure 5 of that Appendix, over the range studied from 5 to 20 monotonic improvement in fitness as the number of sites increases, with the perturbations in the figure simply due to the randomised algorithm used. **Hence it is not clear what logic was used to choose 18** – there is no reference to a threshold that suggests that 18 is "good enough" and the "best" was clearly 20. **However it is a distinct improvement on the 10 earlier suggested.**	(a) We concur. (b) Noted and will be considered. (c) Apologies – yes appendix II (d) Including the industry monitoring sites we will have 27 air quality monitors.	Noted
12	Appendix I	The subsequent calculations in Appendix I use this figure of 18 and in a sense use it as a constraint. It is also applied to the Sample Survey Sites. (a) Having a similar number of sites for the two samples does make sense statistically as an allocation of resources. (b) The subsequent calculations of sample size within sites worked within this constraint. This implicitly assumes that replication within sites can to some extent compensate for fewer sites. This can be true to the extent to which variation with sites is of a similar magnitude to variation between sites. Appendix I makes reference to the need to better understand such issues.	Agreed.	Noted
13	Appendix I	The sampling process for Sample Survey Sites follows a standard two stage process, the first stage sampling "cells" and the second regions within cells. (a) This method avoids needing to define regions across the entire study region while still providing proper sampling. Hence it is cost effective and adaptable.	Agreed.	Noted

Item No.	Section No.	Peer Reviewer Comment	Calibre/Curtin Response	Peer Reviewer Close-out Comment
		(b) The use of systematic sampling (with a random start point) ensures that the coverage is geographically reasonably complete. **(c) Overall we are satisfied with the site sampling procedure.**		
14	Appendix I	For the colour monitoring it is proposed to select three rocks (presumably rocks with petroglyphs) at each site. (a) It is not clear where the number three came from, although it does seem reasonable. The number of sites will constitute a total of 54 petroglyphs, a considerable increase over previous studies. **A written protocol will need to be developed for this rock sampling.** (b) A number of spots on each rock "will be selected as targets". It is not clear how they are selected. It is not clear whether each "spot" might be a pair of points (as in the terminology of the CSIRO), one on the engraved area and one adjacent but on the background rock.	Section 11 contains the number of rock samples and petroglyphs selected. Appendix I has a revised sampling protocol based on field practicalities.	The details on the rock sampling protocol now in Appendix 1 follow good spatial sampling practice for point data. We recognize that petroglyphs are not points and in some cases it may be necessary to decide just where the centroid (or some other reference point) is, but this seems unlikely to be a significant problem.
15	Appendix I	The statement (page 13 off Appendix I) that "the number of spots on a given site should be roughly commensurate with the number of sites" is unclear since it is based on a table of variance components from previous work where a "site" and a "rock" were essential the same. (a) Information is essentially lacking on how rocks within a site (current definition) may vary from each other – it is not known whether two rocks from within the same site are more likely to be similar to each other than two rocks from different sites. (b) Data will become available to resolve this and better optimise the sampling but in the meanwhile some decisions may need to be made. The suggestion (Section 5.2.3) of 10 fixed spots on each rock (each being a pair of points to cover on and off the engraving) seems reasonable.	(a) We agree that there is a dearth of reliable information about the relative magnitudes of different sources of variability. Indeed the preliminary fieldwork has raised further questions about sources of variability associated with shadowing of rock surfaces by other rocks, physical effects such as water runoff and bird droppings, and other processes. (b) We concur.	Noted, but we also **recommend that an explicit review point be introduced to ensure that refinements (or corrections) to processes can be made as early as possible.**
16	Appendix I	The Appendix considers the power when using the scanning grid. It is not clear what assumptions are behind this.	Section 5.2.2 of Appendix I indicates that there is no reliable information available about spatial variability across the rock surface at different spatial scales. It also cautions about additional sources of variability. A very conservative approach is to assume that spatial correlation is very high at short scales so that a scanning grid is equivalent to repeated observations of a single spot. Then the "spot-within-site" variance is used.	Noted.
17	Appendix I	It is also proposed to conduct at least some analyses with the full reflectance spectrum rather than just the three co=ordinates in (L,a,b) space. This will also increase the statistical power as well as potentially giving greater insights. (a) The use of an improved spectrophotometer (JAZ compared with the BYK at least) will also increase power through a reduction in noise.	Acknowledged.	Noted
18	Appendix I	The proposed analysis will consider linear trends, typically over time. This provides a good way of increasing statistical power Appendix I rightly points out the dramatic increase in power as more years are observed. (This is an underappreciated fact of statistical life.) (a) One consequence of this will be that after the first four or five years that are the scope of the initial study, the monitoring program will increase substantially in statistical power up to a time when it is no longer reasonable to consider just linear trends. However this is contingent on the monitoring processes being kept consistent.	We concur.	Noted

4 Air quality

4.1 Engineering Air Science – Peer review report and Review comments sheet for Detailed Study Design (Part A)

Peer Review - Air Quality
Murujuga Rock Art Monitoring Project: Detailed Study Design.

Prepared for:

Government of Western Australia
Department of Water and Environmental Regulation

Draft Report: 200801
November 2020

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Citing:
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1 Introduction

The Department of Water and Environmental Regulation (DWER) commissioned Engineering Air Science (EAS) to undertake an independent peer review of Murujuga Rock Art Project Detailed Study Design (Puliyapang, Curtin University, 2020a) in aspects relevant to air quality. With the aim of investigating petroglyph (rock art), characterising and quantifying acceleration of the natural weathering processes, the draft Detailed Study Design outlines the proposed air quality investigations to assist understand air quality impacts from anthropogenic emissions across the regions of petroglyphs on the Murujuga. The air quality investigation includes air quality monitoring and flow and dispersion modelling. It is proposed to apply Computational Fluid Dynamics (CFD) to simulate the atmospheric boundary layer flow structure and dispersion of anthropogenic emissions from industry within the Murujuga region.

This report provides a more general background to the context including a brief review of general air quality monitoring and modelling topics for readers not specifically involved across the specialist subject. The primary review, consisting of specific comments related to individual aspects of the Detailed Study Design is included as an attachment within the tabulated DWER format document as Appendix A.

2 Background

Rock art at Murujuga, (The Dampier Archipelago including Burrup Peninsular) in the Pilbara region of WA, is believed to be the World's largest and oldest collection of petroglyphs (rock art). The Aboriginal engraved petroglyphs are of immense heritage value and of great cultural and spiritual significance to Aboriginal people.

The region is also home to many industrial facilities located in close proximity to the petroglyphs. Concern in relation to the effect of anthropogenic emissions to the atmosphere, leading to acceleration of the natural weathering process, has resulted in a substantial amount of investigation, particularly over the past 15 years. Most of the independent investigation of current rock and petroglyph characteristics and deterioration potential have been undertaken by CSIRO (Gillett, 2010). These include monitoring of colour change and spectral mineralogy of the rock art, and studies to understand the potential of the industrial pollutants to accelerate deterioration of the petroglyphs. Additionally, air pollutant monitoring and modelling to quantify the petroglyphs' exposure to industrial air pollutants has been undertaken by CSIRO and industry.

Shortcomings in the design, methodologies, and analysis of the historic monitoring program were identified within independent reviews with recommendation that the program be redesigned. The Department of Water and Environmental Regulation (DWER) released the Murujuga Rock Art Strategy in February 2019 with the aim of establishing a monitoring, analysis, and decision-making framework in partnership with the Murujuga Aboriginal Corporation (MAC). As part of the strategy implementation, Puliyapang Pty Ltd, a joint venture between Tocomwall and Calibre, in partnership with Curtin University, Artcare and ChemCentre, was appointed to develop and implement a new Murujuga Rock Art monitoring program over a 5- year period.

Initial deliverables to guide design and implementation of the monitoring program consist of a Conceptual Model (Puliyapang, Curtin University, 2020), and Monitoring Studies Data Collection and Analysis Plan. The independent peer review is focussed on the development of the Monitoring Data Collection and Analysis Plan, with individual reviews focused on the various aspects of the plan commissioned separately. The review presented within this document focuses on air quality aspects of the plan, aimed at understanding the distribution of impacts to air quality across Murujuga to assist in final design of the air quality monitoring plan. The primary elements incorporate the proposed air quality monitoring and approach to simulating atmospheric boundary layer flow and the transport, dispersion and fate of anthropogenic air pollutants.

3 Detailed Study Design document

The primary purpose of the monitoring program is to establish whether anthropogenic emissions are accelerating the natural degradation of the rock art, changing the natural weathering process or in other ways causing alteration. The monitoring program will underpin the Environmental Quality Management Framework (EQMF) (DWER, 2019) developed to assist protect the rock art on Murujuga and enable timely and appropriate management responses by the Western Australian Government and stakeholders to emerging issues and risks.

The focus of the EQMF is on monitoring and managing environmental quality to protect the rock art on Murujuga from anthropogenic emissions. Primary motivation of the Murujuga Rock Art study is to ensure the rock art is not subject to accelerated deterioration as a result of anthropogenic emissions, and enable robust scientifically supported decisions in relation to protection and management of the rock art. The primary purpose of the air quality aspect of the study is to understand and quantify air quality impacts across rock art distributed over the peninsular to provide detail on exposure of rock art to anthropogenic emissions. Parallel studies within the investigation are researching air pollutant exposure levels that may lead to accelerated degregation of the rock art.

The initial phase of the program is the development of a Conceptual Model and Monitoring Studies Data Collection and Analysis Plan to support the design and implementation of the monitoring program and the development and implementation of the EQMF. The Conceptual Model will guide the Monitoring Plan which is underpinned by the Detailed Study Design describing the monitoring studies and analysis proposed to enable characterisation of rock art and identification of potential for accelerated rock degradation due to increasing exposure to anthropogenic emissions.

Primary elements of the monitoring program include a combination of non-invasive monitoring aimed at characterising the rock art, and monitoring and modelling of air quality to understand the exposure of rock art to air pollutants, particularly anthropogenic emissions from local and regional industry. This is coupled with laboratory experiments on non-art rock samples to understand their characteristics and response to environmental exposure. Components of the proposed Detailed Study Design include:

1. Non-Invasive monitoring
    - Spectral analysis of petroglyphs

- Prescribed air quality monitoring - near locations of spectral analysis
- High resolution laser scanning of monitoring sites and DGPS location mapping for all spectral analysis measurement points
- Peninsula scale air quality modelling
- Sub-scale air quality modelling using high resolution laser scanning data

2. Laboratory experiments on non-petroglyph samples
    - Detailed characterisation of the rock microbiome and response to environmental exposures
    - Detailed characterisation of the inorganic geochemistry of the rock patina and response to environmental exposures
    - Detailed characterisation of the organic geochemistry of the rock and interaction of organic pollutants with element above
    - Isotope analysis of key emissions to enable source apportionment of measurements from air quality monitoring samples
3. Determination of site selection and sample sizes

Monitoring studies proposed in the Detailed Studies Design must be properly replicated and logically developed and designed to test clear hypotheses and adhere to best practice principles of experimental design, including but not limited to:

1. Identification of the study objectives and testable hypotheses.
2. Development of an appropriate data collection and analysis program, including a pilot study, and review and endorsement by an appropriately qualified and competent statistician.
3. Measurement and/or sample collection, processing and analysis, including quality assurance and quality control (QA/QC).
4. Reporting of the results and evaluation against the original study objectives and hypotheses.
5. Assessment of feasibility and cost-effectiveness of the proposed study.

The Detailed Study Design is to provide detailed descriptions of the methodologies and procedures, including but not limited to:

- Detailed descriptions of the proposed field and laboratory data collection program, including rationale for the proposed design and any departures from best practice principles of sampling program design with a justification for the proposed departures;
- A detailed description of the proposed equipment and instruments, methodologies and procedures, including the rationale for their selection and an analysis of the strengths and weaknesses of the proposed approach;
- A description of the QA/QC procedures;
- A description of the data management, data validation and verification, and data quality assessment procedures relative to the objectives of the monitoring studies and the proposed data analysis; and
- The details of literature and other material referred to within the Detailed Study Design.

4 Air Quality Investigation

An understanding of the atmospheric environment to which the rock art is exposed is critical, as ultimately the chemicals present in the air (natural or anthropogenic) are what the rock surface will interact with, and potentially chemicals in the rock surface react with. Air pollutants can interact as they flow over the rock art, dry deposition occurring as atmospheric particles deposit directly on the rock surface, while deposition of gaseous air pollutants such as sulphur dioxide, nitrogen oxides and ammonium can lead to acidification. Pollutants can also be removed from the atmosphere and deposited through wet deposition process in precipitation events, cloud-water or occult deposition through direct contact with mist and dew.

To understand air quality and the exposure of the rock art to air pollutants, a combination of field monitoring and modelling of the air pollutant transport, mixing and interaction with the ground is proposed.

4.1 Air quality monitoring

Ever increasing options are becoming available for air quality monitoring. However, there is also large diversity in instrument accuracy and reliability, as well as instrument cost and the cost of the overall supporting requirements to install and maintain instruments. The potential options are too diverse for detailed discussion, however there are two primary approaches to monitoring pollutants within the air:

- Batch methods collect samples for later analysis within a laboratory, providing detail on the average impact over the period the sampler was installed. Diffusion tubes are a passive batch monitoring method that collect a sample from the diffusion of the pollutant into a tube containing an adsorbent and reactive material. Laboratory procedures are applied to analyse the amount of pollutant present in the tube after it has been exposed for a period to provide a time averaged pollutant concentration. Such methods are simple and cheap and can provide detail on spatial variation over a region in screening assessments, however there are limitations including lower accuracy and no indication of concentration variability.
- Continuous methods that provide in-situ continuous analysis for real-time, or near real-time, detail of pollutant concentration variation with time. With temporal resolution of minutes or less, continuous instruments can provide statistical detail on pollutant concentration variability which can be correlated with monitored meteorological conditions (wind direction, wind speed, atmospheric stability, etc.) to assist in developing an understanding the origin of significant pollutant sources and the meteorological processes leading to major exposure events.

The purpose, objectives and budget of a monitoring programme should be considered when choosing monitoring methods. Compliance monitoring can generally only be carried out with high-precision instrumental methods. Where feasible, compliance methods should generally be used for specific investigations and research studies, particularly where there is advantage in understanding short time period fluctuations in pollutant concentration.

Many compliance standard monitoring systems require mains power in addition to site constraints around separation from obstacles, restricting locations they can feasibly be installed.

4.2 Air quality modelling

Representation of pollutant behaviour in the atmospheric flow through modelling transport and dispersion provides an alternative means of understanding pollutant impacts to that of monitoring. The approach relies on representing the important physical (and chemical) processes of pollutant emission into the environment and subsequent interaction with the atmospheric flow. Physical and mathematical approaches have been extensively applied for many decades. Two scales of air quality modelling are discussed within the DSD, peninsular scale and sub-scale air quality modelling. A brief explanation of the two scales of modelling is provide below:

- **Peninsula scale air quality modelling** would aim to understand air quality exposure across Murujuga but particularly across the Burrup Peninsular region where industry and rock art coexist. The typical process involves coupling atmospheric dispersion modelling with meteorological modelling of the region. This is the normal approach to air quality assessment applied for Environmental Authority and investigation studies. The meteorological model employs locally monitored and/or larger scale meteorological (weather) model data to provide a representation of local meteorology over the model domain, providing detail on wind speed and direction and the thermal structure of atmospheric boundary layer on a 1-hour time-scale over the diurnal cycle. They model the mean wind flow and parameterise the turbulence based on estimates of the primary surface momentum and energy fluxes. This detail along with the characteristics of individual pollutant emission sources, provides the basis on which the dispersion element of the modelling tool assesses the distribution and fate of pollutants in the local environment.

  Pollutant concentration predictions are made at specified locations (grid and discrete) for each hour of the day for the selected simulation period, nominally 1-year. Assessment for a period (24 hr, 1-month, annual average) is derived from averaging of the individual hourly predictions for the designated period. Tools for these post-processing tasks are included within the modelling system, as are pre-processing tools for developing files of input information, including hourly detail on wind, temperature and other meteorological parameters, ground or surface characteristics, and details on individual pollutant emission sources, primarily stacks for industrial facilities. Model scales vary from many 100’s of km, even 1000’s of km with grids of 10’s to ~ 100 km, down to order 10 kms or less with grid point spacing down to a 100 m distance or less.

- **Sub-scale air quality modelling** involves applying a model to investigate aspects of the pollutant transport and dispersion processes that are not reliably represented within an atmospheric dispersion model, the peninsular scale air quality modelling. Traditionally, such investigations have focussed on aspects of the initial pollutant emission process that may not be well represented within a dispersion model, interaction of multiple emissions points in close proximity, interaction of emissions with adjacent structures for instance, improved representation of near-field plume behaviour being the critical feature of the investigation. The approach can be equally applied to investigate critical variation of impacts over a smaller area where resolution with an atmospheric dispersion is not possible.

The basic approach is to model the fluid mechanical behaviour of the meteorological flow condition. The mean flow condition is established, and the turbulence is modelled based on the local flow characteristics, the influence of buildings and structures or other surface features and thermal effects in the local region. This is known as fluids modelling and can use either physical modelling (reduced scale model in a wind tunnel for instance) or the intensive numerical modelling of Computational Fluid Dynamics (CFD).

CFD is the branch of fluid mechanics that numerically solves the fundamental mathematical equations which describe fluid behaviour. A fully enclosed geometrical domain is established to represent the bounds of the real fluid behaviour of interest or investigation. The external walls of a building for instance will represented the bounds of the geometric domain when investigating air flow over the building. The volume within the geometrical domain is divided into small parts, or volumes, known as the grid or mesh. Flow physics and boundary conditions defining the flow character, such as inlet flow rates, the character (roughness) of walls or other real physical boundaries, etc, are established, and a complex set of partial differential equations, derived from the conservation laws, developed and solved through the application of numerical methods.

CFD can be applied to virtually any fluid mechanical issue, assisting to understand the fluid behaviour through provision of flow field detail in both space and time. The approach is particularly beneficial in more complex configurations, where fluid behaviour is likely to depart from that prescribed through empirically based design methods. CFD can be used as a quantitative design tool or as qualitative tool for narrowing down or discarding various prototype designs through their numerical simulation. However, due to the applicability of CFD to any fluids issue, the tools are general, requiring individual configuration for each simulation, i.e. establishing meteorological flow characteristics, emission characteristics, surface characteristics for each simulation. Additionally, individual post-processing and analysis is necessary to provide validation and a more full understanding of the resultant output. While scripts can assist these processes, from a practical perspective of both man hours and computation time typically only limited, specifically targeted, simulations are performed.

5 Detailed Study Design – Air Quality Review

Specific review comments that refer to individual sections of the Detailed Study Design document in relation to the field of Air Quality are presented within the tabular format of the Department of Water and Environmental Regulation Independent Peer Review Comment Sheet in Appendix A accompanying this report.

Further discussion of two primary air quality elements and importantly their integration is provided in Section 6.

6 Further Discussion Detailed Study Design – Air Quality Review

6.1 Air Quality Monitoring

A primary proposition of the Black et al (2017)[1] paper was that the critical acid load for the soil/rock character associated with the Murujuga rock art should not be as high as 200 meq/m^2/yr, as concluded in the CSIRO (Gillett, 2010)[2] monitoring report and previously used as a basis for the regulation of industrial air pollution impacts to the art. Black et al (2017) suggesting "*an appropriate critical acid load for preservation of rock art on Murujuga would appear to be less than 25 meq/m^2/year.*" The CSIRO report provides estimates of total acid load due to sulphur and nitrogen near the industrial areas of Murujuga of 25 meq/m^2/year in 2004/2005 and 32 meq/m^2/year in 2007/2008, currently in excess of the < 25 meq/m^2/year critical load proposed as appropriate by Black et al (2017).

The acid load was determined from the air quality monitoring programs across the period 2004/2005 to 2007/2008. The monitoring programs reported extremely low concentrations of sulphur and nitrogen within the Murujuga air shed region compared to state based ambient air quality guidelines. Monitored concentrations averaged across a period of 1-month by the sampling instrument were often barely detectable by the methods used (passive sampling). Being removed from any major urban area, air pollution is typically due to local activities, and then primarily resulting from sources near or within the Burrup Peninsular region. The background concentration is generally only at trace level, at or below the limit of detection of the passive sampling monitoring devices. Thus, it is potentially only the direct impact of local sources that will contribute to the monitored sample in a detectable manner. These impacts may be of limited concentration, duration, and frequency, and thus may not accumulate to a discernible level with respect to the passive monitoring devices.

Continuous real-time monitoring with lower detection limit (ppt) would provide improved understanding of pollutant concentration magnitude, duration, and frequency. However, such monitoring equipment typically requires mains electric power and operation within a controlled environment (air-conditioned). In isolated areas the need for mains power can restrict instrument choice, with the more suitable monitoring systems unable to be utilised extensively.

It is proposed to deploy a trace NO_x analyser to provide continuous real-time monitoring of NO, NO_2 and NO_x, although instrument power requirements may prevent the planned use of solar power for this purpose. However, deployment of limited, strategic continuous real-time monitoring, in conjunction with the more extensive passive and solar powered monitoring network, would capture transient events and assist in developing an improved understanding of industrial impacts to air quality, and the verification and validation of models particularly in the near field. Pollutants to consider for additional continuous monitoring include SO_2, NH_3 and particles ($PM_{2.5}$, PM_{10}, TSP) with a focus on regions close to industry where elevated concentrations may be expected and mains power is more readily available. Monitoring strategically placed to target regions of higher impact

[1] Black J.L., Box I., Diffey S., 2017. Inadequacies of research used to monitor change to rock art and regulate industry on Murujuga ('Burrup Peninsula'), Australia. Rock Art Research 34, 130-148.

[2] Gillett R., 2010. Burrup Peninsula Air Pollution Study: Report for 2004/2005, 2007/2008 and 2008/2009 Technical report, CSIRO Marine and Atmospheric Research, Victoria.

for the pollutant of concern with greater emission uncertainty, i.e. SO_2 near shipping operations, TSP near materials handling operations, can reduce uncertainty of model predictions.

With respect to continuous real-time monitoring it should be noted[3]:

"*In advance of potential changes to industrial air emissions on the Burrup Peninsula, Woodside voluntarily recommenced ambient air monitoring in 2019 to further understand ambient air quality in the region. The program is expected to extend the historical dataset and complement ambient air quality monitoring proposed under the Murujuga Rock Art Strategy.*

It is Woodside's intention to continue the ambient air monitoring program until its absorption or replacement with the coordinated approach established under the Murujuga Rock Art Strategy.

Woodside's current ambient air monitoring program uses up to three powered monitoring stations to continuously monitor applicable pollutant gases and meteorological conditions, such as wind speed and direction."

Ambient Air Monitoring Station Locations[2] include Karratha (484,892 7,707,575) Burrup Road (476,665 7,721,038) and Dampier South (470,239 7,716,142). It is understood a Serinus® 44 analyser is installed for NOx monitoring (NO, NO_2, NOx, NH_3) along with O_3, BTX and meteorological monitoring.

Strategic enhancement to these systems through expansion of instrumentation and/or locations around critical industrial impact regions could assist enhance knowledge of how local industry affect air quality in the Murujuga region.

Low-cost air quality monitoring instrumentation has also advanced over recent years and can operate with solar power options. Although unlikely to reliably quantify background concentrations, and thus period averaged exposure, with continuous real-time monitoring capability they may provide indicative detail for periods of significant industrial impact. Model predictions and high temporal resolution output from compliance standard continuous real-time monitoring, such as that of Woodside, could provide an indication of peak industrial concentrations and thus the potential capabilities of low-cost monitors to resolve incidents of industrial impact. Operation alongside compliance standard continuous real-time monitoring systems would provide opportunity to assess performance.

A further important consideration with the installation of any air quality monitoring system is the security of the system; how to prevent the system components from being damaged or interfered with, especially when located in publicly accessible areas.

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3 https://www.epa.wa.gov.au/sites/default/files/PER_documentation2/NWS%20Project%20Extension%20-%20Appendix%20A%20-%20Air%20Quality%20Management%20Plan.pdf

6.2 Air Quality Modelling and Site Characterisation

A dispersion model is a statistical analysis tool providing a concentration field prediction for each modelling period, typically 1-hour although can be less, based on site, emission, and meteorological knowledge for that period. The predicted fields can then be statistically analysed, generally with tools incorporated within the modelling package, to obtain detail such as period averages, maximum, and period average maximum (i.e. maximum 24-hour average across 1-year) across the domain. Many air quality regulatory authorities around the world now wish to understand annual variation in air quality impacts, particularly for more critical situations, necessitating modelling for a period extending up to 5-years coupled with analysis of annual variation. The predicted concentration fields are continually used in understanding air quality impacts and the development of monitoring networks.

Computational Fluid Dynamics (CFD) modelling can theoretically achieve a similar outcome. However, the practicality of application across a large region (domain 10's of km), with a substantial number of emission sources, and capturing the critical variation in meteorological conditions, is highly questionable particularly if simulating an extended period.

The coupling of dispersion modelling, using regulatory air quality dispersion modelling tools, and fluid modelling (wind tunnel, water tank, CFD, have all been applied over many decades) is often found to be the more practical approach to understanding and simulating complex air quality issues. In this approach the fluid model is used to investigate fluid mechanical issues involved in the air flow and turbulence field and their effect on local dispersion and plume behaviour e.g. flow over buildings or terrain where local recirculation is critical, the effect of wind speed and direction on the interaction of adjacent emissions. The meteorologically based dispersion model is applied in the representation of meteorological influence on the atmospheric flow and turbulence structure, and subsequent plume transport and dispersion, i.e. atmospheric stability, thermal internal boundary layer development and influence on plume behaviour.

All simulation methods apply a model which ultimately is based on some form of assumption and/or parameterisation. Physical models (wind tunnel, water tank) apply scaling parameterisations and assumptions based on the equivalence of non-dimensional parameters (Reynolds number, Richardson number, etc.). Regulatory air quality dispersion models apply parameterisations for atmospheric turbulence and plume behaviour, and thus dispersion, derived from theory and experimental investigation within the laboratory and the field. Peer acceptance of the applied parameterisations is extremely high and primary limitations well understood. The turbulence is derived from the flow and thermal character of the atmosphere (mechanical and thermodynamic effects). While uncertainty exists, much of the uncertainty of a dispersion model prediction arises from uncertainty in model input as opposed to error in the model predictions. There is also large stochastic variation evident in meteorological and dispersion parameters measured within field campaigns as the state of atmospheric flow is never fully stationary.

CFD models also apply assumptions and parameterisations, but this is with respect to the input boundary conditions and the equation set and turbulence model. The equation set and turbulence model are responsible for the flow field, and turbulence generation and dissipation based on local properties within the flow field. Iterative procedures are applied to the flow and turbulence fields within the domain to converge to a 'balanced' flow in which the flow parameters, including mean flow and turbulence, are described across the domain. With an ability to capture flow and turbulence based on the domain structure, including flow recirculation, the CFD model can depict fluid mechanical issues that a dispersion model is not able to explicitly resolve. These may include issues such as recirculating flow environments, including flow around a building or buildings within an industrial complex; the interaction of two plumes emitted from stacks in close proximity to each other; the effect of a rock outcrop on deposition in and around the rocks in comparison to an adjacent flat region; the potential of resuspension of material deposited onto a rock outcrop under one meteorological condition when higher wind speeds or different wind directions occur. These are all elements which cannot be explicitly resolved with a dispersion model.

The input parameters, or boundary conditions, applied to the CFD model can at best be derived in a similar manner to those of atmospheric dispersion models, and thus would have no more certainty than those applied in the atmospheric dispersion model. However, atmospheric dispersion models have been developed to receive specific boundary conditions, or input, including meteorological model output, surface and upper air measurements and other surface parameters that characterise the effect of the ground state on the flow. The input data enables the atmospheric dispersion model to estimate the atmospheric structure over the model domain for each model period (i.e. 1-hour). The structure includes the vertical wind temperature and turbulence profiles, all of which affect the transport and mixing of pollutants emitted into the atmospheric flow. The atmospheric structure will vary across the flow field, with a 3-dimensional model aiming to represent this variation across the domain. This is achieved through a combination of numerical and parameterisation techniques, with primarily turbulence derived from parameterisations of surface-based inputs.

With a CFD model the aim of representing the flow structure will be equivalent, as will the general approach with a combination of numerical and parameterisation methods employed. The primary difference being that turbulence within the CFD model is developed within the numerically solved equation set based on local flow conditions and gradients. To achieve this the CFD model requires a grid structure of substantially higher density, which comes at a substantial cost in computational time to obtain a numerically derived solution. CFD models, or tools, are also general tools that can be applied across virtually any fluid dynamical issue (liquid or gas and can include particles and mixtures). As such they generally require individual configuration to suit the specific scenario being simulated, which is achieved through configuration of the domain and boundary conditions for an individual simulation. Application to different areas of fluid mechanics is specialised, with knowledge of both the modelling tool and the critical fluid mechanical issues required. Simulation of idealised neutral atmospheric boundary layer flow with idealised boundary conditions is relatively straightforward, however application to complex boundary conditions, involving both vertical and horizontal variation, and the representation of non-neutral atmospheric flow conditions is far more involved. With larger CFD domains, such as that to encompass the full Murujuga region and associated industrial emissions, synoptic variation conditions may also require consideration with respect to boundary conditions.

Different CFD modelling approaches are also better suited to different flow conditions observed within the diurnal cycle of atmospheric flow. The application of CFD to atmospheric flow, particularly atmospheric flow fields representing a distribution of atmospheric stability conditions important to atmospheric dispersion, is not straightforward. The simulation methodologies applied in the CFD modelling would require validation to provide confidence they are adequately representing the flow structure. This would be a very substantial project in itself, and ultimately, while a prediction of air pollutant impacts could be obtained, it will incorporate error and uncertainty as with the atmospheric dispersion model, and potentially more. Demonstration of an overall improvement, in terms of representation of pollutant impacts over time, of the CFD model configuration compared to an atmospheric dispersion model would also likely be a substantial task. Even though the CFD model can incorporate a more detailed representation of the flow and dispersion, it is not necessarily the case that it will provide improvement in representation of flow structure, pollutant transport and dispersion, concentrations and impacts.

Blocken and Gualtieri (2012)[4] discuss the application of CFD to environmental fluid mechanics based on the previous work of Jakeman et al (2006)[5] and Robson et al. (2008)[6]. In relation to model evaluation and testing of models 5 questions were proposed as discussed below:

1. How well does the model reproduce an independent data set?

   This would need to be tested for the developed CFD model/s

2. How well does the model perform under unusual conditions?

   This would need to be tested for the developed CFD model/s

3. Is the complex model better than a simpler one?

   This is not necessarily the case and would likely vary dependent upon the specific conditions simulated. While the CFD could be configured to better represent certain scenarios, for general application across the range of meteorological and emission conditions it is likely the atmospheric dispersion model will perform better. For instance, atmospheric chemical reactions and gaseous deposition are not discussed in the CFD model design.

4. Can the model be used to improve understanding of underlying system function?

   Most definitely a CFD model can be used to improve understanding, but more with respect to a specific issue where fluid mechanics is important and cannot be adequately resolved within a dispersion model. Many of these scenarios can be parameterised into the dispersion model once an understanding has been developed.

5. Finally, and most importantly, does the model help to answer questions about the system function and can it be used to make predictions about the future?

[4] B. Blocken, C. Gualtieri, Ten iterative steps for model development and evaluation applied to computational fluid dynamics for environmental fluid mechanics, Environ. Model. Software 33 (2012) 1–22.

[5] Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environ. Modell. Softw. 21(5), 602-614.

[6] Robson, B.J., Hamilton, D.P., Webster, I.T., Chan, T., 2008. Ten steps applied to development and evaluation of process-based biogeochemical models of estuaries. Environ. Modell. Softw. 23, 369-384.

A well-developed and validated CFD model could be used to answer questions about system function and predictions, but so can an atmospheric dispersion model. Each tool has strength in different aspects of the issues involved with the flow and dispersion over the Murujuga region and understanding impacts to rock art. The coupling of the two tools will most likely provide the best outcome, using CFD modelling to increase understanding of sub-scale fluid mechanical issues enabling improved representation within the broader scale atmospheric dispersion model.

6.3 Integrated approach

Indications are that concentrations of primary pollutants on the Burrup Peninsular and the Murujuga region are generally low in comparison to human health-based objectives, both natural and anthropogenic. There is concern however that even at these low concentration levels potential exists for the acceleration of petroglyph weathering and degradation Black et al (2017)[1].

Monitoring and model validation to date has primarily compared period averaged monitoring with period averaged model predictions, and often the periods have not been coincident. The recent Perdaman Urea Project AQIA (Jacobs, 2020)[7] provides a limit statistical analysis of continuous real-time monitoring with 2 scenarios of TAPM predictions across 3 monitoring locations. Generally good to excellent agreement is observed in relation to the higher concentrations (peaks), while the agreement is not as strong for annual average monitoring results and model predictions. Detail on conditions that lead to higher impact events is not provided. Detail such as wind and stability conditions can provide insight into the processes that lead to measured concentrations, assisting in developing an understanding of model uncertainties and limitations.

Atmospheric processes involved in the transport, dispersion, and fate of air pollutants in the Murujuga region are complex. Monitoring provides a method of quantifying pollutant concentrations at a limited number of specific locations. However, monitoring has been limited to period averaged methods across most locations with greater uncertainty and understanding of industrial contributions to pollutant impacts also limited. Additional analysis and statistical methods can provide ability to identify source contributions and extrapolate monitored concentration over a region, however detail on events leading to high impact episodes is not provided within available literature.

The integration of continuous real-time monitoring of pollutant concentrations and meteorology with dispersion modelling provides ability to better understand processes that lead to high impact events, and conditions where a model is not performing well. Understanding model performance, and particularly conditions for which a model does not perform well provides opportunity to investigate why a model may not be performing well and develop improvements to the model. For instance, a model may represent higher impacts from nearby industry well, but with inadequate detail of background pollutant concentration characteristics provide disparate representation of longer-term average pollutant concentrations.

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[7] https://www.epa.wa.gov.au/sites/default/files/PER_documentation2/Appendix%20D%20-%20Air%20Quality%20Impact%20Assessment.pdf

With the ability to represent individual pollutant source and the influence of meteorology on the transport, dispersion and fate of the emitted pollutants, a dispersion model can provide a scientifically based estimate of pollutant concentration over a region. Coupled with detailed continuous monitoring model uncertainty can be reduced, providing greater confidence in the predicted location of higher impacts and their magnitude. Tools such as CFD modelling of fluid mechanical behaviour of the atmospheric flow and emission interaction can also assist improve the reliability of models. The final component is the understanding of emissions. To understand industrial impact, reliable detail, coinciding with monitoring and modelling temporal resolution, of pollutant emission rates and stack emission parameters (flowrate, temperature etc.) is critical. Continuous emissions monitoring data may provide more reliable detail for critical stacks with significant variation in emission characteristics.

Jacobs (2020)[7] outlines industry-based monitoring which is used to provide comparison with the model configurations applied in the study and covers for periods more recent than the CSIRO study. Industry monitoring and modelling data can provide considerable information on the likely current distribution of pollutants across the Murujuga region, with detailed review of assumptions and configurations likely able to provide insight into potential uncertainty. Cooperation of industry is critical in understanding air quality and how the contribution of individual industries changes in the immediate vicinity of the industry and more regionally. Access to reliable and informative industry data related to air quality assists develop understanding of local air quality including primary uncertainties and limitations of methods applied in the studies.

The monitoring and model prediction data that form the basis of the Jacobs (2020)[7] report likely provides the current best available detail on air pollutant concentrations for the Murujuga region, with the additional modelling commissioned by DWER potentially enhancing this detail. It is not clear how the proposed CFD modelling would emulate the dispersion model predictions across the full range of meteorological conditions to provide equivalent estimates, and certainly not clearly improved estimates. Continuous real-time monitoring suggests the Jacobs (2020)[7] dispersion modelling has performed well in elements where industrial emissions detail is important and of higher quality. When characterisation of emissions in the model is less certain the model appears to perform more poorly, i.e. shipping SO_2 emissions, background emissions which can lead to disparity in annual average concentration, and diffuse emissions across the urban areas. The use of a CFD model will not generally lead to reduced emission uncertainty but can reduce uncertainty in relation to the emission interaction with the immediate atmospheric flow environment and the initial emissions behaviour. The two sets of modelling, in conjunction with coincident continuous real-time monitoring, could provide the initial basis for investigation of more critical model uncertainties, enabling development of improved model configurations to provide better air quality pollutant distribution predictions across Murujuga. The air quality monitoring and modelling associated with the Murujuga Rock Art Monitoring Program could further enhance investigation into dispersion model uncertainties associated with industry on the Burrup Peninsular, with the use of CFD for investigation of identified sub-scale uncertainty associated with near-field fluid mechanical issues, and strategic monitoring potentially aiding investigations near more critical rock art locations.

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Appendix A

Murujuga Rock Art Monitoring Project: Detailed Study Design

Independent Peer Review Comments Sheet

Included document

Peer Review_Murujuga Rock Art Monitoring_StudyDesignPartA (002)_Air Quality.doc

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: John Taylor, Engineering Air Science.
Document Title: Murujuga Rock Art Monitoring Project: Monitoring Studies Data Collection and Analysis Plan (*Part A*) " Detailed Study Design" (PART A)
Document Revision: Version 1 (July 2020)
Date of Review: 9 November 2020

Note: A close out report was not provided for Part A as many of the issues raised by this review will not be resolved until the work required for Part B.

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1	1.2	Research Objectives 3. Determine which atmospheric pollutants are present in industrial and natural emissions on Murujuga, and which are capable of causing degradation or change of the petroglyphs. While local emissions on Murujuga are most likely to cause highest impact to the petroglyphs, understanding of emissions in the surrounding area and their behaviour, could also be important in relation to overall loads. Diurnal changes to atmospheric structure can lead to occasional, or repeated, impacts from more distant sources. Regional pollutant emission sources, in addition to those on the Burrup Peninsular, require identification and consideration with respect to potential to have a discernible pollutant impact across the Murujuga rock art.	DWER commissioned and has received results from a broad dispersion modelling study of the region surrounding Murujuga (RAMBOLL study). Components of this work were the development of an emissions inventory for the region, and modelling for 2 comparison years (2014, 2030). This data will inform the broad scale siting of AQ monitors, further refined with more detailed CFD modelling.	
2	1.2	Research Objectives 4. Under controlled laboratory conditions with small samples of rock, measure the effect of a known amount of pollutant chemical on the constituents of the rock surface and sub-layers; Air pollutant events at a specific location will be transient and thus variable in magnitude, duration, regularity etc. Is consideration being given to investigating how the dynamic nature of pollutant chemical exposure events, with short period concentration events, may affect the rocks and petroglyphs as opposed to pollutant loads representative of longer term, period average concentrations?	The transient nature of air pollution at specific locations is acknowledged. This is one of the practical challenges facing the research team. In terms of the laboratory study, we are looking to establish and explore mechanisms which may impact the rock art, through this approach (albeit simplified) we could consider a single high pollutant dose, or applying pollutant concentration profile (based on for example the CFD study).	
3	1.2	Research Objectives 5. Measure the concentration of atmospheric pollutants to which rocks are exposed, across the Peninsula; The use of diffusion instruments to measure pollutant concentrations provides an average exposure or total dose over a period 1-month say. Higher quality, continuous real-time instruments can provide detail of the character of significant exposure events, magnitude, frequency, meteorological conditions, etc., in addition to the seasonal and annual variation provided by diffusion instruments. High temporal detail of pollutant concentrations assists understanding of the meteorological and emission characteristics that lead to exposure events and assessing performance of modelling tools in representing pollutant behaviour. The ability to provide mains power can restrict the use of continuous real-time pollutant monitoring instruments in ambient environments. Measuring atmospheric pollutant concentrations with continuous real-time instrumentation, where feasible, would greatly assist understanding of impact events and associated critical meteorological conditions.	We agree with the reviewer that continuous monitoring would be ideal. However, there are some practical challenges faced here in terms of the remote environment and power requirements of continuous monitoring equipment. If power is available then it would certainly make sense to employ continuous/real-time monitoring. We have for example located a powered site where we plan to deploy the AIRBOX, this would also support the inclusion of additional equipment. We would look to include the NO sensor with this set up as well as use of an FT-IR.	
4	1.2	Research Objectives 6. Identify the weather conditions, environmental conditions and industrial output conditions which are likely to pose the greatest risk of degradation to petroglyphs;	The variation of air pollution levels is understood and we acknowledge that there would be a loss of sensitivity in using diffusion based instruments, where we obtain an average value over the monitoring period. However the use of diffusive samplers will overcome many of the practical challenges of deploying the monitoring stations to the field. If power is readily available then the use of continuous monitoring would be explored, however should not be the	

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		Air pollutant events at specific locations are variable in magnitude, duration, regularity etc. Knowledge of temporal behaviour of impacts and meteorology provides ability to understand impact events, potential source, and meteorological conditions, and assists in identification of conditions leading to greatest risk. However, this knowledge is most reliably obtained through continuous real-time monitoring, the outcomes of which can also be applied to understand model uncertainty and improve model representation. Greater uncertainty is introduced through the application of models to interpret temporal variation from period averaged monitoring. Even though monitoring locations may be remote, the ability to provide continuous real-time monitoring, of particularly critical gaseous pollutants, would greatly assist in achieving Objective 6 and also assist in quantifying and validating model performance with respect to representing critical conditions. The monitoring location selection criteria should be weighted with consideration of the ability to obtain mains power and thus operate continuous real-time, compliance standard, gaseous and particulate monitoring instrumentation.	sole reason for choosing a particular site. We must also consider the statistical validity of any site selection to give the best possible results. Restricting ourselves to powered sites would leave the majority of the study area unmonitored.	
5	1.7	Air Quality (Objectives) Coupled air quality modelling and monitoring can achieve improved ongoing understanding of air quality over a region such as the petroglyph distribution. Use of intensive meteorological and air pollutant monitoring, and fluid modelling provides opportunity to developed optimised air quality modelling for application, in unison with continued monitoring, to determine exposure of petroglyphs to critical air pollutant impacts on a statistical basis. An optimised air quality model, with reduced uncertainty, can assist representation of meteorological effects on the variation in both short- and long-term pollutant exposure, capturing annual variation for instance. Fluid modelling can be applied to assist understand sub-scale near-field effects not, or only roughly, represented within atmospheric dispersion models, i.e. site generated turbulence; plume interactions; enhanced deposition within recirculation regions (gorges etc.). Consideration should be given to the development of an optimised atmospheric dispersion model of regional air quality to couple with ongoing long-term monitoring and aid extrapolation of pollutant concentrations across the full region of petroglyphs for current industrial activity, and aid assessment of cumulative impacts resulting from potential future increased industrial activity.	We agree this would be useful and should be considered particularly for ongoing modelling.	
6	2.1.4	Spatial Datasets While a source offset (location mismatch) is not ideal for elevated buoyant releases it will generally only result in an offset of the predicted impact region of the plume by a similar amount, independent of whether an atmospheric dispersion model or CFD model of atmospheric dispersion is applied. The exception would be if the initial emission behaviour is subject to near-field effects (buildings or terrain) when the relative location would be important. In this case disparity in relative location of the emission to the structure could have a substantial influence on the initial plume behaviour, distorting the initial downwind concentration field for both atmospheric dispersion and CFD models. As you move further from the source, and the plume spreads, the effect becomes less significant with respect to variations in predicted concentrations.	This is agreed. However, given the layout of Murujuga it is likely that emissions sources, and monitoring stations will be in close proximity. In this case, local effects may be significant for both. For this reason, we have proposed CFD as a tool to improve the links between the data measured at discrete points (the monitoring stations), to the air-quality across the peninsula. The purpose of the CFD is not to duplicate plume or dispersion modelling (which has since been carried out for the peninsula).	
Proposed Study Design				
3.1 Rational for the proposed design				
7	3.1.2	Need for closely-located observations in the component studies The simulation of plume behaviour and dispersion can provide a means of interpolating atmospheric observations between locations based on known pollutant emissions characteristics and meteorological conditions. Atmospheric dispersion models have been employed to understand the distribution of air pollutants related to industrial activity for many decades. Capabilities advanced considerably through the latter period of the 20th century and early 21st century through field campaigns and experimental research including fluids modelling. They have long been utilised to understand regional air quality impacts, the contribution of individual industries and assist in the development of monitoring networks. Conversely, the monitoring network can assist in verification and validation of model performance, allowing interpolation of air quality impacts	Agreed. The aim of the CFD modelling is to characterise measurement uncertainty in the monitoring network prior to it's deployment. The additional resolution afforded by CFD allows better siting of the monitoring network prior to the monitoring campaign. Poorly sited monitors may be costly to move, while poor quality data recorded may need to be ignored – with the CFD we are able to avoid this at the start of the project. D315 In terms of co-location of monitors and rock-art monitoring sites, there is an immense number of petroglyphs at Murujuga. While co-locating will be attempted for the more important sites, it is not possible for all. Also, in many instances co-location is not possible for cultural reasons.	

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		across the region of the model domain when the model is considered to adequately represent the more critical aspects of pollutant transport and dispersion. While there is uncertainty in any simulation, atmospheric dispersion model or CFD model, arising from input data uncertainty as well as the model representation, there can also be significant uncertainty in air pollutant monitoring data. Diffusion tubes are only considered an indicative technique, and their inability to identify short-term fluctuations make them less useful around emission sources such as industrial plants, especially where background concentrations are very low (trace level) and industry impact potentially small as well. While near co-location of environmental and rock monitoring sites will improve connection, interpolation between monitoring sites can be assisted through simulations coincident with the monitoring period.		
8	3.1.2	Detection limits Detection limits become more critical when monitoring industrial air pollutants in cleaner environments, as there are potentially periods when monitoring sites are not substantially exposed to industrial pollutants. The investigation needs to ensure detection limits of monitoring systems are adequate to reliably determine background concentrations, and thus differentiate industrial impacts from the background concentration. If low winds speed conditions are critical for elevated industrial pollutant impacts, detection limits or thresholds of wind monitoring instrumentation can also be critical to assist understanding of meteorological conditions through low wind speed periods. Meteorological instrumentation should be adequate to reliably monitor wind speeds conditions important in understanding pollutant impacts.	Using CFD this becomes something that can be investigated prior to deployment. It is possible to incorporate detection limits when sampling the CFD models, and characterise the network including these limits. The proposal is that the monitoring network in-toto is able to record the air-quality across Murujuga under as near as all conditions.	
9	3.1.2	Effect of pollutants on rock The impact of industrial pollutants at nearby ground level locations is transient, and highly variable dependent on emission characteristics and meteorological conditions. Representation of these effects would necessitate investigation of the effect of short-term, high concentration pollutant exposure events on rock.	This is something which can be explored through our laboratory studies.	
10	3.1.4	b. Spatial interpolation of atmospheric monitoring observations There is considerable uncertainty in previous monitoring data, particularly that obtained with passive diffusion devices. CSIRO state an overall precision for passive gas measurements of about ±20%, while uncertainty of individual measurements may be ±50%. With limited monitoring sites uncertainty in extrapolated estimates at other locations would be enhanced. With appropriate industrial emissions detail, dispersion models can be applied to predict or estimate pollutant distributions on the Burrup Peninsula and Murujuga region coincident with monitoring periods to provide alternative or additional detail to concentration fields interpolated or extrapolated from the monitoring data. Some of the uncertainty with atmospheric dispersion models could be reduced by the application of fluids modelling to improve representation of near-field effects such a plume interaction with site structures or other plumes. Dispersion models could also be applied to better understand historic industrial pollutant impacts across the Peninsular if such detail was beneficial in interpreting existing disparity in observed rock characteristic, should such characteristics be observed to already exist across the Murujuga rock art.	Agreed. Particularly “Some of the uncertainty with atmospheric dispersion models could be reduced by the application of fluids modelling to improve representation of near-field effects such a plume interaction with site structures or other plumes.” This is what we intend to do with the CFD modelling.	
11	3.2.2	Laser Scanning of Study Sites Laser scanning can also be applied to industrial sites to provide information on site structures and features relevant to wind flow and the initial behaviour of plumes emitted from site operations. Such detail would be highly beneficial to characterise industrial site features, primarily within the CFD modelling, but potentially also beneficial in atmospheric dispersion modelling.	We have incorporated aerial data (to a resolution of 1m) of the key industrial sites at Murujuga. For sites of particular cultural importance, we aim to laser scan at a higher resolution to identify any flow characteristics which would make a site more/less affected than the baseline.	
3.4	**Air quality modelling, monitoring at receptors and source apportionment**			
12	3.4	Atmospheric dispersion models can provide a robust simulation of pollutant transport from known emission sources across the Burrup Peninsula. Compared to CFD tools, atmospheric	This is not mentioned in the current Part A document, but this work was already commissioned by DWER, and has since been undertaken by their consultants. The CFD in	

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		dispersion models more readily incorporate meteorological influences using well validated methodologies, with 3-dimensional models applied to air quality assessment able to provide 3-dimensional detail on meteorology and pollutant concentration. They can also incorporate atmospheric chemistry and have other features designed and validated across the globe that make them ideal for understanding air quality impacts both statistically and at specified time frames coincident with monitoring. Atmospheric dispersion models are developed to run from numerical derived weather data, including re-analysis or forecast, monitored surface meteorological data or a combination of both. CFD models are a general tool to model fluid behaviour, nearly any fluid behaviour. While they can be applied to atmospheric flow and dispersion, they require individual configuration and validation for the purpose. Validation would be primarily against data sets used to develop and validate atmospheric dispersion models. Why is it proposed to use only CFD?	this project is to improve the utility of the air-quality measurements recorded at Murujuga, particularly to be able to better validate dispersion modelling. The dispersion modelling was conducted with a grid size of 1.3km to be consistent with the modelling assumptions. However, while this gives an overall idea of where a monitoring site should be located, it is not precise enough to account for the local scale topology. The aim of the CFD is not to replicate the hour by hour exposure on sites at Murujuga.	
13	3.4	Many air quality monitoring instruments can provide continuous real-time monitoring for both particulate and gaseous air pollutants. The primary constraint being the power supply, for the instrument and to maintain a stable (air conditioned) environment within which the analysis component of the instrument operates. Those that are able to operate from an on-site power supply, such as a solar and battery system, typically provide lower quality outcomes due to; limited resolution of gaseous pollutants, or inadequate air flow to sample larger particles in particulate sampling instruments. Without a controlled operating environment, the accuracy of the monitor can be influence by variation in temperature, humidity and wind speed, among other factors. There is a clear benefit to obtaining accurate real-time pollutant concentration data, and thus for using higher standard compliance or trace monitoring equipment. The AirBox is, or can be, equipped with multiple high level scientific instruments that would primarily be applied to a high level monitoring campaign developed to improve understanding of a specific complex issue that is deemed critical to overall exposure. Currently, understanding of air quality impacts across the Burrup Peninsular is limited, with no specific meteorologically related dispersion issue identified. What is the advantage of the AirBox over establishing a series of individual instruments with specific purpose at multiple locations over an extended monitoring campaign of a year or longer?	We agree with the comments. However the Murujuga region is rugged and remote, with limited powered sites. Therefore the original proposal specified only passive monitors, with the exception of NO, which can only be measured using realtime monitors. We agree with the general principle that the preference would be to install realtime monitors, however the caveat is we do not yet know if transient or long term average emissions/deposition are more important for the rock art condition. As per above, we now have RAMBOLL modelling data which covers the whole airshed and allows us to optimally design monitor locations. We will endeavour to deploy realtime monitors where power infrastructure exists or where MAC will permit sufficiently large solar power installations, however much of the monitoring proximal to the rock art must remain as small unobtrusive passive monitors. Weather stations will however be included at all sites which will permit extrapolation of transient/peak values (in conjunction with RAMBOLL and CFD models). The final/optimised monitoring design will be presented in the Part B document.	
Prescribed monitoring Equipment and Procedures				
14	3.4.1 xiii	Weather Station GRWS100 comes with 10 ft tripod (~3m). Standard meteorological measurements for wind speed and direction are at a height of 10 m. The higher location better avoids localized terrain or vegetation influence on monitored wind conditions, although more complex to install and maintain. The proposed wind monitoring height needs clarification.	While 10m may be ideal, there are a number of potential challenges. One would be the foundation/footing requirements for a 10 m high pole/tower in an area with the most severe cyclone rating in Australia. This would also likely cause significant disturbance to the monitoring sites, which we would like to minimise. It is worth noting that the closest airport measures wind at 5.8 m. It is also worth considering the purpose of the measurements, we are more interested in the environment near the study site, rather than large scale regional wind/weather patterns.	
15	3.41 xiii	Weather Station The propellor wind monitor (05103-L) with the GRWS100 has a starting threshold of ~1 m/s. CSIRO monitoring of wind speed (Figure 27, pg 63, Gillet 2010) indicates ~17.5% of wind speeds < 1.0 m/s and equivalent proportion $1.0<U<2.0$ m/s. Low wind speed conditions can provide for periods of highest air pollutant impacts. Ultrasonic instruments provide improved resolution of low wind speed conditions and may be a better alternative where understanding of low wind speed conditions is important.	Worth investigating. This is fair point. It would be desirable to capture low wind speeds as well, where as the reviewer suggests an ultrasonic instrument may be more appropriate, or should be considered alongside the propellor wind monitor. The WINDSONIC1-L can measure from 0 - 60 m/s and can be used with the proposed datalogger.	
16	3.41 xiii	Weather Station Details on the rain gauge are absent. Measurement of precipitation is critical for the operation of the deposition sampler	This would be a TE525MM-L metric tipping bucket rain gauge which measure in 0.1 mm increments.	
17	3.41 xiii	NO Sensor While the use of continuous real-time pollutant monitoring in conjunction with meteorological monitoring is of great advantage there are concerns about the viability of the proposed NO	The NO sensor does have quite significant power requirements. While this would not be an issue in the AIRBOX, or at a powered site, it may pose challenges elsewhere. A sufficiently large solar array, with associated deep cycle batteries would potentially meet this challenge, though this does not account for any additional cooling or sample pre-heating requirements.	

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		monitoring with respect to power requirements. It is stated that the NO monitor will be powered by a solar system. The Sernius® 40T has a start-up power requirement of 265 VA and operating of 190 VA (nominal) due to air flow and heating requirements within the unit. With additional ancillary equipment the total daily power requirement is around 10 kWh. Instrument power requirements are stated as "100 - 240 VAC, 50 - 60 Hz (autoranging)", i.e. mains power. Discussion with Ecotech (Ecotech 2020) indicate the instrument would require an air-conditioned enclosure to meet AS 3580.5.1-2011, as well as a heated inlet to avoid moisture ingress which can quickly damage the instrument. Thus, the total daily power requirement would be higher. Regular calibration is also required to adhere to AS 3580.5.1-2011 necessitating calibrated gas cylinders associated with each instrument. The feasibility of the deployment of the Sernius® 40T NO Sensor with a solar and battery power system is questionable, and sites for which mains power is available should be considered for this, and potentially other continuous real-time compliance standard air quality monitoring instruments. It should also be noted that a similar instrument, Sernius® 50T, can provide equivalent real-time monitoring of trace level Sulfur Dioxide (SO_2). Real-time ammonia (NH_3) monitoring can be achieved alongside NO and NO_2 with the Sernius® 44, although with a decrease in instrument sensitivity. continuous real-time monitoring of SO_2 and NH_3 could also be beneficial for understanding primary pollutant sources and the magnitude, frequency, and duration of potentially significant pollutant impact event, as well as providing detail to better understand the conditions under which pollutant impacts are observed and provide information to assist identification the pollutant source and validate dispersion simulations.	The instrument can operate at up to 40*C, however as mentioned may not be AS compliant at this temperature. Only 3 days had peaks above 40*C at Murujuga in the last 12 months, and only briefly. The requirement for calibration gas is acknowledged. Since measurement of NO is a requirement of the tender we need to meet this, so we would still deploy the NO sensor, at any powered site and with the AIRBOX, however additional consideration is required for any non-powered sites. This may require the sensor to be used in shorter measurement periods (i.e. not continuously) to keep power requirements reasonable. A generator is not considered a viable option here, owing to the emissions produced. The suggestions of the alternative sensor models are welcomed and will be considered for use in the AIRBOX and any powered sites.	
18	3.41 xiii	Deposition Sampler Initial washout, at the commencement of a rain event, is likely to provide the highest rates of pollutant wet deposition. The limits or characteristics to be used for determining change from dry to rain (wet), or mist, and the time frame over which a change is enacted, particularly on the commencement of rain, have not been discussed. Is there any understanding of the relative wind directional aerodynamic influence of the '3 Bucket' deposition sampler and how this may influence deposition across different particle sizes depending on the location of the open bucket with respect to the wind direction, i.e. near the upwind edge, the downwind edge or at an oblique angle between? Dust settled on the rotating has potential to enter the open bucket during rain events or wind conditions that may resuspend deposited matter. This may impact both total deposition rates and the rates recorded during the three mutually exclusive meteorological conditions.	Relative wind aerodynamic influence would need ot be considered. This could be tested prior to deployment to inform siting of the sampler. We plan to incorporate a raised edge around the opening of the sampler to avoid any settled dust entering the collection bucket. Validation tests will be conducted prior to deployment.	
19	3.41 xiii	Passive Sampling Tubes Passive sampling techniques such as diffusion tubes are commonly used to provide indicative air pollutant concentration information over a period, short periods (hours) within indoor work environments and longer periods of 1-week to 1-month or longer within the ambient environment. Typical application in ambient air quality is within urban and industrial environments where the combination of emission sources may lead to elevated impacts in relation to longer-term (1-month to 1-year) average pollutant concentrations close to guideline or standard levels. CSIRO (Gillet 2010)1 employed passive sampling methods within their studies. Detection limits report within the CSIRO investigations are generally lower than those reported within Table 3-6 of the Detailed Study Design (DSD), e.g. for ammonia. CSIRO reported detection limits between 0.1 ppb to 0.6 ppb for 2004/2005 investigation whereas, Table 3-6 (DSD) reports a detection limit of 1.5 µg/m3 (~2.2 ppb @ 25°C). CSIRO monitored concentrations across the Peninsula below this level and only those from Site 9 (Karratha) in a range above the stated detection limit of Table 3-6 (DSD).	The nature of the results obtained using passive sampling tubes is understood. In many cases it is likely we will be looking at remotely located unpowered sites, which make them the most practical option in terms of both operating requirements and logistics. As mentioned in responses to previous comments, we would look to employ continuous monitoring where possible. This would likely mean a different mix of monitoring equipment at different sites. The original tender requires us to measure a number of different species and most of these can be done with passive sampling tubes, or through deposition sampling, the exception here is NO. Hence the need to explore powered options for the NO sensors. Consideration was given to preparing our own sampling tubes, with analysis to be performed locally, however given the requirements of the tender around using approved, validated methods there was some concern there would be delays in terms of testing and verification of our tube and determination of detection limits. This is something we would be open to revisiting, particularly if results in the initial monitoring phase suggested that we were not collecting detectable samples.	

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		The detection limit is related to the blanks (unexposed tubes) used within the monitoring program alongside the sample tubes that are exposed to the monitored environment, and thus the stated detection limit is likely higher than what may be achieved within the investigation (i.e. more sensitive detection may be obtained within the investigation). However, even with the lower detection limits of the CSIRO study, analysed samples that report pollutant concentrations lower than the limit of detection are discussed and the impression is that this outcome was not uncommon. Furthermore, results of recent monitoring conditioned in the Yarra Pilbara Nitrates Pty Ltd (YPN) Technical Ammonium Nitrate Plant (TAN Plant) Approval indicates gaseous pollutant concentrations continue to be generally below the limits of detection stated in Table 3-6 of the DSD document. Thus, more detail is necessary with respect to the passive sampling tube detection limits and clarification the proposed DSD approach, tubes and analysis, will provide adequate resolution of monthly average concentrations across the proposed species to enable quantification of pollutant concentrations and definition of concentration gradients should any gas concentrations be significantly enhanced above background levels. Ideally, to adequately quantify background gas concentrations, quoted detection limits below the background concentrations recorded within the CSIRO studies and current Yara monitoring would be desirable.		
20	3.41 xiii	Data logging Establishing regular automated data downloads and preliminary quality assurance with alerts, can provide additional redundancy as well as more rapid and reliable identification of any problems with the monitoring instruments and systems. Have telemetry options, use of a local telemetry network, been considered for communication of more remote sites to a local network hub?	Based on available network coverage maps, most of the Burrup Peninsula has 3G/4G coverage. This would be used to stream data back to Perth. This way we will have both onboard data logging and data being frequently streamed.	
21	3.41 xiii	Power Supply Clarification is need on energy requirements for the proposed NO analyser, solar and battery system requirements, particularly with respect to the operational requirements (air-conditioning, heated inlet). If installation of a solar powered NO analyser at each monitoring site is feasible, consideration should be given to integration of the proposed two independent solar systems (meteorology and gas analyser).	See previous commentary re the NO monitor.	
22	3.41 xiv	Deployment of Monitoring Stations Verification of adequacy of solar and battery power systems through an extended period of operation, particularly systems associated with Sernius® 40T and potential additional Sernius® or similar monitoring instruments, prior to remote installation should be undertaken. Discussion on monitoring system security is absent.	The monitoring stations will be fenced, with a locked access point and appropriate signage. Power requirements are being assessed based on instrument start up requirements, inverter efficiency and daily hours of sunlight on the Peninsula.	
23	3.41 xiv	Field Blanks Field or trip blanks are integral in ensuring the integrity of each diffusion tube sample batch. Duplicate field blanks provide for quality control of blank samples, similar to duplicates of the field samples, and provide an improved degree of confidence in the accuracy of field passive sampler results. Given, on occasion, average pollutant concentrations may be near, or even below, the limit of detection of passive sampling methods, confidence in the blank reading is critical as it provides the zero offset for exposed samples of the associated batch. Where is it considered field blanks will be located on site, at a site of higher impact or a background site of lower or potentially indiscernible impact?	This has been clarified in the document.	
24	3.42 ii	AirBox Monitoring The AirBox appears a well-equipped, semi-mobile, atmospheric laboratory developed to assist	Noted. We will consider these comments in preparation of the monitoring plan to be presented in Part B.	

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		investigation into critical complex air quality issues. It may well be beneficial in understanding both meteorology and air quality on the Burrup Peninsula, and establishing and validating model configurations and parameterisations. However, careful consideration of the issues involved with more critical air quality impacts in the Murujuga region should be undertaken prior to initiation of an AirBox monitoring campaign. With many factors affecting the behaviour of pollutant plumes emitted into the atmosphere including wind speed and direction, surface characteristics (terrain features, radiation budget, moisture, etc.) critical conditions may not necessarily be through the peak of dry or wet season, but across a transitional period between. A campaign targeting meteorological conditions leading to critical air quality impacts may be beneficial if such critical conditions are identified. However, a more general understanding of the character of impacts across a longer period may be of greater benefit. For instance, continuous real-time monitoring of additional gaseous pollutants (SO2, NH3) and particulate matter (PM2.5, PM10, TSP) at selective locations across a longer term may provide the ability to better understand pollutant impacts across the rock art, and modelling uncertainties, than an intensive field campaign limited to specific, short periods.		
25	3.42 ii	AirBox Monitoring The AirBox website indicates the instrument requires 3-phase power connection. Assuming power is available at the Water Corp Tank site, consideration should be given to the installation of a 'permanent' continuous real-time monitoring station for particulate and key gaseous species, as well as the standard remote monitoring instrumentation at this location It could provide the ability for continuous monitoring and enable inter-comparison/validation of the remote monitoring systems as well as model simulations. Identification of alternative sites to the Water Corp Tank that can provide access to mains power connection would provide for additional continuous real-time monitoring. A compliance-based system able to monitor trace gas levels across critical gaseous species in real-time would provide not only information on average air concentrations but also detail on exposure variability including peak concentrations and duration of exposure events. Such a system could include installation of the Sernius® 40T NO Sensor and similar instruments for other gases that generally require controlled environments for Standard compliant operation. Additionally, with the water tank location between the major industrial (LNG and NH3) plants, at considerably different wind directions, a comprehensive monitoring system at this or similar locations, provides potential to characterise pollutants from individual plants as well as provide ability to test and validate air quality and numerical (CFD) model configurations. With a high density of rock art in and around the major industrial sites, there is potential for additional 'permanent' powered monitoring sites with continuous real time gas and particulate monitoring to add additional benefit to understanding pollutant behaviour across the critical rock art areas.	Agreed. We have considered a permanent monitor, subject to approvals from DWER Water Corp, etc. and will pursue this further. All monitors deployed as part of the study (apart from the AirBox if used) are intended to be handed over to MAC/DWER at the conclusion of the studyy and maintained as part of the EQMF (ongoing monitoring/management).	
3.5	**Computational Fluid Dynamics Modelling**			
26	3.5.1	Modelling and site characterisation The simulated pollutant field of Figure 3-19 (DSD) is not considered representative of the pollutant field that would be experienced over the Murujuga region over the extended period associated with the proposed monitoring. Such a field may arise due to specific conditions such as line sources, substantial terrain influence, or a short period (hrs) with a sharp wind change. Generally, a more uniform concentration distribution will develop over time. The isopleths presented in Figures 6-3 to 6-10 of SKM (2009) are more characteristic of a ground level concentration distribution developed over an extended period. The distribution is more uniform, and generally decreasing with radial distance from the region(s) of highest concentration. While stable atmospheric conditions will constrain dispersion leading to more narrow plumes, they are only one atmospheric state. Without more detail, including an analysis of the stability distribution (frequency), it is difficult to understand how critical atmospheric stability conditions may be in relation to air quality impacts across the peninsular. The wind speed distribution	The result in Figure 3-19 is for 1 condition of the 14 indicated in the table. The SKM report is the cumulative effect of conditions, which is not what we are simulating, rather we are using a series of discrete simulations to design the monitoring network to optimally capture the pollutant levels at Murujuga. With regard to stability, while it is not apparent in the Figures, there are prevailing winds across Murujuga (which are apparent in the 9am/3pm wind plots from the BoM, not included here). "While it is possible a monitoring instrument … " - See other comments above re considerations for passive (1 month average) and continuous monitoring. This will be reviewed and finalised in the Part B document. "Thus, a dispersion model prediction for each individual hour is derived assuming the pollutant travels with the mean wind for the model period (1-hour), and mixes or disperses based on the atmospheric turbulence for that period" – With the CFD we are simulating these "1-hour"	

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		provided would suggest periods of highly stable conditions are limited. Additionally, elevated, and hot emission sources are unlikely to interact with the ground under stable atmospheric conditions, but rise and travel over the peninsular for some considerable distance before they are turbulently mixed to the surface, potentially only after sunrise. While it is possible a monitoring instrument or network may for periods not detect any pollutants from nearby emission sources due to meteorological conditions, over time meteorological conditions provide a smoothed distribution, which in turn provides a smoothed distribution of ground level pollutant impacts. The bulk of the proposed pollutant concentration monitoring is the use of average sampling techniques where-by the pollutant sample is accumulated over a period (1-month). The analysis provides the total sample amount and the concentration determined as an average over the period for which the sampling device was installed. The temporal resolution of the proposed passive sampling monitoring network is 1-month. Due to spectral energy considerations, and the 'spectral gap' with low energy between ~ 20 minute and 3 hours, the ideal time scale for representation of meteorological characteristics is ~1-hour. Spectral energy below the 1-hour, primarily below 20 minutes, relates to turbulence, while that above 1-hour relates to diurnal and synoptic variation. The 1-hour period provides a relatively stationary period for which a mean and turbulent component of the wind conditions can be defined. Thus, a dispersion model prediction for each individual hour is derived assuming the pollutant travels with the mean wind for the model period (1-hour), and mixes or disperses based on the atmospheric turbulence for that period. Predictions for an extended period are developed through the summation of predictions for each individual model period. A CFD model is generally applied in a similar manner to that of a steady-state air quality model, with a set meteorological condition (nominally 1-hour period) simulated to converge to a steady-state flow configuration. However, obtaining a steady-state flow configuration to provide a concentration distribution for the model condition (1-hour period) takes considerably greater computational time (orders of magnitude) than for a dispersion model. Hence, summation of individual CFD concentration field predictions to represent an extend period can become complex, requiring assumptions and approximations to constrain computational requirements to achievable levels. CFD models are better applied to specific near-field fluid mechanical issue related to a set range of conditions as opposed to estimation of pollutant concentration statistics over a longer-term period, or at greater distance from the emission location.	periods, such that the 14 we have chosen represent 90% of the expected 1-hour periods across the year. From these "wind" simulations, we introduce the known emission sources, and identify the local emissions for the condition simulated. The change in "background" emissions (i.e. due to flow out, and subsequently back into the domain) are not captured, but as stated these are more dispersed so local effects are less dominant. The approach is possible with dispersion modelling, though the coarser grids do not aid greatly in positioning the monitoring stations, and local effects may still dominate the readings (i.e.. a station within the 1.3km grid cell, but near to a road – which will dominate the measurements, indeed this is evident in Fig 20 of the CSIRO report). In terms of the summation, as we are using CFD to enhance the monitoring network the summation of pollutants will be the real atmospheric effects. The CFD's aim is to be able to best measure and record it.	
27	3.5.2	Detailed description of the proposed data collection program The detailed description fails to provide more than a broad overview of some potential CFD simulations, nor provide any meaningful justification of the use of CFD in preference to an atmospheric dispersion model. Why would an atmospheric dispersion model not be adequate, and how would the CFD model be configured to ensure a more reliable representation of import dispersion process and an improved prediction is provided? Atmospheric dispersion models comprise of two primary elements: a meteorological component which is used to establish the state of the meteorological flow of the atmosphere for each period the model is applied to (typically 1-hour) a dispersion component that is used to calculate the path and rate of spread (dispersion) of the pollutants released within the model for each model period based on the meteorological structure. Additional pre and post processing tools are often also incorporated into the modelling package to assist with development of input information and analysis of the often-large data sets generated by the models. There are two primary types of dispersion model, Steady-state: which employ a uniform wind field across the domain for each hour, with the	Firstly, CFD is not used in preference to atmospheric dispersion modelling, indeed it is designed to complement it by quantifying and reducing the uncertainties in the real measured data. DWER has separately commissioned atmospheric dispersion modelling, which has recently been completed. In response to "The structure of the Murujuga…" . We recognise the limitations of CFD for conducting mesoscale simulations, likewise the computational effort that would be required to simulate a complete year. However, as the review points out there are also compromises in dispersion modelling: - resolution is low (c/w CFD) - small scale local effects cannot be captured - plumes released in proximity may not be captured accurately - many assumptions on emission rates, and operating schedules are necessary to make, and such data is often difficult to come by, and usually is broadly estimated. Hence, the CFD simulations proposed are aimed at recognising the relative strengths and weaknesses of each approach, particularly by using CFD to improve the monitoring network. The higher resolution, and the ability to characterise the network's uncertainty prior to deployment should substantially improve the quality of measured data.	

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		plume assumed to travel to the domain edge within that hour and disperse based on that hour's meteorological conditions and turbulence structure. They do not maintain any history of the previous hour. 3-Dimensional: within which the emissions are moved within a 3-dimensional flow field and dispersing based on the local turbulence characteristics. The pollutants remain within the domain until they are advected out of the domain, i.e. retained form 1 hour to the next if they have not moved beyond the domain within that hour. In regulatory applications dispersion predictions for both model types are generally based on a grid (radial or square) that is at, or close to, ground level. The dispersion grid can be any size and in environmental assessment application individual grid elements may typically range from 100m to 500m spacing dependent upon the specific application, although for research or other specific application more dense grids can be applied. The gird can be applied over large regions, again dependent on the specific application, with smaller grids of the order 5 km or less and larger regions covering distances of 50 km or more, even whole countries and continents, although with even larger grid spacing. In 3-dimensional models the dispersion grid can be a sub-grid of the meteorological grid and thus dispersion estimates can be made on at a finer resolution than the meteorological wind field developed by the meteorological component of the model. Additionally, predictions can be made for specific locations through the declaration of discrete receptor, and at elevated locations (flagpole receptors). Thus, dispersion models can effectively provide pollutant predictions across a domain similar to a CFD model, however each location for which a prediction is required needs to be explicitly defined, and the greater the number of locations the longer simulation time required. The meteorological modelling element of advanced 3-dimensional dispersion models often use input from weather model re-analysis simulations. The meteorological field is refined with local surface characteristics, and if available and appropriate, meteorological data, to provide a detailed field of meteorological characteristics, energy, momentum, and moisture exchange to capture the diurnal variation over the region of consideration. Many of these tools are openly available, with source code, particularly many developed in the US. Dependent on the domain configuration, the meteorological modelling element can capture critical local and regional influences including recirculating flows such as sea and land breezes, valley drainage and other flows of a similar scale, as well as incorporating synoptic scale effects on the general flow field. The dispersion models are designed to capture critical meteorological influences on pollutant transport and mixing, however apply meteorology based parameterisations or simplified approaches to represent fluid mechanical effects such as plume rise or the flow over a building and its effect on the plume path and mixing. A fluids model is configured to capture the fluid mechanical affects, so can not only explicitly model the flow over the building and the plume rise, but capture the influence plumes released in close proximity to each other may have on the combined plume behaviour, for instance. CFD models can be applied to meteorological behaviour within atmospheric boundary layer flow, however the complexity of the simulations is substantially enhanced, and validation of the developed flow and turbulence structure would be necessary. Validation would likely have to rely on parameterisations that form the theoretical basis of dispersion models unless an intensive field monitoring campaign in relation to meteorological conditions is also undertaken. The structure of the Murujuga region is complex from a mesoscale meteorological perspective, with islands and channels, the open ocean, and the large land mass of mainland Australia intersecting. Consequently, surface exchange budgets will be complex, and potentially result in local and regional recirculating atmospheric flow conditions at times. Physick (2001) reporting an anticlockwise wind directional rotation through 360 degrees on a diurnal cycle can occur in the region leading to recirculation of pollutants. A CFD model would require a substantially expanded domain to capture this type of meteorological behaviour, as well as potential incorporation of atmospheric chemical behaviour of pollutants along with the physics to		

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		adequately represent pollutant concentrations. There are numerous fluid mechanical issues a dispersion model is not able to explicitly resolve. Equally, there are many atmospheric processes that are difficult to represent within a CFD model on an individual basis. Attempting to couple these complex processes within a CFD model will further enhance uncertainty.		
28	3.5.2 1	Meteorological data The wind speed distribution reported in Table 3-9 shows a marked disparity to that recorded by CSIRO (Gillett, 20101 Figure 27), particularly with respect to the frequency of winds less than 2 m/s and above 5 m/s. Table 3-9 (DSD) reports more than 50% of the time wind speed is above 5 m/s at Karratha Aero, while the CSIRO measurements indicate only ~ 5% of monitored wind speeds above 5 m/s. Is this due to the exposed nature of the Karratha Aero site compared to the CSIRO monitoring location, difference in measurement parameters (i.e. wind monitor height). Additionally, there are two further BoM sites within 40 km of the Karratha site: LEGENDRE ISLAND : 004095 ROEBOURNE AERO : 004090 Further data may also be available from the 3 recently installed Woodside AQMS in the region. Wind speed plays an important role in plume rise as well as the structure of the atmosphere throughout the diurnal cycle. Local surface features can influence surface wind conditions significantly. The Karratha BoM wind monitoring data, speed and direction, may not be representative of the conditions experienced more generally across the proposed CFD domains and thus for application as a broad boundary condition for the CFD modelling.	The data on the weather station is not provided, but the image (Picture 3) suggests that the height of the anemometer would be ~3m. The Karratha Aero site is at 5.3m elevation, this would make a 25-30% difference to the recorded wind speed. The site is also relatively sheltered, situated in a U-shaped rocky area of similar height (not visible from photo, but in aerial imagery. It is suspected that cyclone activity may also change the values to the higher end (the presented distributions are for a 5 year period). We also have hourly data from Legendre Island, and have also requested access to Woodside's monitoring data. Performing the analysis, with Legendre Island BoM data, results in almost the same set of 14 cases, with only the last 2 different (which accounts for broad characterisation). In terms of correlation, Merging both sets of data gives the following agreement in wind direction for the calm and medium bands – with reasonable agreement between stations. Note that the final selection of simulations will be determined in conjunction with the projects statisticians, and will also incorporate findings from the recently completed dispersion modelling report. For the CFD simulations, a uniform spanwise profile is planned to be used. While this may not exactly represent reality, it is representative enough to inform the placement of stations in the monitoring network. (Note that this approach is also used with good results for siting of individual wind turbines in large wind farms).	
29	3.5.2 1	Meteorological data The turbulent structure within the atmospheric boundary layer develops due to a combination of mechanical (shear) and thermal (buoyant enhancement or suppression) on a diurnal cycle. There is no discussion on atmospheric stability and how this variation will be incorporated into the proposed wind conditions, and CFD simulations.	Including the temporal boundary layer development is not planned for the simulations as this is better captured in dispersion models. We intend to periods where the boundary layer is assumed stable. Sufficient periods will be modelled to give a representative dataset for characterising the meteorology.	
30	3.5.2 1	Meteorological data While not explicitly clear, it appears the CFD simulations will be limited to the 14 wind speed and wind direction categories outlined in Table 3-10 (DSD), either the primary compass direction or the average within each compass band; plus two additional 'worst case' simulations derived from a soon to be completed dispersion modelling study. The use in a model of average wind directions to represent a distribution over a band will lead to prediction of a distorted concentration field, with a near gaussian concentration distribution extending laterally to the mean direction of travel from each source. When results from different industrial source groups and across the different wind direction categories proposed are combined, the result will not capture the effect of the continuous distribution of wind direction, speed and atmospheric stability that the pollutant emissions experience. Use of earlier BoM data, categorised in 10-degree increments, in steady-state dispersion models requires randomisation across the 10-degree sector to avoid peaks concentrations on the direct downwind direction with troughs as you move laterally away from the direct downwind direction. Combining all source and wind conditions based on limited specific wind categorisation (speed and direction) will lead to a distorted concentration field (criss-cross pattern) due to inadequate resolution of the wind directional, wind speed and atmospheric stability distributions.	The 16 indicated simulations are based on the initial budget indicated to DWER. As we are not performing summations over the year the influence of the "criss-cross" pattern in wind direction is of lower importance. We will discuss with DWER the possibility of increasing the number of simulations (we have already analysed the wind data to 16, 24 and 36 segments).	
31	3.5.2 2	Emissions Inventory Detail on pollutant emissions is critical in understanding plume trajectories and their interaction with the ground through the range of meteorological conditions. NPI data can be used to provide estimates of overall pollutant emission rates but provides minimal detail on the character of the emission. To reliably represent emissions within a dispersion or CFD model detail on release characteristics is required including detail on whether the pollutant is released	This data was compiled as part of the now completed dispersion modelling project. This data (in the most part) will provide the emissions inventory for the CFD simulations. In addition, more accurate locations for some stacks have been requested from the relevant operators in the area. Some of the previously submitted AQIA have similar tables to those in the Perdaman AQIA, but including detailed locations. For sites with a small number of stacks, aerial imagery (and or the Landgate aerial scanning) provides sufficient detail to locate them accurately.	

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		from a fugitive type source such as operations on a stockpile or leakage from a storage tank; or point source such as a stack. For point or stack sources detailed characteristics including release height, release diameter/area, exit velocity, and exit temperature in addition to the release location and individual pollutant release rates are necessary to adequately characterise pollutant behaviour. Buoyant plume rise and determination of the plume rise height are critical in determining the distance a plume may travel prior to being mixed sufficiently to interact with the ground. Specific information detailing ideal parameters necessary to correctly characterise plume behaviour within the model should be summarised in the DSD. The AQIA for the Perdaman Urea Project (Jacob 2020) details stack emission characteristics and pollution emission rates applied in that recent study, although the emission parameter tables do not include specific stack location detail. Emissions from shipping also need consideration, ancillary engines if used at berth or anchorage, and ship movement through the shipping lanes. Plume buoyancy and the potential influence of the ship bulk on initial plume behaviour is a near-field fluid mechanical issue that may warrant further investigation to reliably characterise the initial behaviour of the emissions should impacts from shipping contribute significantly to impacts across rock art areas. There is no discussion in relation to incorporation of shipping emissions within the CFD modelling.	For shipping emissions, the data will be sourced from the dispersion modelling recently completed. This made use of AIS data for ships in motion, and berthing data for berthed vessels in addition to shipping registers to establish engine sizes and fuel. This data was not available when preparing the DSD, and the desire was not to unnecessarily duplicated the effort required to compile it. A similar comment is made to emissions from road traffic, which will also be based on the data in the dispersion modelling report.	
32	3.5.2 3	Modelled Species Other species to consider include: Total Suspended Particulate (TSP) particles larger than PM10 are released from materials handling operations and will deposit more rapidly, potentially leading to higher dust loads around these operations. They are also more likely to be resuspended by wind action (wind erosion). Volatile Organic Compounds (VOC's) and Ozone (O3) involved in photochemistry	We will consider all species that the RAMBOLL plume monitoring study has found to be significant, which includes most/all of these species.	
33	3.5.2 4	Site Topography 5 m resolution DEM is also available through Landgate across virtually the entire Dampier region and will provide more detailed, recent data than the SRTM beyond the extent of the 1 m DEM. 1 m resolution DEM and point data can be applied to identify building location, dimensions, and heights for explicit inclusion within a CFD model. It and can also assist in clarifying the location of larger stacks.	Agreed. Note that the recent Landgate data is extensive, and includes the region down to the salt lakes, and almost to Legendre Island (see figure). Beyond this we will used the highest resolution we are able to source (which is likely the 5m data). In addition to the DEM we have the 3D aerial scans which will be used to reconstruct buildings and structures.	
34	3.5.2 4	CFD Simulations Given the critical application and complexity of the proposed CFD fluid modelling simulations, the description of the proposed application is vague, lacking any specific detail on the methodologies to be employed or potential issues to overcome, and any reasoning for decisions. The OpenFOAM toolkit is identified as the modelling system, which, as stated is well validated with open-source, auditable code, can be easily and stably distributed across multiple processors and highly suited for application on High-Performance Computing (HPC) environments. The open-source nature of OpenFOAM is advantageous for HPC application. There is limited detail on the model configuration and application: "boundary conditions set to match the wind conditions." It is unclear if this is the single point wind condition from Karratha BoM site, wind condition derived from a meteorological model or the use of a parameterised model to adapted monitored wind conditions across the CFD domain boundary. Boundary conditions in relation to other meteorological parameters are not discussed.	"boundary conditions set to match the wind conditions." - It is unclear if this is the single point wind condition from Karratha BoM site, wind condition derived from a meteorological model or the use of a parameterised model to adapted monitored wind conditions across the CFD domain boundary. We are not modelling every set of conditions at Murujuga, but only the most representative. For this reason measured data is preferred. Karratha was suggested as it is the closest station to the industrial sites on the Peninsula – A comparison with industry data will be made to determine to what extent the conditions at Murujuga are different. Boundary conditions in relation to other meteorological parameters are not discussed. We intend to apply isothermal conditions for temperature, and 0 concentration for the pollutants. There is no detail on the specific equation set, solver, turbulence model and associated constants that it is planned will be employed in the flow simulations. Atmospheric boundary layer flow CFD simulations documented in the literature are almost predominantly applied to neutral flow conditions. Non-neutral atmospheric boundary layer flow conditions are often the most critical with respect to ground level impacts of air pollutants.	

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		There is no detail on the specific equation set, solver, turbulence model and associated constants that it is planned will be employed in the flow simulations. Atmospheric boundary layer flow CFD simulations documented in the literature are almost predominantly applied to neutral flow conditions. Non-neutral atmospheric boundary layer flow conditions are often the most critical with respect to ground level impacts of air pollutants. There is no discussion on assumptions and limitations appling to the proposed CFD simulations, and what features of atmospheric flow behaviour will not be represented as a result. It is stated species transport and deposition of particles will be simulated. This would suggest atmospheric chemistry and gaseous deposition will not be represented with the CFD model. The potential impact of acid gases on the rock art is one of the critical issues in relation to the entire study, while atmospheric chemistry can adjust the concentration of pollutant gases and includes the formation of PM2.5. Air quality dispersion studies have represented these features in previous studies. Discussion on the CFD simulations does not include atmospheric chemistry and gaseous deposition.	There is no discussion on assumptions and limitations applying to the proposed CFD simulations, and what features of atmospheric flow behaviour will not be represented as a result. (For the above 3 points – there will be appendices with further detail in the final report – this would be a big addition to the DSD) It is stated species transport and deposition of particles will be simulated. This would suggest atmospheric chemistry and gaseous deposition will not be represented with the CFD model. The potential impact of acid gases on the rock art is one of the critical issues in relation to the entire study, while atmospheric chemistry can adjust the concentration of pollutant gases and includes the formation of PM2.5. Air quality dispersion studies have represented these features in previous studies. Discussion on the CFD simulations does not include atmospheric chemistry and gaseous deposition. This is correct – we are not trying to predict the absolute annual exposure at each site, but design a monitoring network which is able to accurately record the exposure that has actually occurred.	
35	3.5.2 4	CFD Simulations Stack emissions "stack velocities … will be accounted for by imposing momentum source constraints … and matching velocity. " Again, a vague description of the approach to capture a critical element of plume behaviour. It is not clear from the brief description that the initial plume behaviour upon exiting a stack will be adequately captured. More detail of the approach to representing stack emissions is necessary and potentially validation across the expected range of emission parameters. Representation of potential non-stack emission sources also requires discussion.	In general line and point emission sources will be discretised into point sources, such that the point resolution is finer than the grid. These then become source terms for each transport equation, applied to the cells which the points fall. Volumetric emission rates are able to be directly applied, while source terms for areal sources can be determined by knowing the area of the source in the cell, and the cell volume. The simulations will be run as two separate simulations – one for the flow, where the stack flow conditions will be imposed, with matched velocity to the emission source data. Validation for plumes has been undertaken, predominantly with data from [1], [2] and [3]. Validation for non-stack emissions will also be undertaken where suitable validation data exists. Fan, L. N. Turbulent buoyant jets into stratified or flowing ambient fluids California Institute of Technology, California Institute of Technology, 1967 Slawson, P. R. & Csanady, G. T. The effect of atmospheric conditions on plume rise Journal of Fluid Mechanics, 1971, 47, 39-49 Chu, V. H. & Goldberg, M. B. Buoyant forced-plumes in cross-flow. Journal of the Hydraulic Division ASCE, 1974, 100, 10805-10808	
36	3.5.2 4 (Note: two section 3.5.2 part 4 in DSD)	CFD Simulations Deposition It is proposed to account for particle deposition using a representative settling velocity after Wu et al (2000) . The referenced Wu et al (2000) paper refers to sediment (sand/silt) within water flow. However, the suspended-load transport is simulated through the general convection-diffusion equation with settling-velocity empirically determined. The approach includes an entrainment flux and thus in Wu et al's work is applied to also estimate resuspension, and thus accumulation or removal of deposited matter through a mass-balance. While there are certainly benefits to understand both deposition and resuspension on rock art surfaces, the work of Wu et al considers sediment behaviour in water, with a relatively thick sediment layer at the base of the flow. It is not clear how the approach will transpose to particles in air, with validation of the effectiveness of the modelling approach necessary. If the approach is found to be effective it could be beneficial in understanding the typical lifecycle of particulate material deposited on the rock art surfaces through changes in meteorological conditions. There is no discussion on CFD deposition simulations of gaseous species, nor deposition during rain or fog events.	For the particulates, we have successfully validated and used this model and approach in modelling dust suppression at these scales. We don't intend to simulate complex deposition processes, but will be determine the ground level concentration as an indicator of pollution levels. Similarly comments apply to deposition due to rain and fog events. Detailed chemistry is certainly possible using CFD models, but is not likely to add much benefit as an aid to locating the monitoring stations.	
37	3.5.2 5	Post-processing and quality assurance Again, a general overview with little specific detail on verification and validation of the model performance.	We are proposing to model stable atmospheric boundary conditions, with simulations determined to best capture the prevailing conditions at Murujuga. Capturing the diurnal cycle, and unstable atmospheric conditions is possible with CFD, but as the commented, dispersion modelling is less computationally expensive for this task.	

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		The transport and dispersion of the pollutant emissions are controlled by the flow character, velocity characteristics both horizontally and vertically, and turbulence structure being critical. While the model will produce a result, how is it proposed to demonstrate the model is adequately characterising the flow structure through the range of atmospheric conditions and the diurnal cycle? Other critical elements for which specific validation should be performed include plume rise and dispersion, the deposition processes, and other processes required to be built into the model to adequately represent pollutant behaviour on the Burrup Peninsular and broader Murujuga region. The proposed methods for validation of the CFD model configuration and demonstrating the model is adequately representing the critical flow processes require discussion.		
38	3.5.2 6	Pollutant exposure at sample sites From the detail provided it is not clear how the CFD model results for the specific simulated conditions will be used to predict concentrations across the proposed receptor locations; how variations in wind direction within a sector, wind speed within a category and atmospheric stability, and the range of actual meteorological conditions that may be experienced will be incorporated into the prediction of concentration for each specific receptor location. A dispersion model can provide a pollutant concentration prediction for each hour of a period (1-day, 1-week, 1-month, 1-year, 5-years) across a domain and at designated discrete locations, or on a statistical basis as in section 8 of Perdaman Urea Project (Jacob 2020)8. Model comparison with a discrete monitoring site is best performed on a statistical basis due to uncertainties in meteorological parameters, measured or calculated, and the chaotic nature of atmospheric flow. The model applies 1-hour averages, whereas changes in meteorological conditions are not constrained to the hour. Furthermore, under some meteorological conditions 1-hour is not sufficient time to obtain a stationary average.	We don't expect, and aren't proposing to capture the complete atmospheric physics. We will use the relative occurrences of the wind conditions modelled to determine for each exposure site, which combination of potential monitoring sites, after characterisation, give the best reconstruction of the modelled exposure.	
39	3.5.2 7	Virtual monitoring sites Again, uncertainty and error in the CFD model predicted pollutant data at each location will be enhanced by the method of interpolation across the wind direction within each sector, wind speed within each range, and atmospheric stability variation. An equivalent analysis can be undertaken with concentration predictions from a dispersion model without the need for interpolation across wind direction sectors, wind speed categories or atmospheric stability ranges.	With access to the dispersion modelling from DWER we will use a combination of both – dispersion for determining the broad locations, and CFD for finer placement to avoid local effects.	
40	3.5.2 8	Fitness criteria for assessing the monitoring network Factors relating to the type of monitoring, amount of information provided, accuracy, cost, and other constraints could also be considered within the fitness criteria, or a cost benefit analysis. For instance, the use of a smaller number of continuous real-time compliance or trace monitors for critical pollutants as opposed to longer time frame average devises such as diffusion tubes. Although more costly, the continuous real-time monitor provides detailed information to assist develop understanding of pollutant impacts at the monitoring site. The continuous real-time instruments can provide measurements across short time periods, with greater accuracy, allowing direct and statistical comparison with model predictions (dispersion or CFD). This can assist understand the source of the pollutant, and over time the ability of the model to represent the conditions under which pollutants impact at the monitoring site, and also validate the ability of a model to represent critical pollutant behaviour. Validation of a model provides greater confidence in predicted concentration fields. Not only is there higher uncertainty with the result of a diffusion tube monitoring device, but there is also no detail on how the pollutant may have come to impact the monitor. A model must then be employed to interpret what may have led to the pollutant impacts received by the monitor, instead of the monitored concentrations assisting optimise and validate the model configuration.	The final fitness criteria are yet to be determined, but we intend to include many of these factors. Cultural constraints are one constraint that we will include, as is an analysis of the incremental cost/benefit to each monitor in the network (i.e.. how much better will the network be if we increase from X monitors to X+1 monitors. Also, if one sensor is unavailable (X -> X-1), what is the (quantitative) reduction in the network's ability to record the air-quality at Murujuga? Potentially, we would also be able to comment on the locations of the previous monitors (with the benefit of modelling and hindsight). See comments above regarding real-time monitors	

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		There is clearly more value with the data collected with the continuous real-time system, for both the accuracy and the value the data provides. However, continuous real-time gas monitoring systems generally require mains power as the instrumentation requires a controlled (air-conditioned) environment, limiting locations they can be installed. The diffusive devices can be easily installed in virtually any location, including adjacent to continuous real-time instruments, the only constraint is they require sufficient air flow and shelter from precipitation.		
41	4.4	Data Management Air quality control Weather station and other real-time data is initially logged to storage media at 5-minute intervals. While this data is streamed/uploaded to the Cloudstor for use and archive, preliminary analysis to provide a Clourstor dataset based on a 1-hour averaging period of standard air quality and meteorological analysis would reduce the potential for disparity in analysis by individual researchers.	Acknowledged. Such a preliminary analysis can be performed.	
42	4.5	Computational fluid dynamics modelling CFD can produce large data sets, although with steady-state solutions there is only one data set for each simulation. Is it planned to archive the configuration and steady-state solution within Cloudstor or only the outputs of the final analysis? Compliance with standard CFD methods of validation and verification (residual monitoring, grid independence, turbulence model constraints) do not necessarily demonstrate the CFD simulation is reliably representing the real flow behaviour. The methods and data sets planned to apply to demonstrate the CFD configuration is adequately capturing the critical physics (and chemistry) of the atmospheric flow and pollutant behaviour are not defined.	The intention (space permitting) is that the case data will be archived along with the final analysis. For validation, we intend to validate that the models are working separately to their application to Murujuga. (ie. the ability to predict flow over terrain will be validated separately to the ability to model plumes correctly – suitably detailed validation cases with both aspects together doesn't exist (as far as we have been able to ascertain).	

4.2 Engineering Air Science – Review comments sheet for Monitoring Studies Data Collection and Analysis Plan

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: John Taylor, Engineering Air Science.	
Document Title: Murujuga Rock Art Monitoring Program: Monitoring Studies Data Collection and Analysis Plan (Part B) [COPP21065-PLN-G-102_B_2021_09_06_MSDCA_Plan_Submitted (002)]	
Document Revision: Version 2.1 (September 2021)	**Revised version for close out comments:** Version 2.2 (November 2021)
Date of Review: 1 October 2021	**Date of Close out comments**: 7 December 2021

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1	1.8 Item 2	Air Quality Fine scale (fluid) modelling is most critical in relation to characterising initial emission behaviour, establishing the effective height and initial dispersion characteristics of a plume primarily due to the influence of the site, and potentially terrain immediately surrounding the site, on the flow and hence the emission. The initial plume structure, developed as a result of the initial behaviour and interaction with local features, can strongly affect the level of plume interaction with the ground, particularly in the region immediately surrounding the site. While the exposure may vary due to local downwind topographical effects such as gorges, fluid modelling is also ideal for investigating such effects, ultimately the ability of any model to provide reliable representation of plume behaviour in the atmosphere is conditional on the adequate representation of the initial plume behaviour. For understanding of impacts immediately surrounding an industrial facility, reliable representation of the initial interaction of emissions with site features is critical.	Agreed. Taken as a comment.	
2	2.1.4	Spatial Datasets While it is important to rectify such issues, as stated in the initial (Part A) review, this will generally only result in a similar offset of downwind impacts, the importance of which diminishes with distance from the source. Location relative to local features that may influence initial plume behaviour can be a more critical concern.	Agreed. Taken as a comment.	
3	3.1.3	*Need for closely-located observations in the component studies* As discussed in the initial review the simulation of plume behaviour and dispersion can provide a means of interpolating atmospheric observations between locations based on known pollutant emissions characteristics and meteorological conditions. The choice of the appropriate modelling tool or tools would be dependent on the elements more critical to the plume behaviours that result in the greatest exposure at individual locations. This can vary with meteorological and source characteristics as well as the site location relative to the emissions. There are various 'scales' of dispersion model that each have their purpose, and strengths and weaknesses in general response to the model purpose.	We considered including additional atmospheric dispersion modelling but were not convinced that it would improve the study. We have been advised that DWER/EPA(WA) are intending to use the CAMx (RAMBOLL) model as the regulatory model for the purposes of assessing any new developments, so this will be the model of record, as such there does not appear to the any benefit in adopting an (additional) dispersion-type model. The advanced chemistry implemented in CAMx is superior to that of conventional atmospheric dispersion models available, and for this reason it has been adopted as it is thought to best predict deposition and local scale interactions. At the fine/local scale, integrated/coupled CFD models will assist in interpolation of coarse scale dispersion results and measurements to the regions (rocks/art of interest). The chemical models in CAMx are however known to break down at scales smaller than 1.33 km grid cells. A dispersion model is (necessarily) a compromise on the complexity of the atmospheric chemistry compared with CAMx, and spatial resolution compared with CFD. At the midscale, the actual	All modelling tools have limitations with respect to the model ability to capture critical elements of the pollutant physical or chemical behaviour and features where they may excel above other tools. The modelling approach should consider which critical elements are the most important and then the most appropriate modelling tool, or tools, would achieve the most reliable description of the critical behaviours. CAMx provides more reliable representation of pollutant chemical behaviour and transport at distance from the primary sources. It has limitations with respect to the representation of site and terrain features that may be significant across the initial stages of dispersion, this may be several km from a significant source of pollutants. CFD provides representation of fluid mechanical issues that may be critical in the immediate environment of an emissions source, however, becomes less reliable, and more complex to configure, when

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		• The Ramboll[1] (2021) study applied an airshed model which looks at pollutant behaviour and factors such as chemical reactions as well as transport and mixing over a large region (airshed). This form of model generally considers scales of 10's km to 100's km with resolution ~1 km to ~10 km, with many emission sources within the model characterised at the grid cell scale. Thus, this form of model typically do not provide dependable predictions within the region immediately around a complex pollutant source such as an industrial site. • The fluids model {numerical (CFD) or physical (wind tunnel, water tank)} is generally concerned with the understanding of the fluid mechanics of specific turbulence structures and flow behaviour that may influence the plume on a local scale {those that develop over a building of industrial site for instance}. Fluid modelling tools can provide improved characterisation and understanding of the behaviour within and immediately beyond the complex flow region, both around the source region, and potentially complex issues remote from a source where the fluid mechanics of the local flow may lead to differences in pollutant behaviour, i.e., enhanced deposition due to recirculation within a gorge. • However, in the region between these two locations the fluid (CFD) model maybe constrained. The structure of the atmospheric flow is generally the critical element with respect to pollutant behaviour through this region. The local atmospheric boundary layer structure develops from the complex interaction of mechanical and thermodynamic effects, primarily derived from the upwind and local surface properties and their influence on the flow. While not impossible, the representation of these effects, particularly the thermal effects, within a CFD model is far more complex than with in a parametrised dispersion model as different atmospheric conditions require different and potentially more involved CFD techniques. The atmospheric dispersion model typically used within EIS studies to assess impacts from industrial operations on the local environment is a model type that is primarily developed to represent plume behaviour in the local region where the atmospheric structure can be important. While not explicitly modelling the flow such as the case for the CFD model, the parameterisations within some of the more complex, or capable, tools can represent the effects of complex dispersion issues on a finer resolution than the airshed model applied in the Ramboll study. Somewhat focused between the airshed model and the fluid (CFD) model, some of these tools can represent features such as buildings and the complex flow structures that can occur due to the interchange between water and land or terrain influenced flow. This type of model also has greater flexibility in the representation of emissions released into the atmospheric flow. While not having the fine resolution or numeric techniques to resolve flow over a building or similar feature, parameterisation based on the primary flow features of obstacle influenced flow are used to provide broad representation. Detail such as terrain and surface characterisation on a scale of 100 m or less is	measurements from the monitoring network (including spatial interpolation) will be able to provide the midscale data without being dependent on the assumptions required to create a numerical model. (Note that if the project was bound to a single modelling approach it is possible that an atmospheric dispersion model would have been the chosen. However, we believe that the CAMx model coupled/augmented with CFD delivers a better outcome compared to a simpler dispersion model coupled with CFD, or the CAMx model with a dispersion model. We also believe that the CAMx model with a dispersion model and CFD would not deliver a better outcome than CAMx with CFD alone).	representing atmospheric structures critical to pollutant behaviour at greater distances from the emission source/s. Concentration gradients in the mid-range distance (~1km – 5+km) are unlikely resolved by the air shed scale model, but also likely require adequate representation of the diurnal variation of atmospheric boundary layer structure. A regulatory dispersion model, typically applied for EIS investigations, provides a transitional tool, with often some ability to represent site features as well as ability to resolve pollutant detail at higher spatial resolution than CAMx. This can be significant in relation to impacts immediately around a significant pollutant source. Pollutant behaviours generally not considered as important close to a source, such as chemical reactions, may not be represented within the regulatory dispersion modelling tool however, the importance of the atmospheric boundary layer structure on plume behaviour within and immediately around the more industrial regions of the Burrup Peninsular can be resolved at greater resolution than with the CAMx or similar airshed scale modelling tools. For instance, the development of the thermal internal boundary layer (TIBL) may be highly critical with respect to the interaction with the ground of elevated plumes. The higher resolution representation of the land-sea interface available with a higher grid resolution regulatory dispersion model, coupled with high resolution of pollutant concentration predictions, would likely better capture disparity in the pollutant concentration field in the near to midrange-field of the industrial region. High level understanding of the specifics of primary sources and their environment and the receiving environment is necessary to understand the tool, or more likely combination of tools, likely to be the most appropriate to provide the most reliable understanding of air quality at the monitoring sites distributed over the region.

1 Ramboll (2021), Study of the Cumulative Impacts of Air Emissions in the Murujuga Airshed,

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		possible, with the use of discrete receptor points enabling pollutant concentration prediction on a finer scale. • While no approach is perfect, there is no discussion on the potential application of this type of tool to help understand potential areas of atmospheric flow and dispersion that may not be adequately considered by either the airshed CAMx modelling applied in Ramboll study, or the CFD modelling proposed as an element of the Monitoring Studies described here. Integration of CFD with a regulatory dispersion modelling approach can lead to improved outcomes above the application of each tool individually.		
4	3.1.3	*Detection limits* Analysis of the Ramboll predictions in relation to anticipated pollutant concentration in periods relative to that of the monitoring instruments could provide useful information with respect to an initial estimate of relevant detection limits. The ability of CFD modelling to provide reliable concentration predictions at the distances and averaging periods relevant to detection limits is unclear. Without representation of the diurnal variation in atmospheric structure, representation of the vertical plume structure could be deficient. Ongoing monitoring undertaken by industry may also provide guidance in relation to the lower concentration level of pollutants the monitoring should ideally be able to achieve.	With respect to CFD, the aim is not predict exposure of the Rock Art over the monitoring program, but to ensure that the actual air-quality monitoring network is able to capture representative exposure, i.e. for the passive monitors. This is to ensure that monitors are not in a "shadow" due to local features and flows, and for the real-time monitors to ensure that potential short-lived peak events would be captured.	While the Calibre/Curtin response to the current plan is different to that of the Part A plan of 2020, it is agreed analysis of the Ramboll modelling coupled with industrial monitoring will provide a best initial understanding of detection limits applicable to air quality monitoring for compounds for which data is available. The ratio of emission rates could provide initial guidance for compounds not previously monitored or modelled.
5	3.4	Chamber Experiments Chamber Experiments of accelerated patina weathering propose to establish dose-response relationships for (elevated) air pollutant concentrations. Is there a clear understanding of the timescales of pollutant impact that are most important? Elevated pollutant concentrations occur on short timescales (minutes to hour or even seconds in extreme) dependent on the emission and meteorological characteristics. Both real-time monitoring and modelling generally provide detail (prediction, measurement) on a 1-hour average or shorter period which can provide period averaged detail. Batch monitoring (deposition, diffusion tubes, …) provides an average over the period of exposure, 4-weeks. Variation in temporal exposure behaviour based on different 'averaging' periods, and thus potentially higher peak pollutant concentrations for shorter duration exposure periods, with periods of reduced pollutant exposure between could also be considered for investigation within the chamber experiments.	Limited prior experiments of this type have been conducted previously. The standard approach for such experiments is to do initial "Range Finding" studies, with (e.g. Logarithmic) increments of pollutant dose and duration, in order to ensure that measurable effects can be detected. We agree completely that there are complexities to be explored with respect to short duration peaks and variations in temporal exposures. We plan to explore these interactions – e.g. chamber measurements will include short duration exposures, followed by extended incubation periods in clean air to encourage microbiome response.	Agreed, with limited knowledge on the effects of the variation of temporal exposure to air pollutants, even preliminary exploration of the interactions would enhance understanding of the potential impacts of air pollutants on rock art.
6	3.5	Air quality modelling, monitoring at receptors and source apportionment Understanding the atmospheric environment and air quality is a critical element of the study. As part of the review of the initial Part A study	We agree that power requirements are certainly a complicating issues, hence our efforts to identify suitable powered sites for some of the monitoring equipment. This will allow us to utilise direct reading instruments at these locations to complement the passive samplers used elsewhere (i.e. at the unpowered sites). The use of the powered sites will also allow us to install support infrastructure such that we can	Co-location of non-mains powered monitoring with powered monitoring of equivalent components can provide improved understanding of the performance of the less reliable non-mains instrumentation.

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		plan (Engineering Air Science[2], (2020)) included a report that provided a general contextual background of air quality monitoring and modelling with reference to the overall study, in addition to the primary review detailing individual comment on specific aspects of the Part A Detailed Study Design. While there are multiple possible tools and approaches to assist understand the atmospheric environment and quantify air quality across both monitoring and modelling, there is no 'one-stop shop' to provide a complete description. It is usually necessary to apply a combination of approaches developed with consideration of the objectives and constraints of the project, including budgets, as well as the strength and limitations of the tools involved. In relation to monitoring, typically the most reliable instruments used for compliance monitoring require a controlled environment for the instruments to operate within set temperature and humidity conditions. The instruments are established in air-conditioned enclosures, with air for analysis drawn from the external environment into the analysis instrument. The power requirement to operate and maintain the set (air-conditioned) environment and run the instrumentation for such a system is not insignificant. Hence establishment of systems to provide accurate air quality data on good temporal resolution would typically necessitate access to mains power as well as considerable resource to establish and maintain due to the size and complexity of the full system, particularly if numerous air pollutants are monitored. Power requirements can complicate monitoring in any location, but especially across an isolated area such as a Burrup Peninsula region where there is very limited infrastructure apart from immediately around the industrial facilities or the limited urban region. Thus, to monitor across the region, particularly at the more remote locations, compromises, and variations in approach to suit individual sites is likely to give better outcomes than use of the lowest common denominator system across all sites, or infrastructure to operate the high-end instrumentation across all locations.	have the direct reading instruments in a temperature-controlled environment.	Additional mains powered sites, particularly remote from the currently proposed or industry powered sites, would always be beneficial if infrastructure and project resources enable.
7	3.5.1	Deposition Sampling While detail of operational parameters for change of depositional bucket are provided, and the concept of attempting to distinguish the deposit amounts under different conditions is sound, the ability to capture the initial washout phase of a rain event is not clear. Are the location of the deposition monitor and the rain gauge readings logged at sufficient rate to enable assessment of deposition gauge location with precipitation rates, particularly through the initial transition of the gauge location. The response or transition time of the gauge is the important detail, however a record of the rain that fell within this transition period and the transition period length could be useful information to assess ability to capture the initial washout phase of a rain event. The recording could be triggered with the trigger for the gauge.	Yes, the rain gauge reading will be logged at a sufficient rate to allow this. We will verify this performance prior to deploying the monitoring stations in the field.	As a minimum all monitoring apparatus/methods developed in-house should be extensively tested prior to deployment including the three component deposition samplers. Rain collected within the 'dry' sample pots may also assist understand if the response time of the system is adequate, however evaporation may also limit longer term retention of water especially in the standard sample collection pot.

[2] Engineering Air Science, Peer review – Air quality, Murujuga Rock Art Project: Detailed Study Design; Draft Report 200801, The Gap, Qld, November 2020.

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8	3.5.1	Prepared "fresh" rock While the combinations are infinite, is consideration of the angle of the rock to the horizontal and/or aspect to the sun or predominant meteorological phenomena (e.g., dominant high wind speed direction) being considered in relation to the rock test sections? Possibly a single rock with multiple "fresh" faces or a series of individual rock sections at range of angles and orientations.	The original plan was to orient the prepared "fresh rock" surface facing directly upwards, though the reviewer raises a good point here in terms of considering different angle, sun/wind exposure, etc. While it would not be possible to use all permutations there may be benefit, in considering some orientations that are not purely directly upwards. Given the need to prepare these rock surfaces, it should be possible to prepare a series of faces on the surface such that we can consider different orientations relative to the sun/wind direction. We have revised the design to include rock "cubes rather than tiles, to permit multiple faces to be measured if desired.	Consideration of under surfaces, surfaces directed toward the ground and thus protected from direct sun or rain impact, may also demonstrate disparate behaviour from surfaces with an upwardly directed component.
9	3.5.1	Gas sampling and analysis The passive sampling field trials investigating tubes brands and monitoring periods will provide more confidence regarding the choice of tube in relation to ability to detect a discernible sample, particularly at locations where air pollutant concentrations are lower. Review and/or further analysis of the ongoing industrial monitoring campaigns alongside the Ramboll and Perdaman Urea Project modelling may also provide more clarity of the order of magnitude of pollutant concentrations to expect across the monitoring network, especially if able to correlate to the monitoring and modelling. The use of only a **single field blank** for each pollutant species monitored with diffusion tubes remains a concern, particularly when redundancy is provided for the actual samples. Failure, damage, or contamination to the single field blank could invalidate the full set of measurements associated with that specific pollutant species.	Agreed. In terms of the field blanks, we intend to use more than one for each pollutant species. This has now been revised in the study design. Given the number of monitoring stations needed, and therefore the number of tubes we are proposing 5 field blanks per pollutant species.	The use of the additional field blanks provides redundancy as well as the ability to distribute and/or co-locate field blanks providing additional detail on field blank variability.
10	3.5.1	Weather measurements A weather station at each monitoring site will provide detail of surface conditions across the monitoring region. The instruments selected appear durable, reliable, and suitable for the location. The application of a 10 m anemometer height where possible will meet the requirements of AS/NZ 3580.14.2014 as well as ability for direct comparison with other measurements to assist understanding of the variation in conditions and the influence of terrain with reduced potential for localised interference. Interestingly, the Ramboll (2021) study suggests that while the three BoM Met Sites within the immediate region indicate wind speed of greater than (>) 5 m/s for ≈ 50% of the time, however these sites appear exposed for the prevailing wind directions. The industry based meteorological monitoring sites on the Burrup Peninsula detailed in the Ramboll report suggest a greater frequency of low wind speed conditions, particularly the Dampier measurements, with the Burrup site also likely exposed due to the hilltop location, but also recording lower wind speeds then the BoM sites. The additional monitoring associated with the study will provide a comprehensive suite of measurements across the region and also the ability to validate the flow fields developed within CFD or other model simulations. Two thoughts to consider are • the inclusion of a second temperature sensor at a 10m height can assist in understanding the structure (stability, temperature gradient) of the lower atmosphere, particularly through the nocturnal period.	Agreed. The use of a second temperature sensor at 10 m makes sense, and may indeed provide useful information. We can certainly discuss bird attack with the supplier. The existing industry monitoring sites in the area (8) measure wind speed at heights of ~5 m, apart from health monitoring sites (3), which have 10 m masts.	If the industry wind monitoring is at the lower height of ~5 m it may well provide some explanation as to why the monitored data indicates a lower wind speed over the peninsula than the model. Bird spikes can assist in limiting instrument bird attack.

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		• are you aware if any elevated (> 10m) meteorological monitoring is available in the local area, or the location and frequency of the closest upper air sounding? It would also be worth discussing with the instrument supplier whether there is a history of any instrument suffering from bird attack, particularly the anemometer.		
11	3.5.1	Sample size, Equipment siting To clarify the final number of sites • 4 mains powered sites with compliant real-time monitoring, two of which also has a passive/solar monitoring, but one is removed from the peninsula region. • 17 passive and solar monitoring stations • 2 industry sites of which are co-located with two mains powered sites to be established within the study, and both of which have existing meteorological monitoring. • 6 industry sites with mains power real-time monitoring and existing meteorology the study has access to the? Are details of instrumentation at the existing industry sites available and do they provide equivalent parameters to the study real-time monitoring? Is it planned to establish the passive sample array (deposition and diffusion tubes) at the 6 additional industry sites or only at the 21 campaign sites? Is there potential to upgrade any solar sites to mains powered sites with compliant real-time instrumentation; the locations of AQ11, AQ7 and AQ8 are in the region of infrastructure that may have connection to power?	There will be 4 powered sites to the specification given here. One may either be located inside an existing (Woodside) powered health monitoring stations or installed nearby (EX07 site). Powered sites will also include deposition samplers and passive samplers. There will be 17 additional passive/solar monitoring stations. The industry sites differ in design between the industries, but all use passive sampling (wet/dry deposition, passive gas monitoring) and some additional solar powered monitors and weather stations. We are currently in the process of obtaining data and monitoring site specifications from industry.	Co-location of a solar powered air quality monitoring configuration at a powered compliant monitoring site may assist understand the performance of the non-compliant low-cost system. As stated in 6 above, additional mains powered sites, particularly remote from the currently proposed or industry powered sites, would always be beneficial if infrastructure and project resources enable.
12	3.5.1	Departure from best practice Ideally the preferred approach would be that the monitoring sites are as removed from a road as far as reasonably practical as this will reduce potential for disproportionate contribution to monitored concentrations. While the SO_x is not such an issue with modern fuels, dirt roads in particular can be a substantial source of PM.	If possible, it is preferable to meet all requirements of AS3580; however, there may be cases where this is not practical. We believe we have fully met AS3580 at all proposed AQ monitor locations.	In respect of dirt roads, exceeding the minimum requirements of AS3580 by considerable distance would be most prudent, unless there is interest in understanding impacts of the dust from the roads.
13	3.5.1	Real-time monitoring A range of instruments are detailed with options still under consideration across several pollutants with different suppliers providing similar instrumentation. With no preference with respect to the possible choices it is trusted the configuration will be finalised to achieve the best outcomes for the overall project. It is noted that the Magee Aethalometer Model AE43 carbon monitor can operate on mains or 12V DC power and thus could potentially deployed at remote solar powered sites for a period if detail at more distant locations is considered beneficial.	The aim here is indeed to achieve the configuration, which will achieve the best outcomes for the project. Deployment of the Aethalometer to remote sites is a possibility. This may be of particular interest on remote sites closer to shipping lanes. This will be considered in the deployment of monitoring stations.	Dependent upon resources etc. deployment of a second Aethalometer may also benefit understanding of shipping emissions.

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14	3.5.1	Open Path FTIR and MAX-DOAS The application of FTIR and MAX-DOAS remote sensing technologies will help identify species and map concentration fields, assisting in the identification of pollutant sources, pollutant behaviour and concentration distribution. The application of both sets of instrumentation may benefit from identification of additional locations with suitable power supply to provide increased coverage. For the MAX-DOAS in particular, the current plan details employment at site EX09 only. While this enables coverage of the central peninsula region it is north of all industry with the 4 km radius only incorporating a single major industry. While other major operations are located close to the 4 km radius, uncertainty as to the origin of the pollutants that are detected in the mapping region will remain.	The initial proposal to use the EX09 site was based on the geography of the site and surroundings, and the availability of power. These instruments could certainly be moved to other powered sites as necessary, and we are considering targeted monitoring campaign with these instruments based on initial data, weather patterns, and information obtained from the RAMBOLL modelling. It is however; acknowledged that even if the instruments are rotated between the four powered sites, there may still be limitations in determining the origin of pollutants.	Rotation through powered sites and targeted campaign would provide the best available coverage to assist understand pollutant behaviour and characteristics.
15	3.5.1	Isotopic Analyser While the instrument can monitor CH_4 and CO_2 in real-time, can it also provide detail in relation to identification of the source of the pollutant gases and is it also planned to use the instrument for this purpose?	This instrument will provide isotope data for C13 and a methane to ethane ratio, which allows differentiation between anthropogenic and natural methane at minimum.	Ability to identify individual anthropogenic sources would also be of benefit.
16	3.5.1	LIDAR Given the instrument would be on loan and thus provide a low-cost application, it data should provide a beneficial add-on to assist parameterise emission rates for major dust sources.	Agreed.	
17	3.5.1	'Low-Cost' sensors Low-cost sensors can offer a cheap alternative for detection of pollutants in real-time providing both qualitative data as to conditions for which pollutant events are detected, and a semi-quantitative assessment of the concentrations to assist in understanding trends. Validation of the capabilities of the proposed instruments through co-location with compliance trace instruments is recommended at least over the period of the preliminary diffusion tube investigation. Of particular interest is the lower detection level and the reliability of the magnitude of detected concentration events, which could be applied to 'calibrate' the individual sensors. Additionally, understanding the capability of the PM device with respect to larger PM sizes generally related to dust and ore emissions due to mechanical activities (loading, dumping, conveying etc.) in comparison to the smaller combustion related PM sources would be of benefit. This type of device are most often only capable of detecting particles in the smaller size range, $PM_{2.5}$ and smaller Periodic co-location of the 'low cost' instruments at powered sites would provide ongoing clarification of their performance. It is noted two sites include Passive/Solar monitoring alongside powered monitoring. It is unclear if this includes co-location of the 'low-cost' sensors with real-time compliance monitoring.	The intent of the low cost sensors is to use many of them. These systems by their very nature will be less accurate than the larger direct reading instruments but offer the ability to obtain measurements from a much larger range of locations. There is obvious benefit in co-locating these sensors with the larger direct reading instruments, and this would indeed be the case for the cases where the passive monitoring stations are co-located with the powered sites.	Understanding low-cost sensor performance through co-location with compliance instruments where possible provides improved confidence in the performance and thus data provided by the low-cost sensors.
18	3.5.1	Data logging and power supply Standard procedures for powered and remote monitoring with on board logging and storage plus direct communication for remote data download to provide redundancy and improved data security (protection against loss of data).	Agreed.	

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19	3.5.1	Equipment siting There are a few comments related to siting and the equipment installed at individual sites within the above comments. Does the study plan incorporating the batch monitoring (deposition and diffusion tubes) elements of the study at the additional industry sites located immediately around the major industries on the Burrup Peninsula?	We plan to add deposition samplers and rock samples to the industry the Health (powered) monitoring stations. We plan to add rock samples to the unpowered monitoring stations.	Agreed it will be advantageous.
20	3.5.1	Analysis of samples The laboratories provide the expertise and quality assurance of methods and techniques, along with the necessary QA and QC including chain of custody procedures and documentation. As previously mentioned, the use of a single (one) field blank in respect of each pollutant for each batch of tubes deployed is of concern as no redundancy is provided.	The number of field blanks has been revised.	The use of the additional field blanks provides redundancy as well as the ability to distribute and/or co-locate field blanks providing additional detail on field blank variability and uncertainty.
21	3.5.2	Source Apportionment Isotope signatures from combustion emissions Wondering if there is an existing database of isotopic signatures that covers a representative range of shipping fuels?	We are unaware of such a database, however Grice et al. have developed a method to determine organic isotope fingerprints, which will be applied in the study.	If pre-existing data is not available application of the known method is most reliable.
22	3.6 and 3.7	**Computational Fluid Dynamics Modelling** Modelling and site characterisation While CFD modelling can provide substantially high spatial resolution of the predicted concentration field across the model domain to assist design of the monitoring network, it is not clear how it is proposed this will be achieved in relation to the proposed CFD modelling and monitoring network. Further explanation of the CFD methodologies is provided in Section 3.7 of the Study Plan, however it is still not clear how the proposed simulations will be utilised to provide a "good representation of the conditions at Murujuga". While an example is provided in the form of a single concentration field, no detail is provided on how the series of concentration fields generated are to be processed in the development of the detail necessary to assess against the monitoring network. Detail on how the CFD predictions will assist in the final siting of the monitoring stations within the 1.3 km resolution achieved with the initial optimisation developed from the predictions of the Ramboll modelling is not evident. From the detail provided it appears the CFD simulations cover a very limited set of meteorological conditions, 14 specific wind speed and direction conditions, based on neutral atmospheric conditions (no thermal structure). While statistically, in the broad classification ranges applied, the 14 set conditions cover a high proportion of wind conditions (speed and direction) observed at Karratha; in relation to the potential variation in the ground level concentration of a pollutant emitted from a nearby source, and possibly influenced by terrain and/or structures close to the point of emissions, the set of conditions is considered very limited.	It is (somewhat) agreed that the ~14 meteorological conditions will not give a perfect picture of the Murujuga airflow. We intend to use the results of the Ramboll modelling to refine the final selection of met conditions – this includes the effects that the reviewer highlights (for example, we have already analysed the Ramboll met data to extract inversion layer heights). The CFD models have been validated (including thermal effects/buoyancy/turbulence) with good agreement, and will be included in the final CFD report. The broad selection for the monitoring sites using the Ramboll data was optimised across the whole of Murujuga. For operational reasons, (i.e. accessibility and access, actual locations of rock art, cyclone resistance, etc) the final locations of monitoring stations are more restrictive – the CFD will be used to select the most promising site amongst a limited number of candidates within each 1.3km grid, for this reason, the reduced coverage of meteorological conditions should not be a problem. (the next response relates to the three paragraphs starting "The Study Plan ..") The tractable number of CFD simulations means that assessment will be based on both quantitative and qualitative interpretation of the results. (detailed results will be compiled for each 1.3 km site showing the results from the CFD simulations as well as indicating the potential monitoring station locations determined from site visits). While initially the 14 conditions listed are proposed, it is expected that additional simulations will be added as a consequence of reviewing the results. For example, the interplay between windspeed, and a buoyant plume, in the presence of structures/topography is expected, however without some modelling the important combinations are not known. However the 14 initial cases allow the interaction to be investigated, and additional conditions added.	Analysis of the Ramboll modelling provides a sensible starting point in relation to identifying potentially more critical meteorological conditions on which to focus the CFD simulation. The process should also consider the limitations with respect to both modelling tools. For instance, the low-resolution grid within the Ramboll model results provides only coarse resolution of concentration distribution closer to the industrial sites and does not resolve the influence of site buildings and structures, adding greater uncertainty to the near-field concentration distribution and thus the ability to reliably resolve disparity in pollutant concentrations between air quality and rock art monitoring sites. While it is not necessary to represent the full distribution of pollutant concentration and impacts across the spatial and temporal extent of the study, it is critical to understand the difference between the air quality at the air quality monitoring sites and that at the nearby rock art study sites. The complexity of industrial sites and emission characteristics, as well as local terrain features such as gorges, can result in substantial variation in pollutant behaviour with small changes in conditions (i.e., wind direction) or location (i.e., within a gorge in comparison to a flat open region). The CFD studies will be most relevant to neutral atmospheric stability conditions, typically higher wind speed conditions, and thus not reliably capture potentially more critical conditions where the turbulence structure of the atmospheric boundary layer is a response to the surface thermodynamics. Integration of CFD outcomes with dispersion models with smaller grid size than the Ramboll modelling can assist representation of site and surface thermodynamic effects in the region within a few kilometres around the industrial sites. Development of the 14 initial CFD simulation cases through analysis of the Ramboll modelling study will provide greater focus on potentially more critical scenarios. Reliable clarification of the potential variation of pollutant exposure between monitoring and rock art sites under

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		Typically, the most significant pollutant impacts at a location result from the pollutant source close to that location. With seasonally consistent prevailing wind conditions, the location at which elevated plumes significantly interact with the ground under the prevailing conditions may also be relatively consistent. The concentration experienced at ground level is dependent on • the characteristics of the emission: - elevation or potential to become elevated (hot emissions) being very important, • the meteorological conditions: - wind speed, direction, and atmospheric stability (turbulent structure) and, • any local features that may alter the flow or turbulent structure and thus behaviour of the emitted plume (buildings, terrain, interaction with other emissions). Substantial variation in ground level pollutant impact can occur on finer resolution wind speed and directional increments than allowed for in the limited set of 14 CFD simulations proposed, particularly near the pollutant source and in the event site structures have a significant effect on plume behaviour. Additionally, the proposed CFD simulations are not considering the diurnal variation on atmospheric structure resulting from radiation budgets, i.e. • daytime heating of the ground due to solar radiation generating convectively driven turbulence • night-time cooling of the ground due to longwave radiation emissions leading to reduced turbulence, especially close to the surface. Approximately 50% of wind conditions are of wind speed less than 5 m/s, conditions for which the thermodynamic influence of the surface begins to influence the turbulent structure of the atmospheric boundary layer. The Woodside monitoring detail provided in Section 3.6 of the Ramboll report indicates wind speeds over the industrial region of the Burrup Peninsula are lower than those recorded at the exposed Karratha Airport BoM site. While, over a period, such as the 4-weeks of the diffusion tube and deposition samples, some of these differences may average to reduce disparity of predictions based on the simulation of a mid-condition, the influence of a fixture, such as a structure or terrain, will be consistent with regard to the wind speed and direction that lead to greatest impacts at ground level, as will the location in which the higher impacts occur. The higher impacts can be over a relatively narrow band of wind direction and speed conditions, and thus with the limited set of simulation conditions may not be resolved. While the Ramboll modelling provided concentration fields on a coarse grid (1.3 and 4 km), the predictions were developed on fine resolution meteorological conditions of 1-hour wind speed and direction with incorporation of the atmospheric structure including features such as capping inversions that limit vertical mixing as well as surface inversion that may restrict surface impact of elevated emissions. The CFD simulations on the other hand provide a very fine grid resolution, however it is proposed to generate these on only an extremely coarse set of flow conditions in comparison to what may be experienced. In developing the optimised monitoring network locations L&K Engineering (2021)[3] processed the 1-hour predictions from the Ramboll modelling into concentrations based on a 4-week average (of		different conditions will most probably require a significant level of further investigation. This may involve more complex CFD simulations or other forms of models dependent on the individual site and industry configuration. Qualitative comparison is likely not as reliable as an actual simulation of the import features of the emission behaviour.

[3] Murujuga Rock Art Monitoring Project: Air-quality monitoring site selection, L&K Engineering, 30 Aug 2021.

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		the 1-hour predictions) in line with the proposed batch monitoring programme. The monitoring network was then developed from minimisation of the error in the Ramboll predicted 4-week concentration field and the concentration field spatially interpolated from the 'monitored' concentration, i.e., the Ramboll prediction for the grid cell containing a proposed monitor location. The Study Plan does not provide a summary of the processing and analysis of the CFD predicted concentration fields and the methods applied to derive or characterise any local effects at the individual monitoring sites. Local flow features or flow patterns that affect pollutant concentrations at a measurement site, or a rock art site for that matter, are representative of the actual behaviour. In the main, such effects usually occur close to the pollutant source when the plume is smaller or of similar size to the flow pattern related to the feature. Once the plume is significantly larger than an object or feature, the feature does not tend to substantially alter plume behaviour, and thus the typical slowly expanding Gaussian concentration profile travelling with the mean wind flow. It is flow structures larger than the plume that can bodily transport the plume, and in so doing alter the concentration distribution from the idealised behaviour represented in a dispersion model. Hence the larger, stronger flow structures that develop when a building is at an oblique angle to the flow will be more likely to result in higher downwind ground level concentrations than the smaller structure developed when the flow is perpendicular to the face. Thus, for a square building the application of simulations at 45° increments may capture the critical directions relative to the building or may fall somewhere between. Either way there is insufficient detail to reliably understand the potential influence of wind direction on the downwind concentration. Further, for a vertically emitted buoyant emission (typical stack emission) wind speed will influence the rise of the emission as it is bent over due to the momentum of the wind. The entrainment of the emission in the developed flow structure will generally occur at a lower wind speed for the larger flow structure than the smaller. Again, with limited variation in wind speed, only one wind speed for 3 sectors, there is insufficient detail to reliably understand the potential influence of wind speed on the downwind concentration. While it is stated that validation of the models used in the CFD simulations has been undertaken, no detail of the validation process, the elements covered, nor the outcomes has been provided.		
23		**Spatial interpolation of near-field air quality monitoring** Advantages to the application of spatial interpolation of air quality monitoring results to provide detail on pollutant concentrations at the rock art monitoring and sample collection sites are understood. The method provides a much simpler approach than the development of validated dispersion modelling systems. Concern however arises in relation to the use of this approach in the locations of peak concentration, where the concentration gradient can also be highest. As discussed above, ground level air pollutant concentrations are typically highest, within, immediately around or near to an industrial facility, dependent on the nature of the emissions, site characteristics and meteorological conditions. While this characteristic is most notable	The initial draft DSD report was prepared prior to the Ramboll modelling and without detailed knowledge of what data would be forthcoming, as such the site selection optimisation was intending to CFD data primarily supplemented by the Ramboll modelling. A key difference between the reports is that in the second revision the Ramboll data had been received and analysed, and it is no longer proposed to perform detailed optimisation using the CFD results. Instead, the CFD results will aid our understanding of values measured at monitoring sites vs exposure/deposition on study rocks/art. In short, the CFD will be directly used to study the near-field flow for the monitoring sites. For the last paragraph ("In the event …") we will not be depending on interpolation of the CFD results, but the resolution of the initial meteorological conditions will be sufficient to identify any simulations that may be required to supplement the 14 conditions	The Ramboll modelling has provided a dataset on which to develop the site selection optimisation, while the application of CFD can assist understanding of the connection between air quality monitoring sites and rock study sites. However, concern remains as to the adequacy of the ability to sufficiently characterise detail of industrial emission concentrations and impacts in the region immediately around industrial sites. Highest ground level pollutant impacts are often observed within the region close to the emission source, particularly with lower level or building influenced emission sources. Pollutant chemical transformation is generally not critical within the time scales of direct near-field impact of industrial emissions.

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		with respect to peak short-term concentration events, it is also a feature of period average concentration field. Although the coarse scale airshed modelling of the Ramboll study provides one of the least reliable approaches for predicting near-field dispersion, due to the large grid resolution applied and typically limited consideration of site features and near-field effects, the predicted concentration and deposition fields often indicate highest impact in and around the individual industry sites. This is supported by many of the results detailed in the report and summarised on page 6 of that report. Additionally, detail available of the rock art distribution indicates regions of higher rock art density are in the central Burrup area, often adjacent to major industry, some potentially along the perimeter fence or within the industrial site boundary. It also appears there are significant terrain features within these regions including ravines and steep slopes. These characteristics, along with the potential site affects, could result in substantial variability of the behaviour of the emissions and impacts across the immediate area. Fluid modelling (CFD) would provide the best opportunity to understand some of the critical behaviours, however it is not clear how the spatial interpolation approach to estimate concentration distributions would perform in the event of substantial variation of impacts over short distances immediately around the industrial facilities. In the event that the most substantial and problematic pollutant impacts on a rock art site arise from emissions of the adjacent industrial facility, the concern is in relation to the adequacy of the spatial interpolation approach to reliably extrapolate to monitored concentration to the associated rock art and/or experimental site in the event of substantial concentration gradients across the scale of the site separation.	proposed. (ie in the case where a plume travels south of a site for a Westerly wind, but travels north of a site for a SW wind, we would also include an intermediate wind direction which affects the site). As agreed by the reviewer, for sites further from industrial facilities, local effects become less important for the more dispersed plumes. For example a CFD study including Collier rocks (South of Legendre island) is unlikely to beneficially refine the Ramboll results (on the assumption there is no nearby industry). <u>Rock Art distribution</u> Current maps of rock art abundance are estimated by the MAC archaeologist to only represent ~5% of all rock art. The location of known rock art (near industry) is an artefact of previous survey effort. We have found and recorded significant/abundant art on the outer islands in recent works. It is believed that art is concentrated around geological features such as gorges which provided shelter and water/food sources. This is true both on the peninsula and islands.	The resolution of the Ramboll modelling (1.3 km grid) is inadequate to resolve near-field concentration variation, and additionally the CAMx model does not incorporate potentially critical features of dispersion in the region immediately around the industrial sites. Statistical extrapolation of monitored air quality metrics would likely require a greater monitoring density to understand potential gradients in concentration to represent air quality at the rock study sites at a distance from the representative, though not co-located, air quality monitoring site. CFD is a tool that can assist with understanding the influence of site and terrain features on the lower regions of the atmospheric flow, and their interaction and influence on emission within this region. To provide sufficient confidence in the variation of pollutant impacts it is typically necessary to carry out a significant number of simulations to achieve understanding across the range of wind direction and speed conditions for which impacts may occur. In the near-field region around the industrial emissions, summation of the cumulative impacts based on the observed meteorological conditions across a period will likely provide a more robust interpretation of the variation in pollutant concentrations between air quality and rock art sites than direct statistical extrapolation of the monitored air quality. Similar uncertainty may also exist in relation to significant variation in terrain between rock art and air quality monitoring locations, including those at greater distance from the industrial emissions. For instance, the pollutant behaviour within a gorge, and particularly deposition behaviour, is likely highly dependent on the orientation of the gorge relative to the wind direction. An air quality monitoring site is generally located within more open areas with the aim of minimising any directional influence and thus would experience different wind conditions than the rock art within the gorge. Deposition behaviour is highly dependent on the wind condition. Again, direct statistical extrapolation of monitored air quality metrics is unlikely to provide representation of such physical phenomena. Application of CFD can assist understand the variation in pollutant behaviour over a range of conditions (wind direction and speed), with the outcomes applied proportionally in relation to observed meteorological conditions coincident with period monitoring results. However, it is very likely a significant number of flow simulations would be necessary to adequately understand variability at each individual monitoring region. The additional consideration of surface thermal influences on the atmospheric flow, whether more regional unstable and stable atmospheric conditions or differential heating or cooling of the sides of a gorge, would add additional parameters and complexity to any investigation. While theoretically CFD can be configured to represent flow behaviour resulting from surface thermal effects, the complexity and resources involved are substantially enhanced. Integration of near-field behaviour developed from CFD modelling within regulatory dispersion models with finer grid resolution than applied in the Ramboll study can also assist.

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CFD Methodology Clarification		-	-	On 25 Nov a document entitled "MRAMP-CFD Methodology Clarification.docx" was provided by Andrew King. This document provided more clarity on the "*process for establishing which sites may require further CFD modelling, and how these will be conducted*" The document clarifies the proposed approach in line with the Calibre/Curtin response within this review document. The newly proposed approach is not consistent with that outlined in the "Monitoring Studies Data Collection and Analysis Plan" document Version 2.1 of September 2021. Specifically, the newly proposed approach employs analysis of the Ramboll study of pollutant impacts to select the wind conditions for initial consideration in the CFD investigation. Detail on the metrics it is proposed to select the wind conditions is not provided however it is anticipated selection based on the Ramboll modelling will lead to the simulation of more important or critical conditions from the perspective of pollutant impact than achieved through the previous approach developed from a very broad characterisation of wind speed and directional frequency statistics. As discussed in the comments to Items 22 and 23 above, confidence is limited with respect to the ability of extrapolation of air quality monitoring site metrics to rock art sites through either statistical methods or based on a combination of limited CFD simulations in conjunction with the results of the Ramboll air-shed modelling study. While analysis of the Ramboll modelling outcomes provides detail of potentially more critical conditions with respect to pollutant impacts for the focus of the 14 initial CFD simulations, it is likely significant additional model investigation will be necessary to provide the most reliable method of extrapolation of monitored air quality metric detail to exposure level experienced at individual rock art monitoring sites. The level of complexity or detail that may be necessary is not possible to predict at this initial stage of the study. However, for some rock art and air quality monitoring combinations a considerable amount of investigation, with numerous additional CFD simulations and potential incorporation of additional modelling tools, may be necessary to provide more accurate and reliable extrapolation of monitored air quality to individual rock art sites. With the extent of monitoring data collected, including meteorological data, and the detailed characterisation and achieving of the monitoring program, retrospective investigation can be applied to further clarify potentially critical aspects of how the air quality monitoring can be more reliably related to the rock art study sites exposure to anthropogenic air pollutants from near-by industrial emissions. Comprehensive industrial emissions detail, such as continuous emissions monitoring (CEM's) data of more significant sources, would assist is characterising emission behaviour.

5 Microbiology and Geochemistry

5.1 Prof. Geoffrey Gadd – Review comments sheet for Detailed Study Design (Part A)

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: Professor Geoffrey Michael Gadd	
Document Title: Murujuga Rock Art Monitoring Project: Detailed Study Design (Part A)	
Document Revision: Version 1 (July 2020)	**Revised version:** Version 1.1 (January 2021)
Date of Review: 26 October 2020	**Date of close out comments**: 5 February 2021

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1	Executive Summary	Despite the criticisms and drawbacks of previous research, it is not mentioned in the document what conclusions were drawn from such previous work. Was the evidence obtained indicative of petroglyph biodeterioration with anthropogenic influences enhancing natural weathering?	There is a significant body of evidence from other rock art sites (with different mineralogy) on which we have based our study design. Much of the work specific to Murujuga is considered inconclusive. Some studies (e.g. MacLeod, 2005), have found association between nitrates and microbial cell abundance; however, the source of the nitrates could not be confirmed.	This does not directly answer the question, i.e. was there any evidence indicative of petroglyph biodeterioration with anthropogenic influences enhancing natural weathering? What was the evidence from the other sites?
2		I do not have information on the expertise or qualifications of the rangers and other staff but is appears that these personnel will eventually be involved in all aspects including field sampling and analyses, assuming total responsibility for field monitoring. Many of the approaches and technologies described subsequently in the proposal are complex and do require expert knowledge and experience, as well as often a thorough grounding in the relevant subject.	The rangers will be fully trained in all protocols and any work that cannot be undertaken by the rangers will be conducted by DWER or appropriate contractors post completion of the current project. MAC rangers will manage the engagement of future consultants to assist wit their on-going responsibilities, in the way that they manage external archaeological studies currently.	OK thank you
1 Study Objectives				
3	1.1 Ultimate goal and guiding principles	"the microbiome study must identify which species of bacteria are present in the rock surface…" As elsewhere in this proposal, it is unclear what exactly is meant by the microbiome and what will be studied. While fungi are mentioned later, often there is an indication that bacteria are the focus. A serious investigation should include fungi as these are often the most significant organisms in many instances of rock and mineral biodeterioration. It is also surprising that lichens (a fungal growth form) are never mentioned. I am not clear whether lichens are significant on the petroglyphs although the few images I have found indicate surface growth. Lichens are pioneer colonizers and important rock biodeterioration agents. They will also affect the colour analyses, surface texture and mineralogy that provide a major focus to many of the monitoring studies proposed.	The definition of the microbiome was already spelled out in the proposal but involves all bacterial, archaeal, and eukaryotic micro-organisms (notably fungi and lichens which comprise endolithic fungi that live in symbiosis with photoautotrophic microalgae; i.e., lichens) that in this case colonise the rock surface and interact together as an ecosystem. It is currently unknown which bacteria, fungi, and lichens are present on the rock surfaces in the Murujuga region. As spelled out in the proposal, we will be using molecular techniques to get a holistic overview of what species are present from sequenced established barcoding genes (bacterial and archaeal 16S rRNA and eukaryotic 18S rRNA (e.g. symbiotic algae in case endolithic liches are present) plus specifically fungal communities (ITS barcoding). Processes involved in colonisation of the rock via the formation of exopolymeric substances (EPS), the formation of iron and manganese oxides and the production of organic acids will be studied (among many other important processes see extended 2.1.3.) from shotgun sequencing analysis of microbial metagenomes. The active expression of these genes in situ will be elucidated from metatransciptomes. Through mapping of the transcriptomes on metagenome assembled metagenomes (MAGs) we will be able to elucidate the activities and role of the key players of the rock microbiome. However, we now added a section where we propose to cultivate bacteria and/or fungi from samples that contain putative Mn and/or Fe oxidizers to verify that these communities are able to do this under lab-controlled conditions. Since shotgun metagenomic analysis has been much more developed for bacterial communities than for eukaryotes, we will use PICRUSt2 to predict the physiological properties of fungi based on 18S rRNA genes (recently added feature in PICRUSt2) and cultivate the residing fungi to verify	There was an overall impression of over-emphasis on bacteria which has now been addressed Characterisation of the complete microbiome through molecular/genomic techniques is a major undertaking, subject to many problems regarding sampling, interpretation of results, and convincingly relating data to possible function/activities, and this will now be complemented by some studies on isolates. Regarding the isolation and tests for Mn and Fe oxidizers, such work has already been carried out on other kinds of rock varnish/coatings, and undoubtedly such organisms will be present as these properties are widespread. However, note that despite years of research, it is still an unresolved issue whether these coatings arise from purely abiotic mechanisms or whether there is a biological component, despite the presence of Mn/Fe oxidizers being recorded. It is a problem that has baffled many for years and according to my recent searches, shows no sign of being resolved to the satisfaction of geologists and biologists. Personally I believe regardless of the above, microbial systems will have important roles on the rock surfaces, and I hope this aspect of the work will prove fruitful.

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			their ability to form Fe or Mn oxides (this will also involve SEM and elemental analysis at the John de Laeter Centre at Curtin University). This aspect has been added to the proposal. We also expanded on the background information about the important role of endolithic and MC fungi could be playing in the formation and/or degradation of rock varnish.	
4	1.2 Research Objectives	Previous comments may apply to Objectives 1 and 2. What substances are meant by "natural emissions" from "plants/fire"?	This encompasses biogenic volatile organics and compounds emitted by bush/wild-fire events, both of which have been found to be significant in RAMBOLL air quality modelling.	OK thank you.
5	1.5 Microbiome	"Rock varnish" is referred to throughout but so are other terms for surface layers, patinas etc. Rock varnish is a term that applies to a specific kind of rock coating that may involve Fe/.Mn oxidation and a variety of metal-oxidizing microorganisms, but this term does not encompass all the varieties of biogenic coatings that may occur, while organisms associated with dissolution are not the same as those found in rock varnish. Further rock varnish is tough and not usually considered in a context of being dissolved. The microbiome study needs clarification over these points and more depth regarding activities of rock-inhabiting microorganisms in effecting biodeterioration and mineral transformations (some other comments are relevant to these points) Does historical information exist about the nature of the rock surface regarding the presence and distribution of rock varnish, or other coatings?	The reviewer may be correct that under normal conditions the rock art microbiome does not represent a consortium that is involved in the deterioration of rock varnish. However, increased exposure to nitrate and/or organic pollutants may select for novel bacteria and fungi to form an acidic biofilm. Fungal hyphen may be able to penetrate the rock through tiny cracks and start deteriorating the weathered rock located just micrometers below. This will also create conditions for smaller bacteria to penetrate the patina. They will probably work together which is now better outlined in the proposal text. We furthermore expanded on the activities of rock-inhabiting microbes in affecting biodeterioration and mineral transformations. The term varnish was perhaps used more broadly in the previous document that is generally accepted. This has been corrected along with provision of a glossary in the revised document.	OK thank you. I agree that pollutants may encourage biofilm growth, perhaps not necessarily an acidic biofilm – nitrate utilization can lead to alkaline conditions (although this does not mean that biodeteriorative effects will not still occur). Yes, the terms used for varnish/coatings etc are pretty vague and attempts to define occupy a lot of debate in the literature! The question "Does historical information exist about the nature of the rock surface regarding the presence and distribution of rock varnish, or other coatings?" is unanswered.
6	1.6 Surface condition	Some of these objectives are covered in the previous sections. Objectives show some repetition/overlap, e.g. 1.5 and 2.6 while most are written as Aims rather than specific Objectives with a defined outcome. For example, 2 objectives aim to "Develop…" rather than achieve a specific endpoint. There is no clear hypothesis provided for monitoring colour, texture and elemental composition: what will such measurements reveal about the possible deterioration, and what conclusions would the accumulated data support?	Objectives 4-8 in section 1.6 refer to the interpretation and analysis of data, which will have been collected as described in objectives 1-3. "Developing a deeper understanding of variation in elemental composition" foreshadows that the data will lead to quantitative results and qualitative conclusions about, and improved understanding of, the spatial variation in elemental composition on the rock surfaces. The precise nature of the results cannot be forecast at this stage. Successful achievement of this objective does not depend on a particular result being obtained. The objective is achieved successfully if the data collected, and their analysis, are sufficient to lead to clear conclusions and understanding.	OK thank you but there must be some kind of hypothesis as to what the measurements will reveal, otherwise it seems that it is a data collection exercise with the hope that interpretations will be clear afterwards.
7	1.6.1 Perceptual and spectral colour	"Change in the visible colour of a surface is a reasonable indicator of change in its appearance…" – this is self-evident, rephrase? While colour change is regarded as important throughout the report, it is not clear what possible mechanisms the authors might think underly any colour change, such as what particular mineralogical changes might occur. Are lichens, surface biofilms and colonies being considered in colour changes? Do such organisms affect the colour determinations? How will any colour changes be correlated with mineralogical changes which may arise from abiotic and biotic weathering mechanisms? The recent studies referring to a Mn/Fe crust as well as the previous colorimetric studies 2014-16 are not cited: they should be to provide useful background information to the reviewer.	With respect to the microbiome. If they are found to be actively involved in Mn or Fe oxide deposition in situ (using the ultrasensitive metatranscriptomics approach) or indirectly under lab controlled conditions, this would tell us that the microbiome is likely to be contributing to colour changes over time. If they seem to be producing organic acids bringing the pH of the patina to less than 4.7, this may ultimately dissolve the patina and then that will also affect the colour. This has already been described in detail in the original proposal but we added additional background information in section 2.1.3. (1) Sentence rephrased to "Change in the visible colour of a surface is a reasonable indicator of change in its composition and condition" (2) At this stage, we have not made any assumptions regarding the links between colour change and mineralogical change. To link these parameters is one of the objectives of the study. This has been clarified with new text in this section "We will integrate results from different techniques to determine the causal relationships amongst natural and anthropogenic external factors that affect the rock art, the physical characteristics of the rock art (e.g., colour, mineralogy,	OK thank you. OK OK

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		I presume mention of the Mn/Fe crust is because petroglyphs are located on rock of such Mn/Fe composition? However, the three main rock types mentioned later are not types generally associated with high Fe/Mn.	indigenous microbiome), and the processes that effect change." (3) Yes, the role of endolithic lichens involved in the deterioration of the surface rocks ha been added to the proposal. The original proposal already described the mechanisms behind the formation of microbial biofilms and their role in colour changes either through patina formation (precipitation of Mn and Fe oxides) or degradation (through the formation of an acidic biofilm). However, in the revised proposal we also extended on the role of endolithic lichens in the formation of an acidic biofilm and the deterioration of the surface layers. See section 2.1.3. (4) See (2) (5) Now cited. (6) It is true that the granophyre's are not Fe- or Mn-rich. However, these elements commonly become concentrated as the rocks weather and more soluble components are lost. New text added to this section "While the granophyre's are not iron- or manganese-rich, these elements become concentrated in the residue left after the rocks weather and more soluble components are lost."	OK OK but is there any reasonable data for the actual elemental compositions of the granophyres?
8	1.6.2 Elemental distribution	Total elemental distribution provides no information on mineralogical changes or transformations that may have occurred or be occurring in the substrate.	This text has been added to section 1.6.2 "Element ratios can be used constrain the possible minerals present, but may not provide a unique identification. For this reason, the pXRF work is complemented by other techniques, such as XRD that can identify the minerals uniquely. Preparation and analysis of thin sections (section 3.3.2) will also enable us to determine the changes occurring within the substrate."	OK thank you.
9	1.6.3 Texture	What are the mechanisms underlying formation or loss of minerals? Texture measurements should be correlated with mechanistic conclusions. Is 10um adequate resolution? Certain mineralogical transformations and microbe-metal interactions lead to nanoscale products.	With respect to the role of the microbiome: As outlined elsewhere in the proposal iron- or manganese oxidising bacteria and/or fungi can be actively involved in the formation of the patina. If they produce an acidic biofilm instead, that could lower the pH on the patina to less than 4.7 causing the oxides to dissolve over time. (1) New text added: Mineral stability depends on the thermodynamics of the mineral systems and environmental parameters such as pH, redox, temperature, and the concentrations of a range of elements, such as Si. Minerals can form by precipitation from solution, or be lost by dissolution. (2) New text added to address this point "The results will be integrated with those using other laboratory-based techniques to link textural observations to inferred mechanisms of mineralogical change." (3) 10 micrometers is the resolution available for the field techniques. Higher spatial resolution is available using the laboratory-based techniques and this has been clarified within the text.	OK thank you but bear in mind earlier comments where several researchers still deny that Fe/Mn oxidizers play any role in coating formation but may be there as incidental colonizers and/or involved in biodeteriorative events. OK OK OK
10	1.7 Air quality	Are any historical or existing data available on air quality? Is there evidence for increased decline in air quality and increased pollution levels over the years?	Historic data do exist - both as industrial compliance monitoring and measurement campaigns. These data have been (or are being) obtained and will be included in analysis.	OK thank you.
2. Evaluation of Previous Studies and Data 2.1. Scientific value, limitations, usefulness for future work				
11	2.1.1 Spectrophotometry	I do not understand why precise location data was not provided since without that previous data may be useless, while other imaging data in "public reports" is unavailable which questions what exactly is meant by "public"	Since writing this document, meetings have been held with those who conducted the original studies. As standard GPS (not DGPS) was used and re-location of sample sites on rocks for subsequent years was conducted entirely using (large scale) photographs, it is not possible to re-locate previous study sites with any accuracy or precision.	OK thank you

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			Expanding on GPS: Prior to 2000, the US GPS satellite signals available to civilian users included the Selective Availability perturbation which added ~50 m error to spatial locations. After this signal was removed, many GPS receivers in civilian use assumed that SA was still active, and did not provide increased accuracy. Furthermore it appears from what Ben says that the original study authors did not use GNSS augmentation such as Differential GPS which increases accuracy from the nominal 10 m to 3m or less.) The relocation of sites used in colorimetric studies is not entirely dependent on GPS co-ordinates. The site are well know and easily relocatable by the MAC rangers and from photographs. The current project requires that all GPS measurements be far more precise than earlier technologies allowed.	
12	2.1.1 i.	Difficulties in site selection are appreciated and the entire population of rocks cannot possibly be sampled. I think the representative approach still deserves merit and could provide detailed data. This should be matched with the known rock composition and rock type since such information presumably can be obtained from a much larger portion of the rock population. Is there a wide diversity of rock type and mineralogical composition across the various sites? If not then a representative approach is more meaningful.	We are unclear what is meant by "the representative approach" in this context. We are adopting defensible, well-established sampling techniques for the survey. We are confident that these will ensure representative samples are taken.	OK thank you.
13	2.1.1 ii	Efforts should be made to use instrumentation that has a proven track record in other studies that have been reported in the literature. Furthermore, all measurements should be calibrated in the field, have adequate controls etc so that results are valid. Discouragement of use of certain instruments in the field may be due to questions of robustness which can be overcome with careful operation.	It is very difficult to find a body of literature on any particular Photospectrometer other than those that have been rejected in the context of this study. Konica Minolta instruments are probably the most widely used instruments in heritage studies and yet there are many reasons why they are not being used here. The best of the previous instruments the ASD FieldSpecPro has very little published evidence. The JAZ has been used in several research laboratories. Perhaps more critical than widespread endorsement is the need for reliable and transferable data. Another reviewer has suggested that the ASD should be used, however there will be as much variability between a 2021 ASD and 2004 ASD and between a recalibrated instrument and its former self. Given that the Program is potentially perpetual it is far more important to focus on how data will be transferred to new systems meaningfully. It is unrealistic to think that the one instrument, with known research use will remain operational for more than 20 years, whereas colour change determinations either have to be conclusive with the research period or be effectively transferred to future instruments with confidence. The first field measurements will be preceded by a cross calibration to the ASD and KM instruments used in previous research. It will only be at the conclusion of this exercise that a clear picture of transferability will emerge.	OK thank you.
14	2.1.1 iii	If some of the previous data was not consistently calibrated, then presumably such data are useless and cannot be used to support the current proposed study? Does this almost mean that studies have to begin again (which clearly affects the ability to reach conclusions about events that may occur over the longer term)?	We would agree with this assessment. The previous studies cannot be treated as evidence. One exception is that we have noted in the Part A document that prior research at least helps to give ballpark estimates of numerical values and variability which can be used to optimise our Study Design.	I see, thank you.
15	2.1.1 v	Progressive/gradual change is assumed to take place, but changes dependent on abiotic/biotic factors may be affected by environmental perturbations, e.g. sudden extremes of weather etc. Are there data available for climatic/weather conditions over the sampling periods, and anything significant in 2010?	This is why we plan to compare the microbiome during the wet and dry seasons. The microbiome is expected to be very different between the two seasons with higher overall activity during the wet season.	OK Question “Are there data available for climatic/weather conditions over the sampling periods, and anything significant in 2010?” not answered.

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16	Fig 2.1	Fig. 2.1. Details lacking. What are the bars? What is the dark line in the boxes? What are the circles? I am not familiar with this style of plot so need some explanation. However if the bars are error/SD then they all overlap so what exactly is the level of confidence in that the apparent change is statistically meaningful?	A boxplot is a standard statistical graphic described in any text on applied statistics. It represents the scatter of data values, and does not have a direct interpretation in terms of statistical significance. The midline is the median of the data values. The box ranges from the lower quartile to the upper quartile of the data values. The linear extension is the 'hinge' typically equal to 1.5 times the interquartile range. Circles show individual data values which are outside the hinges.	OK
17	Fig 2.2	Fig. 2.2. Although a change is also apparent, similar comments as above	Stark differences between the boxplots of data in successive years suggest that the distribution of values has changed abruptly from one year to the next. This is the usual indication that there has been an undocumented change in measurement protocol.	OK
18	Fig 2.3	Fig. 2.3. Similar comments as above	See above.	OK
19	P15	p15. I am not sure I understand the last paragraph. I assume that the linear regressions are not shown here and the numbers in the text are the values calculated from such linear regressions. What is the basis of saying more red and yellow colour is related to natural mineralization? What is the mechanism/evidence for this? What is the assumed mineralogy? One point is that it is not always clear in the document what the intended meaning of “mineralization” is. I assume mostly that the authors mean mineral formation but in the case of colour changes/deterioration there will also be processes of mineral dissolution.	Linear regressions were performed but no graphical display of the regression line was plotted. Instead we have simply reported the fitted trend slopes in the text, and indicated statistical significance. We have added the words "not shown" to the text to clarify. A definition of "mineralization" has been included in the glossary	OK thank you.
20	2.1.1.	It seems that prior results for spectrophotometry provided some useful indications and lessons for the future, but also raise questions about the validity of the data obtained and therefore its potential to inform future studies must be limited or treated with appropriate caution.	Agreed.	Good
21	2.1.2 Inorganic Geochemistry	Can it be clarified what is meant by weathered rind and desert varnish, and how do these differ? It seems that there is a body of mineralogical data that is useful from the previous studies. Again, in my opinion, it seems that colour measurements throw up problems of interpretation.	This has been clarified to " mineralogy of the fresh rock, the weathered clay layer and patina"	OK thank you.
22	2.1.3 Microbiome	This work and summary focuses on Fe and Mn oxidation but is this the only phenomenon occurring? Other mineral types have been referred to. The microbial transformations possible should be considered along with the mineralogy of the rock types. O’Hara (2008) is not a recent study! There is wide published proof of bacterial and fungal Mn oxidation and such organisms are widely implicated in desert varnish: the relevant literature deserves critical re-examination in future research to help clarify this.	To the best of our knowledge, Fe and Mn oxides contribute mostly to the contrast between the petroglyphs and the surrounding patina. As mentioned in the original proposal, we will correlate the microbial diversity and composition with the mineral compositions not limited to Fe and Mn oxides to determine to what extent the microbiome is shaped by the rock surface minerology. We removed “recent” and expanded on the background after reviewing additional more recent references. "recent" has been removed. We added a few relevant references related to the implications of bacteria and fungi with Mn oxidation on desert varnish. See revised 2.1.3.	OK thank you.
2.2 Data and information gaps				
23	2.2.1 Organic geochemistry	What is the relevance of isotopic composition? Are different isotopes of certain pollutants present? What chemical substances are meant by natural emissions? Some of these bullet points are extremely wide-ranging and complex and it is difficult to see how they could be achieved.	A 'rationale' section has been added for the organic geochemistry (Section 3.3.4 i, page 76) to address these concerns.	OK thank you.

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24	2.2.2 Inorganic geochemistry	Again different terms are used – weathered rind and patina. Please define what is meant and what is the difference between these terms. Is it possible to have some sort of controls here (and in other approaches) with completely unexposed rock perhaps from other locations but of similar composition? Most proposed analyses are on the existing petroglyph rocks so it is difficult to assess causes, changes and consequences.	Weathered rind refers to the outer portion of the rock, most of which is not visible at the surface (as patina) as is it much thicker. These terms have now been clarified in the glossary. Agree with the reviewer that it is difficult, but rocks from other locations have too many other factors that are different to act as a control. This approach may work for the microbiome studies, provided fresh rock from Murujuga rocks are used (if permitted by MAC). The following text has been added: " Ideally, it would be possible to compare rocks exposed to industrial emissions to "control" rocks, which are not, but are exposed to comparable environments apart from the emissions. However, this is not possible, and attempts by previous workers to set up "control" sites have been shown to be flawed. " to the text and 2.2.2.	OK thank you. OK
25	2.2.3 Microbiome	A purely molecular approach brings its own set of problems not least difficulties is ascribing function, abundance and activity. Furthermore, culture-dependent isolations are important since evidence exists that often it is the culturable members of the community that are the most active. DNA will be isolated from rock varnish (is this an easy task? Is it suggested that rock varnish can protect DNA like the clay minerals referred to? Insufficient details are provided here as to what functional genes, or what microbial processes. It is often unclear in the microbiome sections whether the authors mean bacteria, or fungi, or both when they refer to “microbial” or a certain process. Fungi are often the most active members of rock biodeteriorating communities but receive little specific mention here. Lichens must be important but are not considered.	We agree with the reviewer and now included cultivation experiments to verify the formation of Fe and/or Mn oxides under lab-controlled conditions. This will be further confirmed with EMS and elemental analysis at the John de Laeter Centre at Curtin University (see also earlier responses to the same problematic). We are very experienced with extracting DNA and RNA from rock surfaces. For example, we recently studied low biomass deep biosphere microbiomes isolated from Cretaceous granites, suevites, and Cenozoic consolidated marl stones from the Chicxulub Impact Crater using stringent controls for cross contamination. This paper is currently in review at Sci Adv. Our group has significant expertise in trace (ancient sedimentary) DNA and trace level RNA work such as functional gene transcripts that are present in low activity frozen permafrost soils (Orsi and Coolen, 2015). Yes. As experts in ancient DNA we agree that extracellular DNA may be protected for substantial periods of time (perhaps thousands of years) through mineral adsorption. We will therefore compare DNA profiles with reverse transcribed RNA of the same barcoding genes (which survive only weeks to days after cell death) to verify which microbes were alive shortly before or at the time of sampling. This was already mentioned in the proposal. We agree with the reviewer. We actually meant both bacteria and fungi but we have now clarified this better in the text and expended on the importance of analysing fungi and endolithic lichens. See also earlier responses.	OK thank you. Ok thank you. OK thank you. OK
26	3 Proposed Study Design	p22 “Effect of pollutants on rock” This appears to be largely unknown in all the contexts mentioned and a highly demanding exercise experimentally.	Agreed, however this is a necessary component of the work.	OK
27		p23 See earlier comments. I think colour data and determination has clear and obvious difficulties in obtaining reliable data and its interpretation, yet spectral/colour analyses were and are proposed to be a major component of future work despite the previously encountered pitfalls. Have simple photographs been taken of various specific sites/rocks over a time period? These would simply show progressive changes with time. This is just like the many published images of rocks/cultural artefacts etc. taken over several years where effects of weathering and microbial colonization are clear. I am surprised that such a simple approach was not apparently carried out.	Photographs exist and additional photographs will be taken where culturally permitted. However such analyses have infinitely greater sources of error than colour/spectral techniques and would not withstand statistical scrutiny.	OK thank you. I think photographic records of the same sites over time would prove useful.

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28	p23, Table 3.1	There are many variables to take account of, which have been carefully detailed, which makes for extremely complex analysis and interpretation as in many field studies.	Yes	OK
29	3.1.3 vi	Impact on microbiome: light is another variable that can affect surface communities. What are the 3 rock types? They are mentioned later but should be stated here. What does "categorical parameters" mean?	The reviewer is correct. UV exposure may select for bacteria and fungi that produce protective pigments and the community may be different from those growing on rocks that are always in the shade and not directly sun exposed. The majority of the petroglyphs are directly sun exposed, but we added "light/UV exposure" to the "vi Impact on microbiome". The three rock types (which have been found with petroglyphs are listed elsewhere but have been added here are: gabbro, granophyre and dolerite). Examples of sample categorical factors controlling the microbiome as explained in the original proposal are rock types, seasons. While quantitative controls could be pH, nutrient concentrations etc.	OK thank you.
3.1.4. Principles of Study Design				
30	a	Control sites. The difficulties are appreciated, and this is a problem that occurs in many contexts, e.g. analysis of polluted sites where an unpolluted control is also difficult. The usual approach as described here is to identify supposed control unexposed sites that in other respects are identical or similar to test sites in important characters, or to use controls at completely different locations or in laboratory simulations. All have problems but what seems to be important in this study is the possibility of detrimental changes with time in the petroglyph materials and this is an important objective that seems achievable. Whether such changes can be correlated with anthropogenic contamination is more difficult but if there is a possibility of different sites with low or high levels of contamination then this would help interpretation.	Agreed, this is the basis for our study design.	OK thank you
31	b	Atmospheric pollution – are there any data on the nature and kinds of pollutants that may occur in industrial emissions? No examples have been provided.	All industries nearby of sufficient size are required to report and monitor their atmospheric emissions. All significant local and regional sources have also been captured in RAMBOLL plume modelling studies, a report on which will be provided to reviewers, we believe.	So what are nature and kinds of pollutants? not stated I do not have this report.
3.2 Non-Invasive monitoring of rock art				
32	3.2.1 i	I think the use of the previously studied sites is important to be included with appreciation of any of the defects mentioned. Other additional sites are also important to apply better methods and approaches.	It is unclear exactly what the reviewer is proposing. We have concluded that previously-obtained measurements of colour cannot be included in the full analysis. Moreover, after discussion we previous researchers, we are not confident of revisiting the exact positions/locations used previously. Previous monitoring data will be utilized only in a meta analysis, with appropriate safeguards.	It is obvious what I suggest although the responses here and elsewhere make it irrelevant since it is seems that little from previous studies is of use or will be considered apart from some monitoring data.
33	ii	Sampling protocols have been carefully considered.	Acknowledged.	OK
34	iii	As mentioned previously, colour changes may reveal nothing about the mechanisms that are causing such changes whether they are abiotic or biotic, or combinations of abiotic/biotic effects. Similarly a lack of colour change does not necessarily indicate that mineral transformations are not taking place.	This is acknowledged. For this reason, the study design also includes laboratory experiments, under controlled conditions, which aim to identify and characterize causal mechanisms that may result in degradation. The spectroscopy includes analysis of the spectrum for non-chromatic changes as evidence by changes on spectral strength of secondary peaks. The spectra cannot resolve any of the alteration mechanisms, only show that change is occurring, both visible and non-visible.	OK thank you.
35	3.2.2	Parts of this section, although thoroughly written, are unclear to me and I am not familiar with this technology. How will such an approach capture air flow and pollutant transport as suggested? What topographical data will be relevant to the problem of deterioration and how will such data inform or integrate with other work tasks?	Topographical change will be assessed using two technologies. Micro-photogrammetry will record a section through and around an engraved channel at very fine resolution, of approximately 10 microns. The 3D model acquired can be analysed in several ways including measurement of the volume of an engraved area or the profile of any cross sections through the channel. This technique, while potentially able to scan large areas, is confined to small areas of no more than 150 mm due to the large number of images generated and consequently processed to construct the 3D model. The second technique, RTI, requires far fewer images with a model constructed from a few dozen images. This technique relies on raking	OK thank you.

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			light to highlight very faint surface variations and can record an entire rock surface of several meters. Comparison between images of different times can reveal subtle changes to surface topography over a broad surface.	
36	3.2.3 i	Fig. 3.6. What is the rationale for the 4-hour gap in the sampling period? Some previous comments on the application and interpretation of colour changes apply here also.	There is no interruption to any site measurements. The four hour gap refers to a four hour operating window, to ensure that surfaces are measured within their designated surface temperature window. The four hours is simply indicating that some sites will be measured only on the morning and others only in the afternoon, but this is entirely dependent on the temperature that drives which sites is measured on any given day. What has been shown is that the 5-degree window prevails for several hours on many days. In practice this means that if a morning site is recorded at 35-degrees it will most likely be that temperature at that time of day in the same month the following year. This is all about reducing thermal error.	I see, thank you.
37	ii	XRF will provide useful information on elemental composition but provides no information on mineralogy or possible mineral transformations. A “natural darkening” is not necessarily a result an increase in Fe or Mn but progressive oxidation of these in the substrate. Significant increases in Fe or Mn (from aerial sources?) are unlikely to be significant compared with natural levels in the rocks. Is the mentioned increase in sulfur from aerial deposition? As mentioned, colour changes may be difficult to correlate with elemental composition, since the latter may not change although there may be shifts in the mineralogy not detected by XRF. XRF should be used in conjunction with mineralogical analysis by, e.g. XRD if this was possible.	This is acknowledged. For this reason, the study design also includes laboratory experiments, under controlled conditions, which aim to identify and characterise causal mechanisms that may result in degradation. The spectroscopy includes analysis of the spectrum for non-chromatic changes as evidenced by changes on spectral strength of secondary peaks. The spectra cannot comprehend any of the alteration mechanisms, only show that change is occurring, both visible and non-visible. Yes - sulfur would most likely occur via aerial deposition.	OK thank you
38	iii	As mentioned previously, colour change and elemental distribution may not be directly connected, while microbial/lichen pigmentation in contributing to colour is not considered. Regarding sulfur (it is not stated what the sulfur chemical speciation might be), the ability to form sulfuric acid from elemental sulfur depends on oxidation which might be mediated by acidophilic bacteria – is there any evidence that such organisms may be involved in bioweathering? Gypsum is mostly white and dihydrate. Loss of water of hydration is achieved by heating but this does not make gypsum black. If it is black it probably means there are other impurities present, or possibly evidence of sulphide formation by reduction of the sulfate by sulfate-reducing bacteria. Any comment on this? I understand spalling to result from mineral formation or expansion under the surface which then pushes off surface layers.	The reviewer makes a good point about the possible role of acidophilic bacteria involved in bioweathering. Our study will reveal if environmental sequences are present that are closely related to known acidophiles. The shotgun metagenomic and metranscriptomic analysis will reveal genes and gene transcripts indicative of active dissimilatory sulfate reduction.	OK thank you.
39	Iii, iv	Details of the approaches used are carefully described though it is not described how data obtained will inform or be integrated with the other analyses carried out, or what hypotheses will be confirmed or challenged. It is clear that vast amounts of data will be obtained using a variety of methods, with which the authors have experience, but a summary of why such data is important and how it will be	As the nature and significance of interactions on the rock surface between air pollution, deposition, the microbiome and rock surface inorganic and organic chemistry are to a large extent unknown, it is difficult to pre-emptively subscribe to one or several mechanisms which may predominate. It is also unknown if there may be synergistic relationships between these mechanisms. It is therefore important that we consider all results together to elucidate these	OK thank you

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		interpreted and help understanding of the problem would have been useful.	mechanisms and any relationships between them. This will require rigorous statistical analyses, which we are well equipped to perform. Here the proposed laboratory studies will be important as it will allow us to test some of these mechanisms and determine their significance. Here we aim to determine is a measurable change is occurring to the rock art/rock surface, what agent or agents are responsible (and what is the mechanism) and how/if is this related to the levels of airborne pollutants. If we can find a particular pollutant or suite of pollutants which we know can cause change to the rock art condition, then we can find out at what concentrations this is likely or significant and propose some form of limit. This will allow recommendations for ongoing monitoring to be made beyond the length of the project.	
3.3 Destructive analysis of non-petroglyph rock samples				
40	3.3.1	"It is proposed that once we have obtained peer review and approval for the work contained in this section, a detailed validation of methods….will be undertaken" . This seems unusual. Surely methods to be used are already known?	Some methods, while known, will still need to be field tested, or adapted for the (harsh, remote, cyclone-prone) environment present at the study site. There are also some techniques we wish to explore here, which will benefit the study more broadly, but will need to be demonstrated. The Part B study design will finalise all these details.	OK thank you
41	3.3.2 Inorganic Geochemistry	Are the sites exposed to low and high anthropogenic emissions already known or how will this be determined?	Yes, to some extent. Since writing the document we have obtained the results of a modelling study on pollutant transport throughout Murujuga, considering a range of pollutants throughout the year. This highlights areas of higher and lower pollutant concentrations, but is limited in resolution. We effectively have an average value over an area of 1-2 square kilometers. Finer resolution will be achieved through our monitoring study and the use of computational fluid dynamics simulations.	OK thank you
42	3.3.2 iii	The rationale for examination of clay minerals is insufficiently explained. Is it taken to indicate weathering ?	Added: " The clay minerals within the weathered rind are important because they provide a substrate for the patina, and the identity of the minerals records the rock's weathering history."	OK thank you
43	vii	Rationale is insufficiently convincing. I do not believe this technique can provide information on "composition and type of microorganism". Supporting evidence, publications etc. are not provided. In addition, how does this technique provide information on the "types" of minerals? It does not measure mineralogy. These statements should be justified, particularly as some of the information will be obtained by other approaches.	Text modified to read " composition of minerals" - the reviewer is correct that TOF-SIMS does not uniquely identify the mineral	Or the microorganism?
44	viii	Several of these approaches are obtaining information from the micro- to nanoscale dimension. How will findings be related to or inform the larger-scale determinations and also in relation to the heterogeneity of the samples and rock surface layers?	We anticipate that the nano- and micro-scale observations will inform us of the processes and identities of the minerals - this information cannot be obtained from the macro-scale observations. The macro-scale observations will be used to quantify the heterogeneity of the processes and mineral distributions recognised from the micro- and nano-scale studies. This information cannot be obtained from the smaller-scaled studies. By integrating across the length scales, we will derive an understanding of the minerals present, the processes occurring, and the heterogeneity and, by relating the macro-scale observations to parameters such as aspect or proximity to the ocean, we will constrain the larger scale controls on those processes. I've added this text to the 'synthesis' section.	OK thank you
45	x	Synthesis. Conceptual models will be derived based on the described analyses and integration with results obtained from other work tasks regarding organic geochemistry and microbiome. While mineralogical studies appear to be the most straightforward, relationships with organic geochemistry	As described in the proposal, to what extent categorical and quantitative parameters impact the diversity and activity of the microbiome can and will be visualized and analysed using a suite of ordination and multivariate statistical analysis. This is quite straight forward.	OK thank you

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		and microbiome studies are extremely complex and therefore highly dependent on these approaches and their ability to provide information on a complex system subject to many variables. I am sure the investigators are aware of this!		
46	3.3.3 Microbiome i	Fe and Mn-oxidizing organisms are frequently cited in this proposal but the major rock types mentioned at the sites are gabbro, granophyre and dolerite which are not associated with high Fe content or the presence of Mn. So where is the Fe or Mn located? Are there other minerals present in the rocks? It would have been helpful to see what the elemental and mineralogical composition of the rock types here as I presume this must have been carried out in previous studies. Rock varnish is also frequently focused on as mentioned but many other biogenic surface coverings are possible including microcolonial fungi, cyanobacteria and microalgae, bacterial biofilms etc. Furthermore it is surprising that lichens have never been mentioned in the rock deterioration context. They are major bioweathering agents but also can act as a protective surface shield. Lichens and microcolonial fungi are also capable of growth and survival under extreme conditions. Are lichens not present on the rocks? Has there been any consideration of lichens? (also previous comments refer to these points) Simple imaging of sample sites and rocks over time would be a simple approach.	Text added at the start of 3.3.3i : "The main rock types at Murujuga are gabbro, dolerite, and granophyre, which contain a range of Fe- and Mn-contents (2–7 and 0.1–0.2 wt.%, respectively: Ramanaidou and Fonteneau, 2019). Fe and Mn are also present within soils and wind-blown dust. " As mentioned earlier, we have now expanded the background and included a study design for analysing the role of fungi, symbiotic algae associated with fungi in endolithic lichens. Cyanobacteria will be automatically identified as part of the 16S sequencing. As mentioned above, visible lichen colonies have occasionally been reported on the rocks in Murujuga, but they are not abundant. Nevertheless, if we get permission to sample lichens from art-free rocks we could indeed study the diversity of the lichen communities and predict the physiological properties of the residing fungi using PICRUSt2 analysis of fungal 18S rRNA genes and transcripts. This comparison will reveal the diversity and predicted physiological properties of total vs. living fungi. The presence of microalgae associated with endolithic lichens will be identified from the paired ITS and 18S analysis. Fungal hyphae and endolithic lichens will also be confirmed using SEM and elemental analysis at the John de Laeter Centre, Curtin University. as well as electron microscopic imaging.	OK thank you
47	v	Detailed advance molecular approaches are described for analysis of the rock microbiome which are hoped to provide information on community composition, abundance and activity. There is no mention of the difficulties that exist in making such conclusions from the molecular data. Microbial community analysis is still a challenging and complex problem especially if attempting to interlink abundance and functional activity, and the heterogeneity of the sampling sites and influence of external variables make this particularly difficult. There is no inclusion of culture-dependent methods for analysis of rock inhabitants. Although there are well known criticisms of isolation methods as a means to interpret the community, such methods can succeed in isolation of dominant types that are active. Several studies have shown that isolated organisms are the ones that are the most active. Isolations would also confirm the existence of viable organisms capable of the metal-mineral transformations that are mentioned. What pollutants will be used in the aerosol chamber? These should be described.	As described in the proposal we will generate metagenomic assembled genomes (this can only be done for prokaryotes incl. cyanobacteria) and map the metatransciptomes to link active microbial processes with the key microbial members that are present. This approach is to the best of our knowledge not yet available or straightforward for eukaryotes such as fungi. However, the physiological properties of fungi can be predicted from PICRUST2 analysis as mentioned in the previous response. - See earlier response where we mentioned that cultivation of bacteria and fungi will now be undertaken and the deposition of iron and manganese oxides will be confirmed using SEM and elemental analysis at the John de Laeter Centre (JdLC), Curtin University. JdLC also offers courses for these type of analyses. We will test the main pollutants that based on multivariate statistical analysis show a significant correlation with microbial community shifts from samples obtained along environmental gradients. The most likely candidates are VOC's, nitrate, moisture, and sea salt exposure. The latter is now better explained in results from previous research section 2.1.3.	OK thank you
3.3.4 Organic Geochemistry				
48	i-vi	A variety of organic geochemistry methods are described in detail which will obtain much data but the rationale, aims and objectives for such determinations is not described, or what hypotheses they will support. Throughout examples of the kinds of compounds that may be encountered are not stated.	A 'rationale' section has been added for the organic geochemistry (Section 3.3.4 i, page 76) to address these concerns. Examples of compounds found in organic geochemical analyses of other sites have been added in 3.3.4.ii	OK
49	3.3.5	Again no specific examples of gases, particles, pollutants are	See answer to comment in 3.3.3.	OK

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		provided. What are the pollutants of interest? Where will such data come from?		
50	3.4.1 Prescribed monitoring	A detailed programme of monitoring is described for atmospheric condition and deposition. A range of "ionic species" is mentioned but what about non-ionic species and substances?	The study is designed around the species specifically listed in the original tender document. Other species of interest could be tested for in our deposition samples if required.	OK
51	viii-xiv	Detailed accounts of the sampling and analytical methods to be employed are provided that are wide-ranging and will provide key information on important variables and chemical species.	Acknowledged.	OK
52	**3.4.2 Source Apportionment (including isotopes)**			
53	i	Presumably industrial emissions are not constant in terms of delivery or composition? Is it possible or necessary to account for this? What are the inorganic isotopes mentioned?	The emissions will indeed be variable. It is not yet known if long term average emissions or peak emissions are more important with respect to the rock art. This remains a question to answer. Due to the remoteness of the site, much of the monitoring will need to be performed using passive (average) samplers. However active samplers will be used wherever possible, either in parallel or standalone. These measurements, together with Ramboll Plume and our own CFD modelling, can be used to determine transient/peak values across the entire study area. Specific isotopes have yet to be decided, however metals (Pb etc.) are likely the most promising. The above two issues will be finalised in the Part B document.	OK thank you
54	ii	A detailed list of possible instrumentation is provided for analysis of specific substances. It is not obvious whether all or some of these will be applied in the proposed study.	The plan is to utilise all instrumentation to give the most complete picture of emissions possible, however not at all sites due to constraints such as remoteness or lack of power. The site selection and instruments to be used at each site will be finalised in Part B.	OK thank you
55	3.5 Computational Fluid Dynamics Modelling	A variety of modelling approaches are described thoroughly that will be informed by data from other sources as well as that obtained in this study. This will provide useful information on the flow dynamics of emissions and specific classes of substances over the test area.	Acknowledged.	OK
4 Data Management				
56	4 Data Management	Appropriate mechanisms for data management are described. Are publications in the refereed scientific literature considered as part of the project outputs?	We aim to disseminate the outputs of the project broadly, this includes the scientific literature as this is the ultimate form of peer review. The project does not explicitly permit publication in scientific literature, however we have reached agreement with DWER and MAC to permit such publications, alongside public release of findings and data.	OK thank you
57	4.3 Microbiome	Other organisms such as fungi, including lichens, contribute to rock coatings not just bacteria. It is important that all relevant groups are considered. This is also important when considering dissolution where fungi are frequently the most active and significant organisms in rock and mineral biodeterioration.	This has already been addressed above	OK thank you
58	5 Summary	It is noted that several aspects of the proposal depend on work to be completed and that "a finalised and fully documented plan….can be developed and submitted for review and approval" which seems to undermine the validity of the current review. Any clarification of this point?	In order to properly and rigorously select the study sites, it was necessary to create a geospatial database that incorporated prior data as well as comprehensive air quality and source apportionment modelling that was only completed by an external party (RAMBOLL) in late 2020. Hence the decision to split the study design into the current (Part A) document and the forthcoming (Part B) document, which will detail the plan, study site locations and replicate numbers in full.	OK thank you
59	Concluding remarks	I note that "an evaluation of the previous monitoring program and scientific studies" was to be included in the Detailed Study Design. While many aspects are referred to, especially	As discussed above, both the project contract and other data needed in order to develop a "world's best practice" scientific study, required that the project plan be split into a number of parts - namely:	OK thank you

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		highlighting some of the drawbacks of previous work, it is not clear what parts of previous studies might be useful or at least provide useful information. Throughout the document, it is often unclear what hypotheses are being tested in the various sections and what will be the main conclusions drawn from the various analyses conducted. Perhaps this is just a consequence of the document style but such statements would greatly help understanding the reasons for the various analyses in answering the main question of the study rather than just a data gathering operation, which is the impression given in several sections. It is difficult to ascertain the proposed timeline for the actions described. In addition, milestones and deliverables are insufficiently specified. An overall Gantt chart/Table would have been useful with such indications and also how the component parts will be integrated to produce the final outputs. Some areas of study clearly reflect expertise within the group as evidenced by the detail in describing methodologies and approaches. The microbiome section contains some rather vague statements that are unsupported by a depth of referral to published information, on focus on specific phenomena that only represent a part of possible interactions. It is also ambitious to conclude that molecular techniques will provide all the answers. Such analyses are constantly changing and difficulties and bias in interpretations are well known. The heterogeneity of the sampling sites also provides great complexity along with the many environmental variables. The analyses will undoubtedly produce much data but whether they will assist in answering the main question could be difficult. Culture-independent studies are not included, while as mentioned lichens are not considered. The diverse communities that will be identified will undoubtedly show capabilities for metal acquisition, organic metabolism, organic acid production etc. but these are ubiquitous properties found in microbial populations from terrestrial habitats. Throughout the proposal, anthropogenic emissions and influences are referred to but the specific kinds of inorganic and organic pollutants are insufficiently described, while insufficient data is included about the levels and nature of such emissions from historical data that I assume was collected in previous studies. The emissions may clearly have different effects on mineralogical and microbial interactions depending on their nature and extent.	1. Conceptual Model (Previously submitted and peer reviewed) 2. Monitoring Studies Data Collection and Analysis Plan **- Part A (Current Document)** 3. Monitoring Studies Data Collection and Analysis Plan - Part B (Forthcoming) Items (2) and (3) essentially form the entirety of the study design document, however (1) explains many of the concepts/hypotheses of how the components fit together into an interrelated whole. The Part B document will include locations and quantities for all studies, including timeline (/Gantt chart) information. We understand that all reviewers will be provided with the recently released RAMBOLL air quality modelling study, which details dominant pollutant species. With respect to the microbiome: In the original proposal the microbiome section "Evaluation of Previous Studies section 2.1.3." mainly focused on what is known about microbe-patina interactions in the Murujuga region, but we now included more extensive background information from previous studies about patina-microbe interactions on geographically distant desert locations. We have now implemented the use of selective growth media to enrich patina associated microbes (bacteria and/or fungi) that are capable of producing Fe or Mn oxides under lab controlled conditions. Subsequent profiling of bacterial 16S and fungal ITS of the selectively enriched microbiome with those present on the rock varnish will verify that these microbes have the potential to be actively involved in patina formation in situ. Whether they were also alive on the patina at the time of sampling will be studied from the sequencing of the more labile (reverse transcribed) 16S and ITS transcripts. We agree that these physiological functions overlap between taxonomically diverse groups and therefore also occur in other habitats, but subsequent analysis of metagenome assembled genomes and mapping of the metatransciptomes will provide a holistic overview of what the key players are doing and what triggers their ability to colonize these rocks. That cannot be deciphered in such detail from the use of (selective) growth media alone. It is well known that only a tiny fraction of environmental microbial communities can be cultured so a comparison with the cultivation-independent molecular approaches is paramount. This is indeed a fast evolving field, however we are not sure why future modifications in molecular and bioinformatics approaches would influence the overall outcomes now and in the future. Most recently 2/3 of the bacterial domain has been reclassified (publicly available in the Silva138 database) and further drastic changes are not to be expected any day soon. In comparison, future adaptations in bioinformatic approaches will have a negligible effect on the interpretation of the data to be obtained now as part of the current study. In the revised version (section 3.3.3.) we now proposed to place sterile slabs at each sampling location during the first sampling expedition in year 1 and compare the newly colonized microbiome with those growing on the rocks (in situ) after we returned to the sampling locations in year 3. These slabs will be cut from one specimen of rock to eliminate rock fabric variability issues. They can furthermore be mounted in the same way at each site to reduce orientation effects. Moreover, this would enable spatial population differences to be determined in areas of different air quality.	

5.2 Prof. Geoffrey Gadd – Review comments sheet for Monitoring Studies Data Collection and Analysis Plan

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: Professor Geoffrey Michael Gadd	
Document Title: Murujuga Rock Art Monitoring Program: Monitoring Studies Data Collection and Analysis Plan	
Document Revision: Version 2.1 (September 2021)	**Revised version:** Version 2.2 (November 2021)
Date of Review: 28 September 2021	**Date of Close out Comments**: 1 December 2021

Item No.	Section No.	Peer Reviewer Comment	Calibre / Curtin Response	Peer Reviewer Close-out Comment
1		This plan has been extended and revised in response to previous reviewer recommendations and other changes and considerations. I find it very well detailed, especially regarding methodology and methodological considerations. The report "Study of the cumulative impacts of air emissions…" has provided detailed additional useful information. Some newer aspects have been added. I have a number of points and queries detailed below.	The Reviewer's comments are acknowledged, responses follow.	
2	throughout	A minor point is that "degradation" is used throughout in the context of rocks or even appearance. Degradation is a term that is more correctly used in the context of organic matter decomposition. Weathering/bioweathering or biodeterioration are more appropriately used terms for rocks.	Agreed. However MAC have stated they prefer the term degradation to refer to accelerated weathering or deterioration due to anthropogenic factors. We have clarified the text wherever possible and refined the glossary.	Thank you. The use of inappropriate terms just clouds precision. Why not just say accelerated weathering or deterioration? Could also use "abiotic" as an adjective. No need to use degradation at all unless it is referring to organic materials.
3	1.3.	A new Research Objective is "Determine if soil monitoring can be used as a more convenient sample source than measurements using rock". However, this at is insufficiently detailed or described in the plan, nor is this approach justified in scientific terms – I am unclear what soil measurements would be relevant to rock surfaces. What is being monitored? Pollutants? Any soil connections with rock microbiome for example? Soil is only mentioned in the Organic Geochemistry objectives. Hardly mentioned in Appendix 1 too. This does seem like an afterthought and I am unconvinced as to its value.	The inclusion of soil monitoring was in response to previous reviewer comments. However this component did not warrant full proposal development until we could determine if soil sampling was feasible. We have clarified the intent of soil measurements – which are included in the organic geochemistry section, as recognized by the reviewer, and also for the plutonium isotope pilot study. Additionally, the previous version stated "Additional soil testing will also be performed in a pilot study to determine the validity of using soil as a less-invasive sampling medium for processes or deposition occurring on the rocks. Noting, however that soil is scarce in many regions containing rock art." After the preliminary fieldwork, it is clear that interpretation of soil related data as a proxy for inorganic chemistry will be much more difficult than studying the patina itself because of a number of confounding factors, including that the soil is absent in places, transported in others, modified by vegetation, residual in places, subject to different weather regimes than the rocks because soil can experience overland flow. All of these factors reduce the value of a soil study other than that for organics and plutonium. This information has been included in section 3.3.2.x. We also intend to compare the microbiomes in nearby soils as a possible source of the rock-associated microbiome. The reviewer is correct in that this was not clearly outlined in the aims of the microbiome work. This is now listed as an additional aim (new aim 2) in section1.6.	Thank you.

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4	1.6.	Microbiome: phrasing - microbes are not just on surfaces but subsurface also. Mention is made of the rock varnish (forming and dissolving) here (and through the rest of the plan). It is still unclear to me whether the rocks and petroglyphs to be sampled have an overall varnish (note that difficulties in use of terms like varnish, patina, rinds etc. was highlighted in the last review). Please can you state clearly whether the rocks have a covering existing patina or whether only some do, and whether it is a heterogeneous covering? I am still unclear what is meant by varnish-dissolving organisms. I understand that once formed rock varnish can be very stable. Are “varnish-dissolving” organisms located on varnish surfaces or within/below?	Analysing the microbiome from the subsurface/underlying weathered rock has been added to the aims. With respect to the patina, all rocks have some patina (unless recently fractured) and this is highly variable. The surface topography ranges from smooth to rough to pitted to flaky. The texture ranges from flaky to matt to glossy. The colour ranges from pale orange to dark orange to burgundy to black, and the thickness ranges from effectively zero, with fresh rock clearly visible below, to over a millimetre. The weathered clay layer commonly separates fresh rock from the patina, and this is also highly variable. This text has been added to section 2.1.2. Apart from rare fractures and the rock art itself, the rocks in Murujuga are entirely covered with varnish. The coverage is heterogeneous. The rock art itself is carved into the lighter coloured underlaying weathered rock immediately below the varnish since this practice created the colour contrast between the rock art and the surrounding varnish-covered rocks. Note that we will not have permission and are not planning to obtain samples directly from the rock art. However as described later in the document, rock slabs with and without rock varnish will be exposed to the natural environment for two years and subsampled during wet and dry seasons to study the rate of microbial re-colonisation and changes in the community vs. functional genes and gene transcripts compositions in the context of changes in environmental conditions that will be measured and analysed in parallel. This has been added as a separate aim in 1.6. The reviewer is correct that the varnish is quite stable once formed but the hypothesis is that (especially during the wet season) the deposited organics and inorganics will become more easily accessible growth factors. We now expanded the background/current knowledge with preliminary results from McLeod, 2005. He performed plate counts of bacteria yeasts and fungi from Murujuga rock varnish (collected during wet and dry seasons) showing a linear relationship between the number of bacterial/yeast/fungal colonies and acidity of the rocks, stating that microbial metabolites were the most likely source of acidity. Furthermore, the number of plated bacteria increased during the wet season and with the amount of nitrate present. During the dry season the pH of the rock surface was higher and bacterial counts were extremely low while viable yeasts and fungi remained relatively abundant during both wet and dry seasons. No attempts were made to characterize the microbial communities. Our ITS/16S/18S barcoding combined with shotgun metagenomics/MAGs/metatransciptomics results will likely reveal which fungi and bacteria are expressing genes involved in the production of organic acids. Moreover, the time series experiments with the slabs to be positioned in the field will reveal the rate in which bacteria and/or fungi colonise the slabs. Field data will also be compared with the cloud chamber experiments. However, in McLeod’s 2005 paper, the fact that these bacteria were culturable in the lab was described as “being active” but it only showed that they were not dead at the time of sampling of course. Showing that bacteria express functional genes involved in e.g. the production of surface pH lowering organic acids (our proposed work) directly on the surface of the rocks goes a lot further in predicting their active role in these processes. This response is also relevant to the rebuttal raised for issue 20 below. The varnish can be quite smooth and thin and in that case the microbiome is more likely to be on the surface. However, closer to the coast where rock art is also located, the varnish can be quite	OK thank you

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		Answers to the above may influence the experimental approach and interpretations.	thick and, in that case, it is more likely that the microbiome is also embedded within the varnish layer. There is no need to adjust the experimental approach, but we have added a few exciting bioinformatics approaches that we can apply to the obtained shotgun metagenomic datasets: Metagenomic bins can be compared with reference genomes using MapDamage2 to determine post-mortem DNA damage, thus enabling us to distinguish between past vs. modern taxa. We will include GRiD, a tool that can infer the growth rate of microbial populations by measuring genome replication rates from shotgun metagenomic data including rare taxa with ultra-low sequence coverage (down to 0.2x). See our review (Capo et al., 2021 in Quaternary) for an overview.	
5	1.7.1.	It is noted that "colour change will not be of sufficient magnitude to provide meaningful interpretation in its own right." Presumably this means that any colour change determinations depend on their interpretation in the light of the other analyses to be conducted?	Agreed. These datasets will indeed be integrated and correlated using biostatistical approaches as described in the study plan. This answer is also provided in the related issues 7 and 17 below.	I see, thank you
6	1.7.2.	One point re elemental analyses is that total elemental determinations may not reveal elemental changes that may result from geochemical/microbial activity. Elemental analyses need to be viewed in conjunction with mineralogical analyses as elemental composition may not change but mineralogy can.	Multivariate statistical analyses will reveal to what extent the various mineral composition and other environmental proxy data, for example, shape the composition and genomic potential of the rock associated microbiome.	OK thanks
7	2.1.1.	Regarding spectrophotometry, it is not clearly explained what any colour changes inform about. Mineralogical changes, microbial colonization, physical weathering etc. could all be involved as mentioned before. It seems that interpretation of colour changes, other than denoting some kind of change in the substrate, are highly dependent on results obtained from the various geochemical and microbiome studies to be carried out which therefore attain greater importance.	We agree with the reviewer. All datasets will be integrated and correlated using biostatistical approaches as described in the proposal. For example, Pearson correlations may reveal to what extent changes in the microbial communities and gene functions/transcripts correlate with color changes. The reviewer acknowledged that we will make an effort to integrate the various datasets later on (item 17). Colour change is simply confirming that some measurable change has occurred. It does not contribute to an explanation of the mechanisms at play. Spectral analysis may contribute to that, but this remains to be developed.	OK thanks
8	2.1.1.	Fig 2.1 does show a change in 2020 though this is not marked in Figs 2.3a,b. Anomalies regarding these interpretations have been carefully described.		
9	2.1.2.	Difficulties in selecting suitable controls are appreciated. There are protocols for random sampling of sites in ecological and related literature, all with some kinds of problems. It could be that the best controls are biodeteriorated and deteriorated locations that are in close proximity at the site.	This could be good if it were possible to recognize this variation, but unfortunately it is not at this stage of our studies. The following text has been added to section 2.1.2: ". If possible, it might be useful to select bio-deteriorated and detoriated rocks from the same locality. However, preliminary fieldwork indicates that there is no clear difference amongst rocks at a locality that can be attributed specifically to bio-deterioation or detoriation at this stage of our studies."	OK thank you
10	2.1.3.	Regarding "patina" development there is considerable controversy whether organisms are wholly or even partly involved in the Mn oxide patinas, despite many organisms being capable of Mn and Fe oxidation. Patina development can also arise from other mechanisms, while black or dark-pigmented organisms can also cause blackening of surfaces.	There is accumulating evidence that extremophilic bacteria play a role in the very slow deposition of Mn and Fe oxides and the formation of desert rock varnish. However, we agree with the reviewer that the second hypothesis is more likely: the deposited petrochemicals and inorganic compounds may accelerate the growth of bio weathering fungi and bacteria that outcompete slow growing patina depositing microbes (if present). We are aware of dark-pigmented fungi and bacteria that can cause blackening of rocks. Pigment forming microbes are expected to be relatively abundant as pigmentation aids in the protection against UV damage. However, in our opinion they will likely appear as dark spots while the Mn oxides are heterogeneous and cover entire rock surfaces at Murujuga. We	OK thank you

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			will surely collect rock surface samples when they appear to contain overgrowth of dark pigmented colonies.	
11	2.1.3.	Primary colonization by phototrophs on rock surfaces does not have to take place for establishment of rock-inhabiting communities. Direct colonization by non-phototrophic bacteria and fungi is well known. The summary of photosynthesis is simplistic – glucose is used by the cells and does not get exuded for the colonizers. Various organic metabolites may be excreted. Lichens can grow on surfaces not just as endoliths which are different anyway and may be relatively simple lichenized fungi. While MCF are known colonizers of rocks and can cause pitting etc., they are very slow growing and such damage is localized to the colonies. Mechanisms are still not fully elucidated. A vast array of free-living fungi colonize rock surfaces – fungi are the most prevalent organisms of rock and mineral biodeterioration in the built environment for example. These are insufficiently discussed here as a contributory agent, as well as surface lichens. Nitrate can be assimilated by organisms for a N source. Use as an electron acceptor is generally under microaerophilic or anaerobic conditions since oxygen is always preferred by aerobes to nitrate. This section seems to overly focus on Mn-/Fe patina formation. Is there previous evidence that such a patina exists on rocks at the site? It seems that some of the mineralogical analyses that will be carried out are highly important in informing conclusions about the microbiome and its involvement.	We have revised the first paragraph of the background in 2.1.3. to address this comment. Lipid biomarker geochemistry (Grice) will determine to what extent the organic compounds are of natural origin (e.g. plant-derived) or pollutants from petrochemical industry such as VOC. We will use GC-MS and/or LC-MS to determine the composition and relative abundance of organic metabolites During our recent field trip we indeed sighted the presence of lichens/lichenized fungi especially on rock varnish but rarely on the carved rock art surfaces. Lichens will be sampled and the identity of lichenized fungi as well the consortium of associated algae and bacteria through ITS, 18S and 16S profiling. We acknowledge that the background may be an incomplete overview, but we will make sure that all our results including the role of the various identified fungal taxa and categories will be discussed properly in the context of the current state of knowledge. As acknowledged by the reviewer in his final remark, we expect to generate a wealth of data, once we get the green light to go in the field and collect samples for analysis. Please note that CI Coolen's expertise is in working with trace amounts of (ancient) eDNA as well as in analysing trace levels of gene transcripts by slow growing microbes from extreme environments. This will be essential to, for example, identify viable (gene expressing) MCF. We added relevant preliminary data from MacLeod 2005 as outlined in remark 4. It is common knowledge that oxygen is the most energy yielding electron acceptor followed by nitrate (under anaerobic conditions). The reviewer is correct that nitrate is more likely to be assimilated as an N source rather than serving as an electron acceptor. However, bacteria that may have colonized the weathered layer underneath the patina may be exposed to microaerophilic conditions acting as nitrate reducers. Albeit that anaerobic conditions are required: it may be worth exploring if microbially mediated coupling of nitrate reduction and Fe(II) oxidation occurs in the rock subsurface. The transcriptomes will tell which genes in the nitrogen cycling are being expressed. Moreover, our biostatistical approaches will determine to what extent the microbiome and which taxa are shaped by nitrate content. See earlier responses about integrating all datasets. We will be able to calculate to what extent microbial communities and functions are shaped by the in parallel measured categorial and quantitative environmental parameters. Except for carved rock surfaces and where there are fractions, the rocks at Murujuga are completely covered with varnish. We have recently obtained preliminary data on the mineral compositions of various patina types from pXRF analysis performed in the field. This is one of the tools to be used in the field to decide which samples to analyse.	OK thank you, nice responses
12	2.2.3.	Not only moisture but rock surfaces can trap airborne pollutants by nature of their texture. It is known that airborne deposition provides a source of nutrients, including use of metabolizable pollutants, and in some cases the pollutants themselves may result in surface blackening, e.g. soot, hydrocarbons.	This is what we will determine as well. We will also sample rock varnish during the dry seasons as well as from nearby soils as a possible source of dust and microbes that are associated with the rock varnish. Natural vs. anthropogenic organic pollutants will be analysed in parallel from lipid biomarker geochemistry. All data will	Since EPS is an undefined mixture containing proteins and polysaccharides and other components then multiple genes will be involved? More than for the known genes involved in e.g. an organic metabolism.

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		Dissolution of metal oxides by organic-acid producing fungi is well known. Fungal organic acids are a major cause of rock biodeterioration rather than EPS. Visualisation of hyphae within rock substrates is not a trivial task with several difficulties.	be integrated and correlated. We will be able to determine which taxa carry genes involved in the degradation of hydrocarbons/xenobiotic/aromatic compounds/PAH We will investigate whether both organic acid producing fungi and bacteria are present as well as functional genes and transcripts indicative of these processes. According to the preliminary results from McLeod 2005, during the hot dry season viable yeast and fungi predominate over bacteria (even talks about a "sterile" bacterial environment) with a general trend to higher pH values. Surface pH decreases during the wet season when both platable bacteria and fungi are abundant. This implies that bacteria in addition to fungi contribute to the formation of organic acids on desert rock varnish. Agreed. However, it will be easy to find genes involved in EPS formation and EPS can be measured and quantified in our geochemistry lab plus visualized using SEM. A colleague from UWA showed us electron microscopic images from Murujuga rock varnish with fungal hyphae. He is a geochemist and a co-CI on the ARC funded project that was funded around the same time as this project and is aimed to date the rock art of Murujuga.	How can EPS be visualized using SEM? Sample preparation results in destruction of EPS and artefactual appearances (often filaments). Do you mean Environmental SEM where samples can be viewed in hydrated state? I specifically referred to hyphae WITHIN rock substrates if this was the intention which might involve sectioning or other techniques. It is easy to see hyphae on surfaces or cracked/ fractured samples
13	2.2.5.	Acidity production by microbial activity. Does this mean a broad understanding of pH changes that occur or will the actual chemical components responsible for acidity be characterised? How will acidity changes in response to microbes or industrial deposition be differentiated?	We will and can analyze the organic metabolites using GC-MS and LC-MS at WA-OIGC under leadership of Professor Grice. Samples will be obtained along an environmental gradient of air pollution and industrial deposits. Surface pH will be measured, and we will attempt to test to what extent type and abundance of pollutants correlates with the microbial community composition vs. rock surface pH. The objective is to derive a broad understanding of the pH changes under a range of conditions.	I see thank you
14	3.1.3.	Do the pollutants in themselves have any significant effect on the rock, especially as atmospheric levels may be relatively low, especially in comparison with the elevated levels that would be used in such experiments? Would such experiments include organisms or be purely rock and pollutants?	The experiments will help us identify potential mechanisms which may lead to damage to the rocks. We would then need to determine if such mechanisms would be at play at the pollutant concentrations on site. This will also depend on what we find the significant pollutants/compounds to be. It may well be the case that if the necessary conditions are met, low levels of individual pollutants may have an impact. In any case, the exposure to elevated levels of pollutants in the cloud chamber experiments will reveal if exposure to real world conditions is likely going to cause long-term changes to the rock varnish geochemistry/ microbiome / colour inferred from spectral analysis. There may be some difficulty in in establishing links between lab experiments and natural processes on the rocks, but a knowledge of potential mechanisms that could harm the rocks will still be useful. There are clear examples of brown gypsum formation in shelters at Gariwerd National Park. Atmospheric SO_2 is considered the source and yet is in extremely low concentrations in that region. As outlined in the proposal, these experiments will involve tracking changes to the microbiome that is naturally present. We will not inoculate the rock surface with specific microbes as it is not representative of the field conditions. Moreover, expanding the number of variables will be logistically very difficult to do.	Thank you

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15	Table 3.2. and 3.3.	Would be extent of microbial/lichen colonization be another potentailly affecting factor?	Possibly, however lichen has not yet been recorded on rock art panels. We will investigate this however. Presence of lichens and other macro-flora will be noted in the MAC Condition Survey component of up to 2,000 sites	I see. The non-occurrence on rock art panels is interesting.
16	3.2.	This is a thoroughly detailed section. I have no comments.		
17	3.3.	The wide range of analytical techniques used should provide an abundance of data to inform models and contribute to answering the important questions. Integration with results of the other investigations is essential for a full picture and good communication and interchange with the responsible teams would be very productive.	Agreed. These datasets will indeed be integrated and correlated using biostatistical approaches as described in the proposal.	OK
18	3.3.3.	Is it just "rock varnish" that will be sampled? Is a varnish present on all the rock surfaces? I was under the impression that rock surfaces are heterogeneous and "bare" rock is present. The question "Does historical information exist about the nature of the rock surface regarding the presence and distribution of rock varnish, or other coatings?" was unanswered in the last review. One point is that a rock varnish may have a protective effect on the underlying material and such "bioprotection" has been considered for rock/mineral surfaces. Could this be a speculative aspect for preservation of the petroglyphs? Lichen colonization should be able to be observed visually on the surfaces. Does it occur to any extent? Again the work described focuses strongly on Fe/Mn deposition and microbial activity but this could be only one of many mechanisms that may occur, and may not in any case result in any biodeterioration. Metal acquisition is not the same as varnish formation. Metal acquisition refers to accumulation of metals within cells through transport; varnish formation is an extracellular biomineralization event. Is the soil monitoring, mentioned as an addition to this project, of any relevance to microbiome studies?	As mentioned in the revised proposal we will also sample the weathered rock below (see earlier response above) for e.g. microbiome studies. As mentioned earlier: Rock varnish is present everywhere except for the carved art and in the rare event of fractures. The varnish is heterogeneous, but the surface area of red iron oxide-rich rock varnish outcompetes the surface area of black coloured varnish rich in manganese oxide. As mentioned above, during a recent field trip, we obtained preliminary data on the rock surface mineralogy using a handheld XRF The mineral composition differs between rock types and location. Also, closer to the shore the patina is more weathered and thicker. During the latest visit to Murujuga there were a lot of sightings of lichens on rock varnish, but we have not been able to spot lichens on the rock art directly. Thus, as pointed out by the reviewer. The rock varnish may be susceptible to weathering by organic acids produced by e.g. lichenized fungi. Note that we added preliminary data from McLeod 2005 that confirmed the presence of organic acids on the rock surfaces and that the rock surface was more acidic during the wet than during the dry season. This data correlated with the number of culturable bacterial and fungal colonies during the wet season, while predominantly fungi were present during the dry season when the rock surface pH was higher. This suggests that bacteria could also play a role in the deposition of pH lowering organic acids. See earlier response to the same comment raised by the reviewer. The reviewer is correct that this was a poor choice. Fortunately, various microbial gene clusters involved in bio-mineralisation have been reported in the literature. If bacteria are present that have the genetic machinery for bio-mineralisation and/or express these genes it will likely be picked up from the sequenced shotgun metagenomes and metatranscriptomes.	OK What gene clusters and what biomineralization? There are many different mechanisms that can be involved in microbially-mediated indirect biomineralization and multiple genes in different pathways. for metabolite excretion, redox transformations etc.
19	3.4.	The cell cultures to be used are not specified. What are they and how selected?	These will be determined based on the preliminary results obtained in year 1. We think that the suggested slab experiments will generate more relevant information than the requested media-based cultivation experiments. The lab-controlled media conditions are namely not directly comparable to field conditions. In contrast, the slabs will reveal the rate in which bacteria and/or fungi start to overgrow the slabs during the two-year time frame and whether they have the genomic/transcriptomic potential to be involved in bio-weathering vs. formation of rock varnish.	OK
20	4.3.	Metagenome and metatranscriptome profiling will not determine "physiological activities" but indicates the functional potential of organisms which may or not occur at a given site. Activities have to be determined by other methods.	Physiological "activities" was indeed a poorly used term. The presence of functional genes only shows that the source organism has the genomic potential to carry out a process. However, due to the extremely short half-life of functional gene transcripts, their presence show that the source organism was alive and active at the time of sampling. Moreover, gene expression is an energetically costly process especially under these extreme conditions and under	OK thank you

Item No.	Section No.	Peer Reviewer Comment	Calibre / Curtin Response	Peer Reviewer Close-out Comment
			such circumstances it seems unlikely that genes are expressed when the cell has no use for it. Transcriptomics will also reveal whether the source organisms is in a dormant state (mainly expressing genes that are needed to stay viable) or if they are expression genes that are, e.g. involved in energy metabolisms/degradation of hydrocarbons etc. Proteomics would indeed prove that the transcript has been translated in a functional enzyme, but this is out of scope for this project. As mentioned earlier, we will be using GC/MS and/or LC/MS to identify and quantify metabolites, notable organic acids (i.e., "metabolomics"). Nevertheless, we now added the bioinformatics tools that can differentiate between past vs. modern taxa and estimate growth rates from metagenomic bins as outlined in an earlier response.	
21	6	The Summary is rather superficial. The main point stated is that the project "will provide a robust and resilient means of determining the response of the rock patina to air pollutants" which does not reflect all the projected outcomes and is also ambiguous depending on what is meant by the "rock patina".	The summary has been revised and expanded.	OK
22	Appendix 1	I am unclear why this is a separate entity rather than being incorporated into the main text body, but this is very well detailed and considers all the approaches to be used.	This was mainly due to different software R/LaTex, used to generate the document. They will likely be integrated for publication.	OK
23		<u>Concluding remarks</u> This version of the workplan is greatly extended and more detailed in response to previous reviewer comments and further considerations by the research team. Some aspects seem much more straightforward than others while some are extremely complex, e.g. microbiome studies which, although improved in this version, I still find rather unclear and insufficiently convincing. However I appreciate this is a difficult problem without easy answers, and am sure that useful fundamental information would be generated.	We hope that we addressed the most important issues raised. Regardless, we are convinced that with the sampling/experimental design (involving samples collected in real time along environmental gradients, time series environmental exposure experiments with slabs placed in the field vs. cloud chamber) we will be able to collect all the data needed to answer the (now expanded) research aims in the microbiome section. In the context of all other data collected as a team we will be able to determine which microbes (including lichenized fungi, MCP etc) are present and whether they are taxonomically related to taxa known to be involved in bioweathering of rocks and whether they carry the genetic machinery and actively express genes that point to their role in bioweathering such as the production of surface pH-lowering organic acids. To name a few. To summarize: we are convinced that we will be able to test all possible scenarios and to discuss them perfectly as a team in the context of the current state of knowledge in the respective fields by the time interim and final reports are required.	OK thank you

5.3 Dr Ron Watkins – Review comments sheet and close out report for Detailed Study Design (Part A)

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: A. Prof Ron Watkins	
Document Title: Murujuga Rock Art Monitoring Project: Detailed Study Design (PART A)	
Document Revision: Version 1 (July 2020)	**Revised Version**: Version 1.1 (January 2021)
Date of Review: 26 October 2020	**Date of close out report:** 9 March 2021

Item No.	Section No.	Peer Reviewer Comment	Response	Peer Reviewer Close-out Comment
1	2.1.2 2.2.2 3.1.1 3.1.2	**Geological mapping and sampling:** It is unclear as to the precise nature of the proposed geological mapping. Delineation of meaningful boundaries within large intrusive igneous bodies can be difficult at the best of times. The widespread development of the dark patina and the cultural sensitivities at Murujuga, may make detailed mapping both unviable and of little value. Narrow dolerite dykes are frequently recognizable and the locating of boundaries between major rock types is possible on the Burrup. However, any finer characterization will be most difficult. The presence of all three rock types, and textural variants, if that is the purpose of the detailed mapping, are unlikely to co-exist within a selected 100 x 100 m sampling site. With ubiquitous weathering/dark patina, lithological variations mostly become apparent only with hammering/breakage rock exposures. There are likely to be restrictions on repeated walking traverses over rock outcrops at Murujuga, which are required for mapping. Sampling itself, can be difficult on outcrops of massive rock, especially of the granophyre, and would normally require sledge hammering, coring, or worse (note the quarry on the northern end of Burrup is a notable exposure of “fresh” rock). Small samples of the weathered surfaces may be non-representative and hard to acquire without coring of sawing. It may be most feasible, in the case of sampling for inorganic geochemistry, to sample “disturbed land” where more realistic sampling protocols and sample sizes are possible.	Mapping will proceed with the aid or a portable XRF instrument (PXRF) to aid recognition of rock units where the details are obscured by the patina. The 100 x 100 m selected map area we chosen to characterise the vicinity of the samples, and the number of rock types within that area is immaterial for the purposes of the project. Sampling will proceed using a diamond coring bit, 25–40 mm diameter, attached to a battery-powered angle grinder or drill. This enables sampling of the selected site and removes the need for hammering. Site selection will be guided by the MAC rangers to be as unobtrusive as possible, and this might include disturbed land, where sampling protocols are less restrictive and larger sample sizes are possible. This text has been added.to the relevant sections.	The main variations present in different “facies” of major granophyric igneous intrusions are generally textural (e.g. overall grain-size, presence/absence of phenocrysts, mineral orientation reflecting flow and lamination, chilled margins of intrusive lobes, etc.). Such textural features would likely impact upon the development and character of the weathering rinds. However, there is most commonly little or no measurable geochemical differentiation. Consequently, any response from PXRF may be of little value as a mapping aid where the selected area to be mapped contains solely granophyre. Responders have made clear that the proposed geological mapping of the 100 x 100 will neither be chosen to, nor expected to, include, more than a single major rock type. Text has been included in the revised Part A document that makes clear the proposed sampling protocols. The discussed use of a diamond coring bit may be viable, but in my experience can be difficult in practice where only shallow thicknesses of rock are to be extracted. There may also be complaints that regular-shaped (i.e. circular) depressions/holes over rock outcrops are more disfiguring that (more natural looking) hammered breakages. I imagine this would almost certainly be the case with proximity to petroglyphs. Collection from disturbed ground is certainly the least intrusive option, especially if agreement is given to return all remains of removed rock samples post study. I can see little impediment to use of rock from disturbed ground in laboratory inorganic geochemistry studies. However, it is evident that this approach may be unsatisfactory where close continuity is essential between inorganic geochemistry, organic chemistry, and other aspects of the proposed research.
2	General	**Marine aerosols:** There is little or no mention in the Study Design of the influences of marine aerosols, despite the exposed coastal location of Murujuga. It is true that such influences have been effective throughout the history of the petroglyphs, and so form a constant “background effect”, but even in this regard the future climatic change (sea-level rise, increased frequency of storm events) might suggest marine aerosols may be a variable factor worthy of consideration. They are almost certainly a prime transport medium for inorganic and organic components to the rock surfaces, including marine pollutants. It is	Noted and added to the sources of variation table. "7 Exposure to marine aerosols Marine aerosols probably transport inorganic and organic components to the rock surfaces, including marine pollutants. Wet and dry salt deposition and subsequent “refluxing” through wetting and drying cycles might physically destabilize rock surfaces. The evaporation pans at the salt works are in close proximity to petroglyph sites and are a specific potential source of marine salts. Cl, SO_4 and Br as ingredients in the surface films provide the potential for formation of additional secondary chemical and mineralogical phases, and effects on pH. Unknown High. We have observed differences in the patina as a function of proximity to the	The need for appreciation of the potential role of marine aerosols in the rock surface geochemistry is now made. It would be instructive to state the nature of the differences in the patina as a function of the proximity to the ocean that have been observed - e.g. solely colour or otherwise?

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		mentioned in the document that gypsum crusts may physically destabilize rock surfaces and the same would be true of wet and dry salt deposition and subsequent “refluxing” through wetting and drying cycles. The evaporation pans at the salt works are in close proximity to petroglyph sites and are a specific potential source of marine salts. Cl, SO_4 and Br as ingredients in the surface films provide the potential for formation of additional secondary chemical and mineralogical phases. Their effects on pH similarly cannot be overlooked.	ocean."	
3	1.6.1 and elsewhere	**Nature and definition of weathering zones:** The often-related picture of weathering of petroglyph bearing rocks, i.e. a very thin dark patina overlying a thicker pale weathering zone, is for most part correctly portrayed in the Detailed Study Design. However, it can be misleading by implying a greater uniformity in the nature and relationships between patina and weathering rind than exists. In practice, these zones are complex and highly variable. The patina can be at least 4 mm or more in thickness upon gabbro (not sure about dolerite), whereas the leucocratic weathering rind is far from ubiquitous, especially on granophyre. For example, granophyre outcrops above the quarry, not too distant from rock art sites, have a strong orange-coloured patina yet near absence of an underlying pale zone. The boundary between patina and rind may be sharp and distinctive, or irregular and/or gradational. Patina and weathering rind often appear as an “overprint” to the residual mineralogy of the underlying rock and are consequently most heterogeneous on the micrometre scale. Such complexities can make delineation between patina, weathering rind and “fresh rock” fraught with difficulty and have implications for the veracity of the surface inorganic geochemical variation and elemental relationships, as may be determined by field XRF (see points 4 and 6).	Agreed. Text added to variability table. 8 Different thicknesses and geometries of clay and patina layers The boundary between the patina and clay layer might be sharp or gradational, and the thickness of the clay and patina layers is highly variable. The patina can be absent to 4 mm thick and the clay layer can vary from 0 to ~20 mm thick. The boundary between patina and rind may be sharp and distinctive, or irregular and/or gradational and are commonly heterogeneous on the micrometre scale. Impact low if sampling is sufficiently representative."	This aspect of the weathering rind and patina geometries has been satisfactorily summarized in the revision.
4	3.2.3ii	**Field geochemical analysis:** Use of portable XRF is fortuitous in being a practical means of non-destructive inorganic geochemical analysis in the field. The technology has advanced significantly in the last decade, but I wonder if the capability to address issues relating to patina composition and associated surface colouration is sufficient, a concern shared by the authors. There is no doubt that the array of laboratory instrumentation has great potential for inorganic geochemical characterisation of the patina and weathering rind with capability to determine mineralogical and chemical variation on the sub-micrometre scale. There remains, however, a fear that the effective detection limits for each of the 15 required elements at an appropriately small beam size will not be sufficient to meet the aims of the project with regard to petroglyph chemical stability. The stated model in which bulk transport of Fe and Mn into and out of the patina is the prime constraint on variation in red/brown and purple/black colouration may be wrong, with overriding influences from the microbiome. In the inorganic sphere alone, variations in the mineral speciation, degree of crystallinity of low-T Fe- and Mn-compounds, or variations in elemental concentrations below the detectable ~10 ppm limit may account for the colour variation.	Portable XRF has limitations in terms of detection ;limits and therefore cannot be considered a viable instrument for elucidating mechanisms. If operated within its detection capabilities, typically relying on results that a 5-10 magnitudes above LDL, then it has a role. Its unique role in this research is that it can tale measurements on surfaces that the destructive techniques cannot. These non-destructive investigations can look at seasonal surface flux for example. Much emphasis has been placed on self evident pollutant loads falling on rocks. Less study has been undertaken on the tenacity of such deposition in seasonal terms. A surface with a high loading of any element only becomes an issue if that element dwells for long enough to cause change and this will be determined by flushing cycles and the solubility of any formed minerals. The pXRF is being proposed as an aid to colorimetric studies in that it can describe in elemental terms differences in colour values. It is also more opportunistic where a variation in a surface lies outside the prescribed targets set up for colorimetric measurement, to provide an understanding of general colour variation trends and to quickly characterize features of interest. pXRF is best described as an opportunistic investigative tool with detection limits too high to investigate subtle chemical balances.	That geochemical analysis by pXRF is non-destructive and is thus one of few approaches to inorganic geochemical measurement that will not disfigure the area of the petroglyphs is not in question. From their response, Puliyapang clearly are not naïve with regard to the limitations of the pXRF technique. If pollutant loadings on rock surfaces do vary in concentration by 5-10 magnitudes and are in the working range of the pXRF, use of the instrument couldl be most valuable. I can see how the technique’s role in elucidating the nature of patina colour variation would be similarly valuable, if the geochemical variation is sufficient. My comment was made in order to warn against over-confidence in the overall potential value of pXRF in geochemical measurements relating to weathering rind/patina formation. It is to be accepted that the unique nature of the Murijuga investigations will call for the trial of a variety of analytical approaches which will inevitably disappoint on occasion.

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5	3.2.3ii	**Application of trace elements and equilibrium thermodynamics:** I am unsure that the suggested use of trace element ratios between conservative and reactive trace elements is possible in the weathered zones. Zr and Nb are unlikely to have homogeneous distribution in the patina or weathering rind given their presence in the underlying rock in rare residual minerals and their strongly conservative character. As is discussed by the authors, I concur that the use of equilibrium thermodynamic data and phase modelling (e.g PHREEQ) to underpin patina/weathering rind chemical speciation will be severely limited given the multitude of ways in which the chemical systems deviate from the equilibrium condition (e.g. they are open systems, are biologically catalyzed and involve organic components, are clearly low-T and non-equilibrium systems, etc.).	Comment on thermodynamic modelling seems to be an agreement rather than a request.	True.
6	3.4.1	**Atmospheric monitoring:** The practical benefits of diffusion cartridges and passive atmospheric sampling are well put. The limitations are equally well stated. I feel this approach <u>will</u> limit the recording of industrial and transport emissions occurring on a short time-scale. Industrial emissions, to date, on the Burrup I believe have by nature been transient. This reflects to an extent the initial stages (construction and testing) of the installations and in future may become more stabilized. Nevertheless, with further additions to the industrial plant, the anthropological emissions are likely to remain episodic and therefore not fully recognized by passive sampling at 4-weekly interchange of cartridges. The use of constant NOx monitoring is thus most beneficial and employment of the AIRBOX, as described in the document, appears central to the monitoring program. The normal prescribed emission monitoring by the companies is most valuable to the project, and the data will need to be made available to the project scientists on a timely basis.	Noted and agreed. Ideally all monitoring would permit greater temporal resolution, however we are limited by both available power/infrastructure and the need to minimise site disturbance. If the AIRBOX study identifies significant short term events, establishment of permanent powered monitoring stations will likely be implemented.	There appears to be general agreement between the authors of the document, myself, and other peer reviewers, that the use of high temporal resolution of airborne contaminants should be a high priority when the research budget is finalized.

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8 March 2021

Government of Western Australia
Department of Water and Environment Regulation

Attention: Naomi O'Hara
Senior Environmental Officer Policy Environmental Policy
Locked Bag 10 Joondalup DC
Perth WA 6919

Dear Naomi,

Close out report: Murujuga Rock Art Monitoring Program - Peer review of Monitoring Studies Data Collection and Analysis Plan PART A

I have reviewed the revised version of the Part A document with respect to each modification stated in Puliyapang's response to my peer review on the Inorganic Geochemistry within the Monitoring Program. I have provided brief close-out comments on the attached document 01.

I have further reviewed the comments made by Murujuga Rock Art SRG (Document 02 Stakeholder Reference Group comments – collation of comments) and those made by MAC, and DWER and DBCA (collated) (Document 03). I provide a response below to comments in these two documents where they relate to the Inorganic Geochemistry component of the Monitoring Program.

Murujuga Rock Art SRG (Document 02)

Item 1 - General: "there is need for a good mechanistic model to show how the patina is made and dissolved and test hypothesis and findings".

Puliyapang's response*:* "The need for a mechanistic model is noted and its development is now mentioned in section 1.5.3".

I see no mention of a mechanistic model in the revised Part A document. Possibly this statement was superceded by Puliyapang's response in the review by Dr John Black?

Item 2 – Evaluation of previous studies and data:

The work of McCloud 2005 is important in indicating the effects of anthopogenic and possibly other deposits on the rock surface in the vicinity of petroglyphs at Murujuga. I was remiss in not referring to this research in my initial peer review. In the revised document, mention of this work is made only in sections relating to the microbiome. It is most directly related to inorganic chemical systems and reference should be added to the section on inorganic geochemistry.

I believe the comment by Dr Black that "…. show 1000-fold increase in acidity compared with rocks collected pre-industrialisation of Murujuga (MacLeod 2005") refers to a 3 unit variation in pH recorded in distilled water held in contact with the rock surface. In normal usage, "acidity" refers to the overall quantity and type of acid present. So,while in equilibrium, pH is one parameter controlling the stability of a chemical phase in solution, it is a poor indicator of the actual scale, rate and overall result of a chemical reaction. pH may be viewed as an effect, rather than a quantity.

McCloud's work very much deserves testing, development and expansion. To a significant degree, results of monitoring of surface deposition will enable quantification of the acid present. Even so wetting/drying, spatial concentration, and saturation, will all play a role and need to be studied. Evaluating the relationship between the pH, as measured by McCloud (2005) and the effective acidity is difficult. Multiple samples for use in laboratory experiments are required. However, rocks from non-culturally sensitive sites can be used and the experimentation/measurements are non-destructive, allowing subsequent return of material to Murujuga.

Item 4 - Development of a mathematical model:

While I do not doubt the assertion that a mechanistic model may assist in identifying hypotheses and focussing future studies, I think it highly doubtful that such a model could be formulated at this early stage in the development of the Monitoring Program. While inorganic chemistry may lend itself to such a model, albeit with major assumptions of the bounding equilibrium conditions, the organic geochemistry associated with living systems is, by definition, non-equilibrium. In the presence of microbes, it is unlikely that any chemical reaction involved in patina growth or decomposition is 100% inorganic. Accordingly, inorganic chemical systems alone can only partially, at best, reflect a model for the development and decomposition of the patina. In this light, Puliyapang's response appears appropriate.

MAC (Document 03)

No responses by MAC refer specifically and solely to the Inorganic Geochemistry component of the Monitoring Program.

DWER and DBCA (collated) (Document 03)

Item 5: Section 1.1 – Study objectives – ultimate goal and guiding principles

In over 20 years of teaching Environmental Geochemistry (to students and industry) and in governmental reports, I have used the following definitions that I suggest may assist in the clarification requested by the DWER reviewer.

Contamination = *a concentration greater than the natural background*

Natural background = *the amount of a substance or an effect occurring naturally at the Earth's surface free from the influence of past human activities*

Pollution = a degree of contamination producing recognisable detrimental effects on the health of humans or other living things

Item 7: The DWER comment and Puliyapang response may imply that all laboratory studies should sufficiently reflect the real world. Such a philosophy, I suggest, is misguided and probably not meant. What is critical is that there should be no uncertainty as to the degree to which the results of laboratory investigations can, and do, reflect the external situation. Many very useful studies are undertaken in the laboratory to elucidate inorganic geochemical behaviour while involving conditions different from nature. Proposals for any laboratory study should account for the limitations of the results if extrapolation to the "real world" is proposed.

5.4 Dr Ron Watkins – Review comments sheet for Monitoring Studies Data Collection and Analysis Plan

MURUJUGA ROCK ART MONITORING PROGRAM

Independent Peer Review Comments Sheet

Reviewer: A. Prof. Ron Watkins	
Document Title: Murujuga Rock Art Monitoring Program: Monitoring Studies Data Collection and Analysis Plan	
Document Revision: Version 2.1 (September 2021)	**Revised version:** Version 2.2 (November 2021)
Date of Review: 22 October 2021	**Date Of close out report**: 19 January 2022

Item No.	Section No.	Peer Reviewer Comment	Response	Peer Reviewer Close-out Comment
1	Exec Summary	Para. 5: The use of “droplet” is likely confusing. Particulate i.e. dry deposition of air pollutants consists significantly of solid chemical particles. Droplets would be important in the form of liquid aerosols. Para.8 Pt.3 (and throughout): A common definition in environmental geochemistry of “pollutants” is substances that are present in such concentration as to cause detriment to living things and the environment. Given the second part of this sentence, a more precise term would be “contaminants”, since the use of “pollutants” could be seen as unnecessarily judgemental.	Revised	✓ The point about use of “droplet” has been successfully resolved. ? No action has been taken on the (I believe unfortunate) use of “pollutants”, but significance remains to be seen.
2	1	Para. 5: “includes”	Revised	✓
3	1.2	Para.3 dot pt: this statement intimates that the running of the monitoring program - results of which are the basis of the EQMF - will be eventually run solely by MAC. Administratively, this may be true, but in practice the monitoring will require individual expertise and QA/QC of wide variety that it is unlikely to exist entirely within MAC and the rangers/monitoring personnel. Possible “in collaboration with Curtin/external specialists” might usefully be added.	Revised. The ongoing monitoring while run by MAC/DWER, may be contracted out to a third party with the appropriate expertise.	? ✓ I s an administrative matter rather than a scientific one
4	1.3	pt 3: “degradation of, or change in, the petroglyphs”	Revised	✓
5	1.5	pt.2: meaning unclear	Revised	✓
6	1.7	Pt. 1: requires obvious limitation - “selected”, “typical”?	Revised	✓
7	1.7.1	Para. 1: allow	Revised	✓
8	1.8	Para. 1 Pt. 1: “sufficiently many”? - sufficient? Pt.2 (and throughout): if you are stationary, the topography cannot change. “highly variable”? “irregular”?	Revised	✓ ✓

Item No.	Section No.	Peer Reviewer Comment	Response	Peer Reviewer Close-out Comment
9	2.1.2	Para. 2: to Para. 6: ambiguity. "collected subsequently (Black *et al.*, 2017)."	Revised	✓ ✓
10	2.1.3	Para. 1: capitalization of "iron" incorrect in both instances. Para. 2: Long sentence is missing some words and punctuation. Para. 5: "also remains"	Revised	✓ ✓ ✓
11	2.1.5	Para. 3: Surely the effect of NOx and SOx, and of organic acids will be to <u>increase</u> acidity. Or did the author mean "decrease the pH"?	Revised	✓
12	2.2.2	Para. 1: What kind of "mechanical information"? requires clarification. Para. 2: Both? - sentence requires re-writing.	Revised	✓ ✓
13	3.1.5 b	Para. 2: "within" or "in"	Revised	✓
14	3.2.1	Para. 12: "owing"	Revised	✓
15	3.2.2	Para. 11: informal/unusual phrasing for a scientific document	Revised	✓ RW also made one further change "is" to "are"
16	3.2.3	Para. 23: replace "Mineralization of this type" with "Crypto-fluorescence"	Revised	
17	3.2.4	Para. 2: Appears that a previous text may have been pasted in without regard to the tense. Paras. 2,3 and 4: these paragraphs very largely describe the methodology of McCloud and Fish 2021. It would be better to state that the methods used by these authors will be employed, and then to critique each method and suggest how each might be "independently validated". Given the stated (in this document) importance of pH in the control of inorganic (and no doubt organic) chemical reactions, a more considered and detailed discussion of the planned evaluation of pH measurement is highly desirable. A considerable variety of approaches are possible and such detailed reliance here on the one method McCloud and Fish 2021, would seem to be limited and irrational. The proposed technique for redox measurement requires similar scrutiny.	These are valid comments. The section has been rewritten to reflect the intended method development for pH and Eh measurements.	✓ ✓ the amended text makes clear the limitations of the proposed means of recording the various electrochemical data. ✓
18	3.3.1	Para. 1: "inorganic and organic chemical methods" omit "perhaps" In light of the stated equivalence of rock surface processes between petroglyph-bearing and non-bearing rocks, it seems misguided for the authors to be so limiting in the quantity of rock to be collected. To my knowledge, there are	Para 3. Clarified with new text "Larger samples will be taken for the gabbro, which is coarse-grained, so larger samples are required to ensure a representative sample at any locality."	✓ sampling regime has been clarified

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		numerous locations, including a granophyre quarry, outside of culturally sensitive areas, or disturbed ground, such as in the vicinity of infrastructure, where significant quantities of the main rock types could, with MAC/elders' permissions could be collected. Standard practice of returning unused sample after analysis can be employed. Para. 3: "organic and inorganic chemical" "samples will be taken" It is not clear whether the stated minimum sample size refers to whole rock samples or rind/varnish samples. 25g would be too little to ensure a representative sample of the gabbro and much of the granophyre rock		
19	3.3.2	Para. 7: "using" Para. 11: why not MnO? Para. 12: matrix-matched what? Para. 31: "to answer construct" - meaning?	Para. 7: "using" – unclear what is requested Para 11: MnO added Para 12: Matrix-matched standards Para 31: can't find the error, might already have been fixed	? suggested change of text has been made by RW ✓ ✓ ✓ yes, error has been corrected
20	3.3.3	Para. 1: Use of a Dremel tool may be viable for removal of relatively soft exterior organic material. However, my personal experience is that it is of only limited use in removing the rock patina quantitatively and without contamination from the tool bit. Para. 8: reference error message! Para. 13: "obtained to" Para. 14: "mapping'	Acknowledged. We typically use a diamond wheel on a slightly more powerful device than Dremel. It is battery operated and portable. The diamonds will not contaminate the sample if a suitable buffer is allowed for. Revised.	✓ ✓ these 3 errors appear corrected during rewriting
21	3.3.4	Para. 11: Again, use of rocks from culturally benign and disturbed ground might be considered?	This has been considered and more rocks will be obtained from such areas if needed. However there are only one or two such locations and they are proximal to each other, therefore they do not give an appropriate spectrum of pollutant exposure history.	✓ comment was informational only
22	3.4	Para. 2: "Both systems (Figs 3-14 and 3-15) are designed …." Para. 6: "will be"	Revised.	✓ ✓
23	3.5.1	Para. 1: the last sentence of the paragraph is incomplete pages 84-87 include numerous typo errors. re: *External Labs*: "variety of United"	Revised.	✓ ✓ RW has made two additional text corrections ✓
24	3.6.1	Para. 3: reference error message	Corrected.	✓
25	3.7	Para. 17: "for the" ? Para. 21: these ~~them~~ Para. 32: recent and data ?	Revised.	

Item No.	Section No.	Peer Reviewer Comment	Response	Peer Reviewer Close-out Comment
26	4.1	Para. 2: correct the sentence	Corrected.	✓
27	4.2	Para. 2: strange font	Amended.	✓
28	App. 1.2	Para. 5: not only microscopic. Weathering rind may be > 10 mm thick and the 'fresh' rock beneath is also to be studied Para. 8: "rock surface"	Revised	
29	App. 7	Para. 1: I question why physical samples for the inorganic geochemistry study will be collected on only one occasion. For a research program of this size, such a limitation would seem impractical and a hinderance to the successful undertaking of the study. Analysis of the first sample collection, inevitably will give rise to questions that require further sampling/analysis to address.	The study design permits additional samples to be collected in a second round of the studies phase (2nd year) if necessary. However at this stage we have no evidence to suggest this will be necessary (or otherwise).	✓ Appendices were not included in corrected/revised document. 'Puliyapang' response is satisfactory.
30	General comment regarding Inorganic Geochemistry	The proposed inorganic geochemical investigations are comprehensive and there is a clear recognition of the limitations of most techniques to be employed. The availability of a wide range of sub-microscopic instrumentation is a particular strength. Possible weakness in the planned research lies in two areas: 1. Rock sampling: I suggest the proposed sampling program is too conservative in terms of number of samples, number of sampling events, and sample size. This is no doubt designed to provide the minimal impact on the culturally sensitive terrain. However, considerable use may be made of rocks from areas of low, or no, cultural significance and areas of disturbed ground, including in areas outside but adjacent to the National Park. In these cases, the ability to work on a larger sample suite may outweigh any disadvantage of less precise provenance. 2. While it is recognized in the document that pH (and Eh, dissolved ions) of the rock surface and shallow interior is a crucial constraint of processes affecting patina growth and dissolution, little emphasis is placed in the planned study of the measurement of these parameters and the relevance of the results. In particular, it appears illogical to initiate the use of the specified methods of measurement in research and monitoring programs before detailed efficacy of these, and other, techniques and the relevance of the measured results have been fully evaluated.	1. N=64 sample rocks have been identified during preliminary site selection, which, combined with preliminary samples from disturbed areas will amount to 80-100 samples, which will be analysed in triplicate. 2. The number of samples will be 80 to 100, which is far larger than any other sampling program on the Burrup. I'd be interested to know the grounds for the assertion that the number of samples is insufficient. Regarding sample size, the value of 25 g is a minimum, and larger samples will be taken where possible, depending on the technique agreed with MAC. 3. There are issues around the field monitoring of Eh and pH related to the time taken for the systems to reach equilibrium. If equilibrium has not been reached then the use of thermodynamic equilibrium diagrams to interpret the processes is invalid. For this reason, additional work is necessary to clarify how Eh and pH measurements can be interpreted, and this additional work has been clarified in the modified text (section 3.2.4).	✓ I believe a lesser number was stated in the initial document or I was referring to the stated absence of the possibility of follow-up sampling after the one collecting trip originally stated ✓ This question has now been addressed in the document.