Project Order

Proforma 2021

1. Short Project Title

Fate of hydraulic fracturing fluids/chemicals and geogenic hydrocarbons in surface facilities and in the subsurface

Long Project Title	A systems-approach to understanding subsurface and surface fates of hydraulic fracturing fluid chemicals and geogenic hydrocarbons
GISERA Project Number	W.26
Start Date	01/07/2021
End Date	31/01/2023
Project Leader	David Midgley

2. GISERA State/Territory

- ☐ Queensland
- ☐ New South Wales
- ☒ **Northern Territory**
- ☐ South Australia
- ☐ Western Australia
- ☐ Victoria
- ☐ National scale project

3. Basin(s)

- ☐ Amadeus
- ☒ **Beetaloo**
- ☐ Canning
- ☐ Carnarvon
- ☐ Clarence-Morton
- ☐ Cooper
- ☐ Eromanga
- ☐ Galilee
- ☐ Gippsland
- ☐ Gloucester
- ☐ Gunnedah
- ☐ Maryborough
- ☐ McArthur
- ☐ North Bowen
- ☐ Otway
- ☐ Perth
- ☐ Surat
- ☐ Other (please specify)

4. GISERA Research Program

- ☒ **Water Research**
- ☐ Greenhouse Gas Research
- ☐ Social & Economic Research
- ☐ Biodiversity Research
- ☐ Health Research
- ☐ Agricultural Land Management Research
- ☐ Other

5. Project Summary

Objective

Community concerns about hydraulic fracturing processes and chemicals are widespread in areas where unconventional gas is produced. For chemical safety, previous reviews, and industries own chemical assessments have identified a group of compounds as having potential environmental and human health impacts (Australian Government Department of the Environment and Energy Reports 2014, 2017). The current study will examine the subsurface migration properties along with degradation and biodegradation (in the subsurface, in flow-back water, holding tank and treatment pond settings) of a group of chemicals previously identified as being of high risk to the environment and human health. The list of chemicals examined in the present study was drawn from Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Beetaloo GBA region report (Kirby et al., 2020) and were determined by this assessment to be of ‘particularly high concern’. At the time of writing the chemicals proposed for examination in this study include: tributyl tetradecyl phosphonium chloride, glutaraldehyde, 1x model ethoxylated- and 1x model propoxylated- alcohol along with coco alkyldimethyl oxide and previously uncharacterised pools of geogenically-generated hydrocarbons, though the final list of key chemicals will be determined through consultation with stakeholders during Task 1.

To achieve these goals this project has two major components; the first aimed at understanding the movement of these compounds in the subsurface and the second seeks to understand the fate of chemicals returning to the surface in flow-back water.

<u>Major Objective 1: Led by Mr. Nicholas Lupton</u>

Understand subsurface movement and abiotic degradation of key chemicals used in hydraulic fracturing fluids in the shale reservoirs of the Beetaloo sub-basin.

<u>Major Objective 2: Led by Dr. Se Gong</u>

A) Understand the fate (abiotic and biotic degradation) of key chemicals used in hydraulic fracturing fluids when they return to the surface in flow-back waters that are held in tanks and treatment ponds.

B) Understand and forensically characterise the unknown fractions of geogenic hydrocarbons produced during hydraulic fracturing in the Beetaloo sub-basin and their fates in surface facilities (tanks and treatment ponds).

Description

Outcomes from the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory revealed public concerns regarding hydraulic fracturing. In addition, the Inquiry made a number of recommendations that aimed to reduce the environmental, social, health, cultural and economic risks associated with hydraulic fracturing in the Northern Territory. This project aims to contribute to the Inquiry's recommendations by providing a systems-approach to understanding key risk chemicals and their lifecycle during fracturing, in flow-back waters and in tanks and ponds in industry facilities. In particular, this project will provide an understanding of the degradation (both abiotic and possibly biological) and transport of these chemicals within the subsurface. In addition, this study will examine the flow-back water produced after fracturing and provide information on the concentrations of unknown geogenic hydrocarbons and the key chemicals (identified in Objectives above) being returned to surface. Further, this study will provide insights into the biodegradation of these chemicals and the geogenic hydrocarbons in flow-back water in holding tanks and ponds in industry facilities in the Northern Territory. Taken together, these data will provide key information for assessing chemical risks associated with hydraulic fracturing.

In order to accomplish these aims, the project will undertake engagement with stakeholders from government and industry to finalise the list of compounds examined in the present study. Field work will collect samples from Tanumbirini and Kyalla sites including samples of fracturing fluids and flow-back water held in tanks and water in treatment ponds. For microbial degradation components of this work specialist collections and preservation techniques will be used. Representative shales will be obtained from core libraries for the subsurface components of this work. These core samples will be subject to experiments under reservoir conditions (e.g. relevant atmospheres, temperatures and pressures) to investigate abiotic degradation and transport in the subsurface, and under relevant environmental temperatures in oxic or anoxic conditions in order to understand the following phenomena.

1. Reservoir fate of residual hydraulic fracturing fluids

After hydraulic fracture treatment of a well, there is a period of production called flow-back where fluids are produced. This recovers a proportion of the hydraulic fracturing fluids leaving a residual within the reservoir. This task would investigate the fate and transport of the residual hydraulic fracturing fluids within the reservoir. This is determined by a range of properties, many of which are strongly influenced by the specific *in-situ* conditions associated with the sub-surface environment. While there have been studies on the fate of hydraulic fracturing fluids for the Australian context these have used properties from the scientific literature (i.e. Mallants et al., 2017). This task would add significant value to the understanding of the degradation and migration of residual hydraulic fracturing fluids by measuring key properties for these processes under reservoir conditions of pressure, temperature, and formation water chemistry for the Beetaloo sub-basin using geological samples from that basin. The derived properties would then be used in representative migration modelling case studies to investigate the fate and migration.

2. Microbial degradation of hydraulic fracturing fluid chemicals in surface facilities (tanks and ponds) and the generation of geogenic hydrocarbons in flow-back water and their fate in surface facilities.

Hydraulic fracturing uses a range of biocides and surfactants to enhance the effectiveness of the process or to inhibit unwanted microbial growth. These compounds return to the surface in flow-back water and are stored in enclosed tanks. Flow-back fluid volumes may also be reduced in treatment ponds. In a similar manner, the process of hydraulic fracturing of the shales liberates a number of geogenic hydrocarbons and also returned to the surface in flow-back water and held in tanks or treatment ponds.

While the risks of some of these chemicals have been identified, very little is known of the microbial degradation of these chemicals in the holding tanks or treatment pond environments in surface facilities. Further, for geogenic hydrocarbons created during the fracturing process, the composition of these fractions (and the chemical risks associated) and the potential microbial metabolic pathways for their degradation remain largely unknown. In the current study, microbial degradation of both the key compounds identified above and the geogenic hydrocarbon fraction will be analysed in a quantitative or semi-quantitative fashion. It is noteworthy, that the conditions in the holding tanks and treatment ponds are markedly different, with the former likely being an anoxic environment (this will be determined in Task 4) while the latter is an oxic environment. In order to mirror the conditions in these environments, microbial degradation experiments in this study will be conducted in tank and pond water collected during the field sampling campaign under appropriate atmospheres, respectively with microbiome data providing additional insights into those microbes involved in the biodegradation of these compounds. Water chemistry data will reveal the occurrence of important macronutrients for microbial growth which may impact microbial activity in these environments. It is noteworthy, temporal changes in the salinity of treatment ponds will shift the microbial community towards members that are tolerant to high salinity which may affect the biodegradation of compounds through alterations of the microbial community.

Taken together, this project will provide key insights into the fate of hydraulic fracturing chemicals, and provide data on the unknown fraction of geogenic hydrocarbons produced during fracturing, throughout their use i.e. after injection, in flow-back and in holding tanks and treatment ponds. These data will be key for stakeholder risk analyses for the use of these chemicals in expanded operations across the basin.

Need and Scope

The Scientific Inquiry into Hydraulic Fracturing' raised awareness of public concerns regarding hydraulic fracturing in particular with regard to water quality. To help ease this concern, it is important to have a systematic understanding of the fate of chemicals (either geogenic or additives to fracturing fluids) used by industry. As described in the Objectives, this study will provide these data. Allowing a systems-approach to understanding the chemicals of concern in fracturing fluids and flow-back waters will facilitate a more informed risk assessment and improved mitigation strategies by the Gas industry and other stakeholders.

Specifically, this study will provide information on:

- subsurface abiotic degradation, and transport behaviour of key chemical additives of concern
- identity of geogenic hydrocarbons produced during fracturing processes and returned to the surface in flow-back waters
- microbial degradation (in both anoxic and oxic settings) of key fracturing fluid additives and geogenic chemicals in holding tanks and treatment ponds.

Relevant State/Territory Government independent reviews

https://frackinginquiry.nt.gov.au/

Submission made during public hearings and community forums related to the NT Scientific Inquiry into Hydraulic Fracturing indicated community concerns about hydraulic fracturing. Of those recommendations aimed at addressing these concerns; this project will provide specific information towards Recommendations 5.5 and 7.10 as described below:

Recommendation 5.5 *That prior to the grant of any further exploration approvals, in consultation with the gas industry and the community, the Government develops a wastewater management framework for any onshore shale gas industry. Consideration must be given to the likely volumes and nature of wastewaters that will be produced by the industry during the exploration and production phases.*

That the framework for managing wastewater includes an auditable chain of custody system for the transport of wastewater (including by pipelines) that enables source-to-delivery tracking of wastewater.

*That the absence of any treatment and disposal facilities in the NT for wastewater and brines produced by the gas industry be addressed as a matter of priority (*https://frackinginquiry.nt.gov.au/inquiry-reports?a=494327).

For Recommendation 5.5: This project will:

- provide information on the concentrations of chemicals of 'high concern' after adsorption, degradation and biodegradation has occurred. These data will critical in determining the management practices required for safe disposal.

Recommendation 7.10 *That prior to the grant of any further exploration approvals, the following information about hydraulic fracturing fluids must, as a matter of law, be reported and publicly disclosed before any exploration activities and production activities are carried out:*

• the identities, volumes and concentrations of chemicals (including environmentally relevant chemical species present as contaminants in the bulk chemicals) to be used;

• the purpose of the chemicals;

• how and where the chemicals will be managed and transported on-site, including how spills will be prevented, and if spills do occur, how they will be remediated and managed; and

• the laws that apply to the management of the chemicals and how they are enforced. That the following information about flowback and produced water must be reported and publicly disclosed online as soon as it becomes available:

• the identity and concentrations of chemicals and NORMs found in that water;

• how and where the chemicals and NORMs will be managed, transported and treated, including how spills will be prevented, and if spills occur, how they will be remediated and managed; and

• the laws that apply to the management of the chemicals and NORMs and how they are enforced

(https://frackinginquiry.nt.gov.au/inquiry-reports?a=494327)

For Recommendation 7.10: This project will:

- provide information on the identities of the current uncharacterised geogenic hydrocarbon fraction in the flow-back water, tanks and ponds and their degradation in flow-back water, tanks and pond settings.
- provide information on the abiotic and biotic degradation of key compounds identified as of 'potentially high concern' in the Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Beetaloo GBA region report.
- provide information on the subsurface migration, adsorption of chemicals of high concern

- provide information on options and methods for using microbes to degrade organic components in the flow-back, storage tank and pond settings.

In addition, NT Scientific Inquiry into Hydraulic Fracturing indicated that there was a "*a major lack of detailed knowledge of the aquatic ecology and biodiversity of surface and groundwater systems, particularly in the semi-arid and arid regions of the NT* " (https://frackinginquiry.nt.gov.au/inquiry-reports?a=494327 (page 21). While GISERA project W17 (Environmental monitoring and microbial degradation of onshore shale gas activity chemicals and fluids in the Northern Territory) will provide microbiome data for subsurface aquifers across the Beetaloo sub-Basin, this project will provide some further data on deep groundwater biodiversity in the subsurface associated with the shale deposits.

Methods

Logistics and sampling campaign

Consultation with Santos and Origin Energy representatives will guide sample collection from Tanumbirini and Kyalla sites, respectively (Task 1). Task 1 will also include the safe and environmentally- and culturally-sensitive planning, provisioning and logistics for the sampling campaign. Determination of the chemicals of interest for this project are drawn from the list of chemicals of 'high concern' identified in the Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Beetaloo GBA region report, will also be checked and verified through consultation with representatives from Santos, Origin Energy and government and regulatory bodies (Task 1). At the time of writing the chemicals proposed to be examined are: tributyl tetradecyl phosphonium chloride, glutaraldehyde, 1x model ethoxylated- and 1x model propoxylated- alcohol along with coco alkyldimethyl oxide.

Collection of samples will involve two staff travelling to the Northern Territory to collect project samples, including those for water chemistry, microbial profiling of communities, microbial degradation trials, chemical analyses, chemical degradation trials and shale core samples (Task 4). The collection of 'live' water samples from anoxic settings for the microbial degradation trials will require specialised equipment (argon, chemical reductants, specialized collection vessels) and technical knowledge to guarantee the integrity of samples for experimental set up. The collection of fracturing fluids will be dependent upon availability and activity at the sites during the sampling campaign. Collection of water samples from treatment ponds will be conducted systematically at both the surface and the sediment of the ponds.

Literature brief

A literature review that builds on work undertaken in the recent GBA project (Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Beetaloo GBA region report) and the literature review for GISERA project W17, will be undertaken to characterise the chemical additives of 'high concern' selected in Task 1. Specific data on their use in hydraulic fracturing fluids, their properties and toxicity will be discussed, along with information on their subsurface migration and adsorption behaviours. The literature review will also examine potential pathways for their abiotic degradation and, where not already covered in GISERA project W17, their biodegradation (Task 2).

Reservoir fate of residual hydraulic fracturing fluids

The method followed in this activity is divided into experimental characterisation and integrated predictive modelling of fate and migration of key compounds of interest for relevant case studies. The pathway for the migration of residual hydraulic fracturing chemicals is dissolution into formation waters and transport by groundwater flow. This groundwater transport process is affected by a range of processes, but two key values are the degradation rate and the adsorption behaviour. For shallow geological formations the temperature is low enough that microbial processes can be an important influence on the degradation rate. Shale gas reservoirs of the Beetaloo sub-basin range in depth from 1500 m to greater than 3000 m deep; at these depths, temperatures are higher and microbial processes are probably less important, with abiotic chemical transformations mainly determining the degradation rate. In order to determine the potential for biodegradation in the subsurface flowback samples will be subject to microbial profiling to determine the diversity of microbes in the reservoir. Assuming the process is primarily abiotic, these degradation process can be influenced by a range of *in-situ* conditions such as pressure, temperature, groundwater water chemistry and the rock geochemistry as well as the chemical itself. Of additional interest are the degradation products which can be of more concern than the parent compounds for some chemicals. Adsorption acts to retard or potentially remove migrating solutes and is likewise determined by a combination of properties and conditions within the formation and chemical properties of the solute. Another aspect is that the residual hydraulic fracturing fluids are a mixture of different chemicals and these have the potential to interact to determine degradation and adsorption.

Experimental characterisation will be comprised of two tasks: experimental measurement of the degradation rates for compounds of concern, and measurement of the adsorption behaviour of those compounds on reservoir rocks. The degradation rates will be measured using a batch reactor approach where a mixture of the hydraulic fracturing fluid, water with the formation water chemistry and crushed or drill cuttings of reservoir rock will be exposed to pressures and temperatures representative of *in-situ* conditions. Batch reactors can operate at pressures over 20 MPa and temperatures above 100°C, with some reactors capable of pressures up to 34 MPa. Periodic water samples will be analysed to determine changes in the quantities of compounds of interest, with this information used to determine the degradation rates (Task 5). Adsorption will be measured through core flooding experiments where dissolved hydraulic fracturing chemicals are flowed through a core sample. The addition of a tracer that does not adsorb or interact with the core will be used to calculate the effective flow velocity, the knowledge of this velocity will then allow for adsorption for the compounds of interest to be determined (Task 9). These properties will then be used, along with other information, in representative modelling of fate and migration case studies based on those used in Mallants et al. (2017) (Task 10).

Profiling microbial communities from flow-back tanks and treatment ponds

The microbial community profiles from the water samples collected from the tanks and treatment ponds will be determined by DNA extraction followed by next-generation sequencing examining the 16S bacterial region. These analyses will provide a baseline of microbial communities from the flow-back water, tanks and treatment ponds (Task 6).

Microbial degradation trials of target chemicals used in hydraulic fracturing associated with shale gas production

Replicated microcosm experiments to determine microbial degradation of target chemicals using flow-back water samples (sampling early and late flow-back waters, if available), tank water samples and treatment pond water samples. It is assumed that the water holding tanks are anoxic environments, prior to experiments this will be confirmed during sampling using a redox meter. Regardless, the flow-back water tank and pond water microcosms will be setup under appropriate atmospheric conditions. A mixture of compounds of interest, at realistic concentrations, will be spiked into microcosms. All microcosm experiments will be incubated at the relevant temperature for the type of water sample and will be held for a period of 8 weeks. Microbial community profiles after the degradation trials will be determined by DNA extraction followed by next-generation sequencing examining the 16S bacterial region and the data will be compared with the baseline microbial community profiles. This experiment will determine which microbes are involved in degradation of the chemicals and quantify the amount of chemical degraded (Task 7) by in-house methods and NMR in a commercial laboratory.

Geogenic hydrocarbons in flowback, tank and treatment pond water

Previous work from the Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Beetaloo GBA region report have identified large fractions of the geogenic hydrocarbons remain uncharacterised. To provide clarity on the composition of these fractions, this project will examine initial flowback water, tank water and pond water from two sampling sites and water from microbial degradation experiments (see Task 7) and provide information on the composition of this fraction using in-house gas chromatography-mass spectrometry methods. In parallel, samples will be examined for TRH (Total recoverable hydrocarbons, C6-C40), BTEXN (Benzene, Toluene, Ethylene, Xylene and Naphthalene), PAH (polycyclic aromatic hydrocarbons), VOC (volatile organic compounds), volatile organic acids, volatile halogenated compounds and chlorinated hydrocarbons and phenols through a NATA accredited laboratory, expanding data already collected and correlating these data with the exploration of unknown fractions forensically examined using gas chromatography mass spectrometry.

6. Project Inputs

Research

While there have been studies on the fate of hydraulic fracturing fluids for the Australian context these have used properties from the scientific literature (i.e. Mallants et al., 2017). This project would add significant value to the understanding of the degradation and migration of residual hydraulic fracturing fluids by measuring key properties for these processes under reservoir conditions of pressure, temperature, and formation water chemistry for the Beetaloo sub-basin using geological samples from that basin. Similarly, while there have been other studies of geogenic compounds in hydraulic fracturing fluids (see for example: Luek and Gonsior, 2017), there is a paucity of information regarding the geogenic hydrocarbon fraction and scant information that is specific to the geology of the Beetaloo sub-basin. On microbial degradation, microbial communities are highly varied between environments and in turn their genetic capacity to degrade xenobiotic compounds is also highly variable. Data on degradation and microbial degradation for these key chemical additives and geogenic compounds that is specific for the Beetaloo sub-Basin will be important in developing accurate risk assessments for the region as gas development increases.

Resources and collaborations

Researcher	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
Se Gong	50.5 days	Geochemistry	>20	All CSIRO
Nicholas Lupton	132.5 days	Reservoir Engineering	>10	
Kaydy Pinetown	21 days	Geoscience	>20	
Luke Connell	9 days	Reservoir Engineering and Groundwater Modelling	>30	
Nai Tran-Dinh	41 days	Microbiology	>20	
Regina Sander	35 days	Reservoir Engineering and Simulation	>10	
Carla Mariani	18 days	Organic Chemistry/Microbiology	>5	
Emma Crooke	37 days	Geochemistry	>15	
Michael Camilleri	65 days	Mechanical Engineering	>20	
James Kear	3 days	Engineering	>15	

Researcher	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
Saeed Salimzadeh	3 days	Engineering	>15	
David Midgley	41 days	Microbial Ecology	>20	
Stephen Sestak	2 days	Analytical chemistry	>30	

Subcontractors (clause 9.5(a)(i))	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
ALS	1-2 weeks turnaround on receipt of samples.	Chemical testing	Many. Commercial laboratory.	ALS. NATA-accredited laboratory.
Intertek	4 weeks	Chemical testing	Many. Commercial laboratory.	Intertek.
Sequencing service provider	6-8 weeks turnaround on receipt of samples.	DNA sequencing, microbiomes.	Many. Commercial DNA sequencing facility.	Molecular Research DNA. Texas, USA.

Budget Summary

Source of Cash Contributions	2021/22	2022/23	2023/24	2024/25	% of Contribution	Total
GISERA	$469,940	$213,465	$0	$0	80%	$683,405
- Federal Government	$371,328	$168,672	$0	$0	63.2%	$540,000
- Origin Energy	$48,135	$21,865	$0	$0	8.2%	$70,000
- Santos	$50,476	$22,928	$0	$0	8.6%	$73,404
Total Cash Contributions	**$469,940**	**$213,465**	**$0**	**$0**	**80%**	**$683,405**

Source of In-Kind Contribution	2021/22	2022/23	2023/24	2024/25	% of Contribution	Total
CSIRO	$117,485	$53,366	$0	$0	20%	$170,851
Total In-Kind Contribution	**$117,485**	**$53,366**	**$0**	**$0**	**20%**	**$170,851**

TOTAL PROJECT BUDGET	2021/22	2022/23	2023/24	2024/25	-	TOTAL
All contributions	$587,425	$266,831	$0	$0	-	$854,256
TOTAL PROJECT BUDGET	**$587,425**	**$266,831**	**$0**	**$0**	**100%**	**$854,256**

7. Project Impact Pathway

Activities	Outputs	Short term Outcomes	Long term outcomes	Impact
Logistics	Confirmed list of chemicals to be examined in the study. A series of documents describing the contacts, sampling site/sites, relevant permissions, sampling equipment and OH&S considerations. Organise materials for this project by examination of core samples available for the Beetaloo sub-basin in Northern Territory repositories, establishing the volume and type of available samples at the two field sites. Identification of any permits, HSE or travel documents required to allow this travel to occur. Liaising with staff from Santos and Origin Energy to facilitate sample collection from their respective sites.	Characterisation of chemicals used in hydraulic fracturing fluids, their properties, uses, toxicity and abiotic/biotic degradation pathways. Knowledge on the biodegradation of chemicals that are potentially involved in shale gas activities as well as an understanding of microbial community changes in flow-back water as a result of the presence of such chemicals. This project will provide information on the abiotic degradation and adsorption/migration properties of chemicals used in hydraulic fracturing	Assist in informing governments, regulators as well as policy-makers on the microbial impact of a selected list of chemicals that may be used in future shale gas activities in the Northern Territory. The project will deliver information on both surface and subsurface degradation of hydraulic fracturing chemicals. Further, it will provide new data on geogenic hydrocarbons and their degradation after flow-back occurs. This information is important for future risk assessment and expansion of the industry.	The impact of this research extends to government, industry and everyday Australians. All Australian communities that are located in shale gas regions as well as industry will benefit from the outcomes of this research, through increased understanding and awareness of environmental impacts that may result from the use of certain chemicals in future shale gas activities. The project provides knowledge of both surface and subsurface degradation of hydraulic fracturing chemicals and geogenic compounds at two pilot sites in the Northern
Literature review	A literature brief on current state of scientific understanding of chemicals of interest used in hydraulic fracturing of shale gas resources, including properties, uses, toxicity and abiotic/biotic degradation pathways.			
Commissioning laboratory equipment and developing experimental program	Modified and commissioned experimental equipment to meet project requirements and experimental program for the degradation and migration experiments under reservoir conditions.			
Sampling campaign	Provision of fracturing fluid (if available), flow-back water, water samples from the holding tanks and ponds. Shale core samples will also be obtained.			
Chemical degradation of HF fluids under reservoir conditions	The rate of abiotic degradation of compounds of interest under reservoir conditions. Identification of measurable products of these chemical degradation processes.			
Profiling microbial communities from flow-back tanks and treatment ponds	Provision of baseline data of microbial communities for flow-back water samples from tanks and treatment ponds.			

Microbial degradation trials of target chemicals used in HF associated with shale gas production	Experimental data on the biodegradation of target compounds used in hydraulic fracturing of shale gas resources in the Northern Territory, including any changes in microbial communities upon exposure to target compounds, and rates of degradation of chemicals.	under reservoir conditions. These will inform a modelling case study of the fate of residual hydraulic fracturing chemicals under reservoir conditions found in the Northern Territory.	Increased community awareness of the potential to degrade (or not) key chemicals or geogenic compounds from hydraulic fracturing fluids.	Territory which will assist those at both the decision-making and policy-making levels of government.
Geogenic hydrocarbons in flow-back water	Semi-quantitative or quantitative analysis and characterisation of geogenic hydrocarbons from flow-back waters and microbial degradation microcosms.			
Migration behaviour and modelling of HF fluids under reservoir conditions	Experimental data detailing the migration and adsorption behaviour of the compounds of interest in shale under reservoir conditions. Modelling of the fate of hydraulic fracturing chemicals under reservoir conditions found in the Beetaloo sub-Basin, Northern Territory.			
Develop fact sheets with key findings	Completed fact sheet(s) with key findings for distribution via the GISERA website and at community engagement events.			
Prepare and submit scientific manuscripts for publication in peer-reviewed journals	Manuscript submission to peer-reviewed journals.			

8. Project Plan

Project Schedule

ID	Activities / Task Title	Task Leader	Scheduled Start	Scheduled Finish	Predecessor
Task 1	Sampling logistics and field trip planning	Dr. Kaydy Pinetown	July 2021	August 2021	-
Task 2	Literature Review	Dr. Se Gong	July 2021	September 2021	-
Task 3	Commissioning laboratory equipment and developing experimental program	Mr. Nicholas Lupton	July 2021	October 2021	-
Task 4	Sampling campaign	Dr. Se Gong	August 2021	October 2021	Task 1, 2
Task 5	Chemical degradation of hydraulic fracturing fluids under reservoir conditions	Mr. Nicholas Lupton	October 2021	September 2022	Tasks 1-4
Task 6	Profiling microbial communities from flow-back tanks and treatment ponds	Dr. Nai Tran-Dinh	October 2021	February 2022	Tasks 1, 2, 4
Task 7	Microbial degradation trials of target chemicals used in hydraulic fracturing associated with shale gas production	Dr. Nai Tran-Dinh	October 2021	May 2022	Tasks 1, 2, 4
Task 8	Geogenic hydrocarbons in flow-back water	Dr. Se Gong	October 2021	August 2022	Tasks 1, 2, 4, 7
Task 9	Migration behaviour of hydraulic fracturing fluids under reservoir conditions	Mr. Nicholas Lupton	November 2021	August 2022	Tasks 1, 2, 3, 4
Task 10	Modelling the fate of residual hydraulic fracturing chemicals	Mr. Nicholas Lupton	May 2022	October 2022	Tasks 1, 2, 3, 4, 5
Task 11	Project Leadership, Task Leadership and Report Writing	Dr. David Midgley	July 2021	January 2023	Tasks 1-10
Task 12	Communicate findings to stakeholders	Dr. David Midgley	July 2021	January 2023	Tasks 1-10

Task description

Task 1

TASK NAME: Sampling logistics and field trip planning

TASK LEADER: Kaydy Pinetown

OVERALL TIMEFRAME: July-August 2021

BACKGROUND: During Task 1, consult with Santos and Origin representatives in the Northern Territory to prepare for sampling of drill site/sites (up to a maximum of two sites), flow-back water, holding tanks, treatment ponds. Task 1 will establish the potential sampling site/sites from Santos and Origin, and the nature of the samples (i.e. sample type, volume, size, depth and number). This task will also include the safe and environmentally sensitive planning, provisioning and logistics for the sampling campaign.

TASK OBJECTIVES:

1. Establish contact with representatives in Santos and Origin to guide the sampling campaign.
2. Establish water and sampling site/sites within the Beetaloo sub-basin.
3. Identify suitable core samples from within the Northern Territory Core repositories.
4. Establish sampling requirements, i.e., type, volume, size, sampling depth, number, availability of initial fracturing fluids before injection etc.
5. Identification of any permits, permission or consultation required for sampling.
6. Preparation of sampling equipment/reagents.
7. Preparation for remote sampling fieldwork including accommodation, vehicle hire and OH&S considerations.
8. Logistics of transporting equipment and samples between CSIRO laboratories in Sydney/Melbourne and collection sites in the Northern Territory.
9. Confirm the list of chemicals being investigated in this study with key stakeholders.
10. Detail the analytical requirements from external labs, to inform design of the degradation and migration experiments.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: This task will yield a series of documents describing the contacts, sampling site/sites, relevant permissions, sampling equipment and OH&S considerations.

Task 2

TASK NAME: Literature review

TASK LEADER: Se Gong

OVERALL TIMEFRAME: July-September 2021

BACKGROUND: Fracturing fluids are primarily composed of freshwater, proppants, and chemical additives such as friction reducers, biocides, surfactants, and scale reducers. Task 2 will focus on the chemicals in the fracturing fluids and review the reasons to use these chemicals in the fracturing fluids, the properties and toxicity of the chemicals and what is known of the degradation, biodegradation and subsurface migration of these chemicals.

TASK OBJECTIVES:

1. Information on why these chemicals are used in fracturing fluids.
2. Information on the properties and toxicity of chemicals.
3. Review previous research examining abiotic chemical degradation and migration properties of compounds.
4. Information on the geogenic hydrocarbons produced during the fracturing of shales at other sites.
5. Literature review of the biodegradation of these chemicals.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Task 2 will provide a literature review on chemicals in the fracturing fluids with details about the role of these chemicals in the fracturing fluids, their properties and toxicity along with information on their mobility in the subsurface, abiotic and biotic degradation. This review will constitute the introduction of the final report and will also be submitted in September 2021 as a stand- alone document.

Task 3

TASK NAME: Commissioning laboratory equipment for reservoir experimental program

TASK LEADER: Nicholas Lupton

OVERALL TIMEFRAME: July–October 2021

BACKGROUND: Task 3 will involve the detailed preparation for the experimental program for chemical degradation and migration under reservoir conditions. Shale reservoirs for investigation (e.g. Kyalla Fm and/or Velkerri Fm) will be decided in consultation with the Technical Reference Group and based on sample availability determined in Task 1. The composition of the hydraulic fracturing / formation fluid analogue will be decided either following flow-back water collection and analysis, or based on reported hydraulic fracturing fluid composition provided in accordance with the NT Petroleum (Environment) Regulations 2016.

The laboratory equipment (batch and core flooding rigs) will be commissioned to meet the project requirements.

TASK OBJECTIVES: The task has the following objectives:

1. Modify and commission experimental equipment to meet experimental program requirements (pressure, temperature, sampling).
2. Finalise the shale targets, formation water and hydraulic fracturing fluid analogues that will comprise the degradation and migration experimental program.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Experimental program for the degradation and migration experiments under reservoir conditions. Modified and commissioned experimental equipment to meet project requirements.

Task 4

TASK NAME: Sampling campaign

TASK LEADER: Se Gong

OVERALL TIMEFRAME: August-October 2021

BACKGROUND: Task 4 will involve two staff travelling to the Beetaloo sub-basin of the Northern Territory with the purpose of collecting water and shale core samples from drilling sites, flow-back water tanks and treatment ponds. While in the field the team will be led by Nai Tran-Dinh who has experience in the Northern Territory at these sites.

TASK OBJECTIVES:

1. To collect preserved water samples for microbial community profiling (Task 6) from the site/sites identified by Task 1.
2. To collect microbiological ('live') and matching bulk water samples for microbial degradation trials (Task 7) from the site/sites identified by Task 1.
3. To collect shale core samples for core flooding experiments (Task 5) from the site/sites identified by Task 1.
4. Perform initial water chemistry analyses of collected water samples through a NATA accredited laboratory.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Collection of microbially preserved water samples, microbiological ('live') water samples and bulk water samples. Collection of shale core samples.

Task 5

TASK NAME: Chemical degradation of hydraulic fracturing fluids under reservoir conditions

TASK LEADER: Nicholas Lupton

OVERALL TIMEFRAME: Oct 2021 – September 2022

BACKGROUND: This task involves the experimental determination of the chemical degradation rates of compounds of interest present as additives in hydraulic fracturing fluid. Accurate determination of the fate of compounds in this unrecovered fluid during or after hydrocarbon production will depend on characterising their chemical degradation behaviour in the deep subsurface, where environmental conditions (i.e. high pressure and temperature, limited microbial activity) differ to the surface or shallower formations. High pressure and temperature batch experiments (each approximately 6 month duration) would investigate degradation under reservoir conditions, with the number of individual experiments dependent on sample availability established in Task 1, and reflecting the number of variables (e.g. target reservoirs, drill cutting size) decided in the experimental program developed in Task 3. Periodic water samples will be collected and analysed to determine changes in the quantities of compounds of interest, with this information used to determine the degradation rates. The chemical degradation of the selected compounds may result in the creation of products that are of further interest. If the composition of the fluid analogue permits analysis, any identifiable products that are generated through the degradation of the compounds of interest will be analysed.

TASK OBJECTIVES: The task has the following objectives:

1. Undertake batch experiments to determine the abiotic chemical degradation rates under reservoir conditions for compounds of interest, for different shale gas target reservoirs decided in consultation with the Technical Reference Group.
2. If experimental conditions permit, analyse for identifiable products of the chemical degradation process.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Experimental data detailing the chemical degradation rate of the compounds of interest under reservoir conditions, and any identifiable products of the chemical degradation process. Data prepared for analysis and final reporting.

Task 6

TASK NAME: Profiling microbial communities from flow-back tanks and treatment ponds

TASK LEADER: Nai Tran-Dinh

OVERALL TIMEFRAME: October 2021 – February 2022

BACKGROUND: The microbially preserved water samples will be subject to DNA extraction along with 16S rDNA sequencing.

TASK OBJECTIVES: The task will include the following objectives:

1. Filter preserved water samples from flow-back tanks and treatment ponds onto 0.1µM PVDF filters.
2. Complete DNA extractions from all samples.
3. Process DNA for 16S NGS sequencing.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Raw sequencing data from microbial community profiling available.

Task 7

TASK NAME: Microbial degradation trials of target chemicals used in hydraulic fracturing associated with shale gas production

TASK LEADER: Nai Tran-Dinh

OVERALL TIMEFRAME: October 2021- May 2022

BACKGROUND: Replicated water microcosms using flow-back tank water and treatment pond water will be established and used to determine the ability of microbial communities present in these waters to degrade chemicals potentially used in hydraulic fracturing associated with shale gas production. Chemical degradation will be determined through direct measurement of the chemicals at NATA accredited laboratories or through this project.

TASK OBJECTIVES: The task will include the following objectives:

1. Establish replicated anoxic microcosms for flow-back tank water samples.
2. Establish replicated oxic microcosms for treatment pond water samples.
3. Spike microcosms with a mixture of target compounds used in hydraulic fracturing associated with shale gas production at realistic concentrations.
4. Analysis of target chemicals before microbial degradation experiments
5. Harvest all water treatments after 8 weeks and perform microbial community profiling and analysis of target chemicals.
6. Statistical analyses of the resultant data.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Replicated experimental data on the degradation of target compounds. Data prepared for analysis and final reporting.

Task 8

TASK NAME: Geogenic hydrocarbons in flow-back water

TASK LEADER: Se Gong

OVERALL TIMEFRAME: October 2021 – August 2022

BACKGROUND: Natural rock formations contain compounds that could be mobilised into flowback and produced water during hydraulic fracturing. Organic chemicals such as phenol, polycyclic aromatic hydrocarbons (PAHs) and total recoverable hydrocarbons (TRHs) were detected in extracts of powdered rock samples based on the GBA report in 2020. However, these compounds only represented a small fraction of the total organic geogenic compounds present in the sample extracts. Most organic compounds in the sample extracts were unidentified and are required further 'forensic' analysis for their identification and quantification. Their risk to aquatic environments is unknown. This task will focus on characterizing the geogenic hydrocarbons in details in the flow-back, tank, treatment pond water associated with shale gas development, as well as water after microbial degradation experiment in task 7 using the in-house gas chromatograph-mass spectrometry (GC-MS) method.

TASK OBJECTIVES: The task will include the following objectives:

1. Detailed geogenic hydrocarbons of a sub-set of samples will be analysed by the in-house gas chromatography-mass spectrometry method.
2. Semi-quantitative or quantitative data of hydrocarbons such as TRH (C6-C40), BTEX, VOCs, PAHs, volatile organic acids, phenols and halogenated hydrocarbons will be screened through a NATA accredited laboratory for all the samples.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Composition of the geogenic hydrocarbons in a sub-set of the water samples (up to 20) and the microbial degradation experiment water samples (up to 12) will be characterised in greater details based on the results of semi-quantitative data of TRH (C6-C40) or quantitative data of BTEX, VOCs, PAHs, volatile organic acids, phenols and halogenated hydrocarbons in the collected water samples (up to 44) and microbial degradation experiment water samples (up to 12) analysed through the NATA accredited laboratory.

Task 9

TASK NAME: Migration behaviour of hydraulic fracturing fluids under reservoir conditions

TASK LEADER: Nicholas Lupton

OVERALL TIMEFRAME: November 2021 – July 2022

BACKGROUND: This task involves the experimental determination of key properties that affect the subsurface migration behaviour of compounds of interest present as additives in hydraulic fracturing fluid. Characterisation of these properties under reservoir conditions is key to accurately representing the migration behaviour, as many properties are strongly influenced by the specific in-situ conditions associated with the sub-surface environment. Adsorption will be measured through experiments where the compounds of interest are flowed through a core sample under reservoir conditions. A non-adsorbing tracer will be used to calculate the effective flow velocity, allowing for adsorption for the compounds of interest to be determined. Core flooding experiments would characterise the properties affecting migration according to the experimental program developed in Task 1. Shale is an extremely low permeability rock, and liquid flow rates within the core floods are expected to be low, therefore the number and duration of core floods will depend on the liquid analysis requirements and on the availability of cores from target reservoirs established in Task 1.

TASK OBJECTIVES: The task has the following objectives:

1. Undertake core flooding experiments which will measure the adsorption behaviour of compounds of interest under reservoir conditions, for different shale gas target reservoirs decided in consultation with the Technical Reference Group.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Experimental data detailing the adsorption behaviour of the compounds of interest in shale under reservoir conditions. Data prepared for analysis and final reporting.

Task 10

TASK NAME: Modelling the fate of residual hydraulic fracturing chemicals

TASK LEADER: Nicholas Lupton

OVERALL TIMEFRAME: May 2022 – October 2022

BACKGROUND:

The migration behaviour of residual hydraulic fracturing chemicals is influenced by the properties investigated in Tasks 5 and 9, and these properties will be used in representative migration modelling case studies to investigate the fate of chemicals under conditions representing the Beetaloo sub-basin. Case studies based on Mallants et al (2017) and planned with Technical Reference Group will investigate the fate of hydraulic fracturing chemicals under the established scenarios. The number of scenarios investigated will depend on the extent of the experimental program completed in Tasks 5 and 9, which are dependent on sample availability. The task will require acquisition of software with the capability for adequately modelling the advective transport behaviour.

TASK OBJECTIVES: The task has the following objectives:

1. Complete modelling case studies that characterise the fate of hydraulic fracturing chemicals under scenarios represented in the Beetaloo sub-basin.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Chapter in the final report detailing the results of the modelling case studies.

Task 11

TASK NAME: Project Leadership, Task Leadership and Report Writing

TASK LEADER: David Midgley

OVERALL TIMEFRAME: July 2021-31 January 2023

BACKGROUND: Information from this project is to be made publicly available after completion of standard CSIRO publication and review processes.

TASK OBJECTIVES: To ensure that the information generated by this project is documented and published after thorough CSIRO Internal review.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: 1) Preparation of a final report outlining the scope, methods, assumptions, findings and any recommendations for future research; 2) Following CSIRO Internal review, the report will be submitted to the GISERA Director for final approval; and 3) Provide 6 monthly progress updates to GISERA office.

Task 12

TASK NAME: Communicate findings to stakeholders

TASK LEADER: David Midgley

OVERALL TIMEFRAME: July 2021-31 January 2023

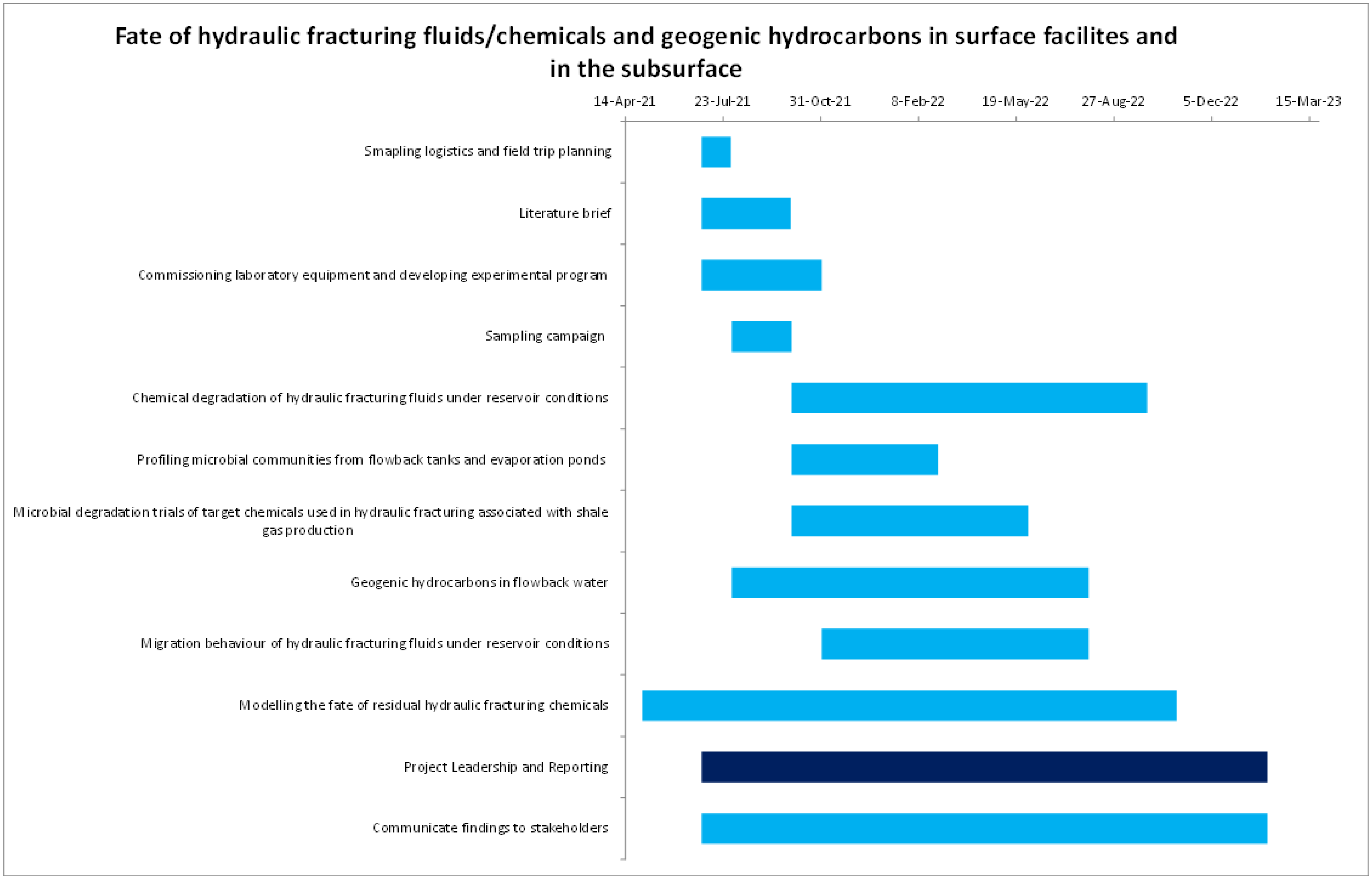
BACKGROUND: Communications of GISERA research are an important component of outreach and dissemination of findings to diverse audiences.

TASK OBJECTIVES: Communicate findings to stakeholders through meetings, knowledge transfer session, factsheet and journal article, in collaboration with GISERA Communications officers.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Communicate results to GISERA stakeholders according to standard GISERA project procedures which will include:

1) Knowledge Transfer session with Government/Gas Industry
2) Presentation of findings to Community members/groups
3) Preparation of article for GISERA newsletter
4) Revision of project factsheet to include final results (a factsheet is developed at project commencement and another will be done at completion)
5) Peer reviewed scientific manuscript ready for submission to relevant journal (optional)

Project Gantt Chart



11. Technical Reference Group

The project will establish a Technical Reference Group (TRG) aimed at seeking peer-to-peer technical advice on contextual matters and to discuss research needs as well as outputs as the project progresses. The TRG will include the project leader and a group of different stakeholders as appropriate which may include:

- Origin Energy representative
- Santos representative
- NT Government representative from:
  - Department of Industry, Tourism and Trade
  - Department of Environment
- Expert in microbiology and chemistry (research institution TBD)

12. Communications Plan

Stakeholder	**Objective**	**Channel** (e.g. meetings/media/factsheets)	**Timeframe** (Before, during at completion)
Regional community / wider public	To communicate project objectives and key messages from the research	Fact sheets (including development of one at commencement of project which will explain in plain English the objective of the project – this will be updated periodically as project progresses). Project progress reported on GISERA website to ensure transparency for all stakeholders including regional communities. Media release (optional)	From commencement of project and with updates as they come to hand. As required At completion
Government	Briefing on research being undertaken and progress	Engagement during project	During
Gas Industry	Industry adopts methods for improving disposal practices	Presentation of findings at joint Gas Industry/Government Knowledge Transfer Session	At Completion
Government	Advice provided to senior bureaucrats / ministers / policy makers	Presentation of findings at joint Gas Industry/Government Knowledge Transfer Session	At Completion

Stakeholder	**Objective**	**Channel** (e.g. meetings/media/factsheets)	**Timeframe** (Before, during at completion)
Community stakeholders	Presentation of research findings	Presentation of findings at via workshop/briefing	At Completion
Regional community/wider public, government, scientific community and industry	To report on key findings	Public release of final report	At project completion
Traditional Owner communities	To explore collaboration opportunities for information exchange	Engagement with representatives of relevant land councils where appropriate to determine interest/availability in making information available to communities	Ongoing

13. Budget Summary

Expenditure	2021/22	2022/23	2023/24	2024/25	Total
Labour	$428,925	$230,831	$0	$0	$659,756
Operating	$52,500	$6,000	$0	$0	$58,500
Subcontractors	$106,000	$30,000	$0	$0	$136,000
Total Expenditure	**$587,425**	**$266,831**	**$0**	**$0**	**$854,256**

Expenditure per task	2021/22	2022/23	2023/24	2024/25	Total
Task 1	$35,392	$0	$0	$0	$35,392
Task 2	$26,671	$0	$0	$0	$26,671
Task 3	$49,962	$0	$0	$0	$49,962
Task 4	$46,504	$0	$0	$0	$46,504
Task 5	$93,931	$32,157	$0	$0	$126,088
Task 6	$11,311	$0	$0	$0	$11,311
Task 7	$72,419	$0	$0	$0	$72,419
Task 8	$82,391	$16,955	$0	$0	$99,346
Task 9	$63,932	$35,300	$0	$0	$99,232
Task 10	$45,815	$52,757	$0	$0	$98,572
Task 11	$50,887	$114,799	$0	$0	$165,686
Task 12	$8,209	$14,863	$0	$0	$23,072
Total Expenditure	**$587,425**	**$266,831**	**$0**	**$0**	**$854,256**

Source of Cash Contributions	2021/22	2022/23	2023/24	2024/25	Total
Federal Govt (63.2%)	$371,328	$168,672	$0	$0	$540,000
Origin Energy (8.2%)	$48,135	$21,865	$0	$0	$70,000
Santos (8.6%)	$50,476	$22,928	$0	$0	$73,404
Total Cash Contributions	**$469,940**	**$213,465**	**$0**	**$0**	**$683,405**

In-Kind Contributions	2021/22	2022/23	2023/24	2024/25	Total
CSIRO (20%)	$117,485	$53,366	$0	$0	$170,851
Total In-Kind Contributions	**$117,485**	**$53,366**	**$0**	**$0**	**$170,851**

	Total funding over all years	Percentage of Total Budget
Federal Government investment	$540,000	63.2%
Origin Energy investment	$70,000	8.2%
Santos investment	$73,404	8.6%
CSIRO investment	$170,851	20%
Total Expenditure	**$854,256**	**100%**

Task	Milestone Number	Milestone Description	Funded by	Start Date (mm-yy)	Delivery Date (mm-yy)	Fiscal Year Completed	Payment $ (excluding CSIRO contribution)
Task 1	1.1	Sampling logistics and field trip planning	GISERA	Jul-21	Aug-21	2021/22	$28,314
Task 2	2.1	Literature Review	GISERA	Jul-21	Sep-21	2021/22	$21,337
Task 3	3.1	Commissioning laboratory equipment and developing experimental program	GISERA	Jul-21	Oct-21	2021/22	$39,970
Task 4	4.1	Sampling campaign	GISERA	Aug-21	Oct-21	2021/22	$37,203
Task 5	5.1	Chemical degradation of hydraulic fracturing fluids under reservoir conditions	GISERA	Oct-21	Sep-22	2022/23	$100,870
Task 6	6.1	Profiling microbial communities from flow-back tanks and treatment ponds	GISERA	Oct-21	Feb-22	2021/22	$9,049
Task 7	7.1	Microbial degradation trials of target chemicals used in hydraulic fracturing associated with shale gas production	GISERA	Oct-21	May-22	2021/22	$57,935
Task 8	8.1	Geogenic hydrocarbons in flow-back water	GISERA	Oct-21	Aug-22	2022/23	$79,477
Task 9	9.1	Migration behaviour of hydraulic fracturing fluids under reservoir conditions	GISERA	Nov-21	Aug-22	2022/23	$79,386
Task 10	10.1	Modelling the fate of residual hydraulic fracturing chemicals	GISERA	May-22	Oct-22	2022/23	$78,858
Task 11	11.1	Project Leadership, Task Leadership and Report Writing	GISERA	Jul-21	Jan-23	2022/23	$132,549
Task 12	12.1	Communicate findings to stakeholders	GISERA	Jul-21	Feb-23	2022/23	$18,458

GISERA
Gas Industry Social and Environmental Research Alliance

14. Intellectual Property and Confidentiality

Background IP (clause 11.1, 11.2)	**Party**	**Description of Background IP**	**Restrictions on use (if any)**	**Value**
				$
				$
Ownership of Non-Derivative IP (clause 12.3)	CSIRO			
Confidentiality of Project Results (clause 15.6)	Project Results are not confidential.			
Additional Commercialisation requirements (clause 13.1)	Not Applicable			
Distribution of Commercialisation Income (clause 13.4)	Not applicable			
Commercialisation Interest (clause 1.1)	**Party**		**Commercialisation Interest**	
	CSIRO		N/A	
	Santos		N/A	
	Origin		N/A	
	Pangaea		N/A	

15. References

Australian Government Department of the Environment and Energy (2017) National assessment of chemicals associated with coal seam gas extraction in Australia – Overview (http://www.environment.gov.au/system/files/resources/03137f85-1bea-46a4-b9e7-67d985b4aeb5/files/national-assessment-chemicals-overview.pdf)

Australian Government Department of the Environment and Energy (2014) Hydraulic fracturing ('fraccing') techniques, including reporting requirements and governance arrangements (http://www.environment.gov.au/system/files/resources/de709bdd-95a0-4459-a8ce-8ed3cb72d44a/files/background-review-hydraulic-fracturing_0.pdf)

Australian Government Department of the Environment and Energy (2017) Risk assessment guidance manual: for chemicals associated with coal seam gas extraction (http://www.environment.gov.au/system/files/consultations/81536a00-45ea-4aba-982c-5c52a100cc15/files/risk-assessment-guidance-manual-chemicals-associated-csg-extraction-australia-exposure-draft.pdf)

Luek, J.L., Gonsior, M. 2017. A Review of Organic Compounds in Hydraulic Fracturing Fluids and Wastewaters. Water Research 123, 536-548. DOI:10.1016/j.watres.2017.07.012

Kirby JK, Golding L, Williams M, Apte S, Mallants D, King J, Otalega I and Kookana R (2020) Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicalsfor the Beetaloo GBA region. Technical appendix for the Geological and Bioregional Assessment: Stage 2. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia.

Mallants, D., Apte, S., Kear, J., Turnadge, C., Janardhanan, S., Gonzalez, D., Williams, M., Chen, Z., Kookana, R., Taylor, A. and Raiber, M., 2017. Deeper groundwater hazard screening research. Unpublished research report prepared by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra.