Australia's National
Science Agency

GISERA | Gas Industry Social and Environmental Research Alliance

Project Order

Short Project Title

Beetaloo basin shale long-term competency after decommissioning

Long Project Title	Assessing the long-term sealing competency of Beetaloo Basin after gas well decommissioning
GISERA Project Number	Oth.2
Start Date	15 August 2022
End Date	15 November 2023
Project Leader	Elaheh Arjomand

GISERA State/Territory

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

Basin(s)

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

GISERA Research Program

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

1. Project Summary

Community concerns about decommissioned wells acting as potential sources of contaminants in the long term (on timescales of 100 to 1000 years) have been expressed widely. These concerns arise from the perceived risk of connectivity between the target natural gas seam and surface aquifers after gas production has ceased and the well is plugged and abandoned. Part of the source of this concern arises from a poor understanding of the behaviour of various rock formations at depths from 500m to 3000m underground once natural gas production has ceased. Improved understanding of how decommissioned wells in the Beetaloo basin maintain their integrity over a long-term period is of utmost importance for these Northern Territory community groups, government regulators, and industry. The plugged and decommissioned wells are sealed to prevent formation fluid leakage to the surface and separate hydrocarbon fluids' movements among different strata. However, a perceived risk exists where the integrity of plugged and decommissioned wells may fail at an individual or at multiple well barriers potentially leading to the creation of leakage pathways. At this point, decommissioned wells under certain conditions may turn into connectivity pathways for formation fluids, thereby posing potential risks to the surrounding environment. Data from other parts of the world indicates that shale formations self-seal over time (known as 'creep incidents'), creating a natural barrier against the hydrocarbon fluid movements, which significantly reduces the risk of contaminants entering the environment. These naturally occurring barriers have been observed by sonic or ultrasonic well logs. In these circumstances, overburden and reservoir shales may creep and seal the annular space within the decommissioned wells, thereby forming a permanent and complete barrier to the movement of fluids deep in the formation to surface aquifers.

This project aims to quantify the self-sealing competency (creep behaviour) of shales in the Beetaloo basin that sit between the target natural gas seams and the shallow Cambrian Limestone Aquifer. These shale creep behaviour results will be incorporated into a simple leakage rate simulator for the Beetaloo Basin. The simulator will cover the impact of shale creep barriers in decommissioned natural gas wells when considered in conjunction the existing regulatory decommissioning requirements. Thus, the likelihood of geological layers in the Beetaloo basin creeping over time and acting as permanent, reliable barriers or altering the source layers' deliverability would be reflected in the resultant estimated potential contaminant flow rates. However, the creep phenomena in shale formations are time-dependent processes that inherently may take decades to seal formation fractures or fill up the annular space. Therefore, activation mechanisms (mostly changing the chemistry of the annular fluid) can be employed to accelerate the creep deformations. This project will also assess options for accelerating this sealing process.

2. Project description

Introduction

Petroleum wells are plugged and decommissioned at the final stage of their lifecycle to prevent the migration of hydrocarbons to the surface and separate the movement of hydrocarbon fluids among different strata. Unintended fluid movement among strata may lead to the contamination of overlying groundwater aquifers and the surrounding environment. However, plugging and decommissioning operations are complex technical well operations, and it is very challenging to ensure the wells' integrity over the long term (on timescales of 100 to 1000 years). Therefore, maintaining long-term integrity of decommissioned well is a sensitive issue and an identified concern among the NT communities.

If the natural shale formations in the NT were to creep and form a barrier against the cement sheath or behind an uncemented casing (filling the annular space), it may naturally self-seal micro-annuli or be actively encouraged to creep and provide a long-term seal directly against the casing. Understanding and utilizing the natural creep characteristics of the NT shale formations in this way could provide assurance as to the long-term integrity of a decommissioned well and potentially reduce the cost and complexity of the decommissioning procedure. In addition, if the shale barrier were to be established prior to plugging the well, the competency of the formed barrier could be verified by performing pressure testing and running bond logs.

This approach has been considered internationally as a potential means of creating long-term barriers to fluid flow within decommissioned wells. For instance, Statoil company in Norway has used this method to resolve critical barrier issues or as a cheaper and safer way to establish barriers on more than 100 wells (Carlsen, 2012).

NORSOK also has identified shale as a suitable barrier, where they are quoted as stating, “Shale, in particular, has all the necessary characteristics which, e.g., NORSOK-D010 requires of a good barrier, being largely impermeable, non-shrinking, ductile (not brittle), resistant to different chemicals substances, wetting to ensure bonding to steel, and providing long-term integrity” (van Oort *et al.*, 2020).

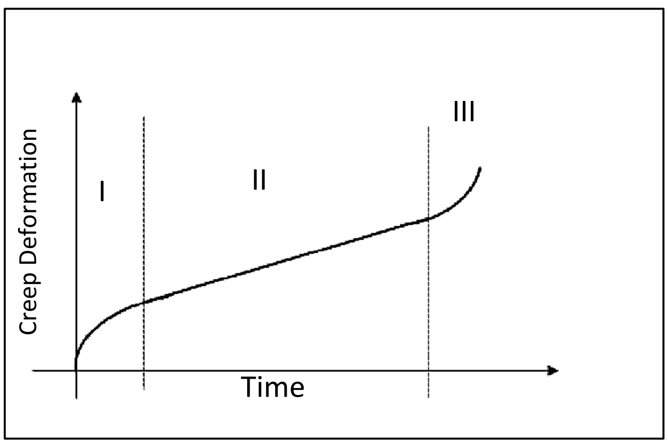
Creep mechanism

Creep in shales is a time-dependent mechanism because of minerals’ deformations under constant stress. Creep can occur in both saturated rocks and dry (unlike consolidation and swelling) due to visco-elastoplastic behaviour in the solid matrix so that strain builds up due to imposed long-term stress to the point in which failure occurs eventually (Cerasi *et al.*, 2017).

The creep rate is dependent on several factors, including internal rock structure rearrangement, particle sliding, compression delayed water that transfers and aggregates rock macro-pores, jumping of molecule bonds, adsorbed water flow in double layers of clay particles, and viscous adjustments of clay structures (Feng *et al.*, 2017). While the swelling mechanism is associated with clay permeability, rearrangement of particles, breakdown of diagenetic bonds, structural adjustment, and chemical alterations (Feng *et al.*, 2017).

Shales are competent to fill the annular space due to the creep phenomenon if they have the following characteristics: low strength and high ductility (low Young's Modulus, low cohesion, low friction & dilation angles), high clay content with comparatively high smectite content, low amounts of quartz and carbonate cementation, moderately high porosity and low compressional wave velocity (Kristiansen *et al.*, 2018)

For a creeping formation to act as a barrier permanently, in addition to the aforementioned shale properties, the existing well characteristics and caprock properties are critical. For example, the caprock must have low permeability and be sufficiently strong, confirmed, and verified by formation evaluation logs, drilling cuttings analyses, and formation integrity tests. It also has to cover an adequate length interval, which might be assessed with pressure testings or logging tools (Strand, 2018).



I: Primary/transient creep

II: Secondary/steady state creep

III: Tertiary/accelerating creep

Figure 1: Creep stages after Kristiansen et al., (2018)

The creep rate is time-dependent and can be divided into three stages as follows (Ozan *et al.*, 2018):

- Primary creep/transient creep,
- Secondary creep/steady-state creep,
- Tertiary creep/accelerating creep.

Figure 1 schematically shows three phases of a creeping process. The primary or transient stage includes large deformation at an accelerated rate followed by a steady-state step. The steady-state phase is known as the strain hardening phase, and it involves the slowest creep rate in which deformation increases at a slow and relatively constant rate. Deformation within this phase is irreversible and classified as plastic deformation. Finally, in the third phase (tertiary or accelerating creep), the deformations increase exponentially, and unstable cracks propagate, resulting in material failure (Fredagsvik, 2017). The duration of each creep stage depends on the shale rock constituent materials and the applied load. The strain magnitude in shale rocks directly correlates with the applied axial differential load, while the confining pressure has no impact on the strain magnitudes. When shale rock undergoes higher stress levels, the shale rock shows a secondary creep due to the stress accumulation (Liu et al., 2021). The tertiary creep occurs when the applied load becomes greater than the yield stress, resulting in crack initiation and large strains (An, Killough and Xia, 2021).

This project will investigate the self-sealing (creep) competency of the Beetaloo basin shale reservoirs, which leads to the creation of natural barriers within the reservoirs. The mineralogy of the Beetaloo basin shale and its mechanical properties will be determined to evaluate the potential sealing competency (creep rate) of this specific shale. However, the creep phenomena in shale formations are time-dependent processes that naturally may take decades to fill up the annulus or seal the formation fractures and block the hydrocarbon fluids' movements. Therefore, activation mechanisms (mostly changing the chemistry of the annular fluid) are to be employed to accelerate the creep deformations.

Developing a leakage rate simulator

Well plugging and decommissioning can be accompanied by many limitations and expenses that can entail section milling, possibly pulling the casing string, carrying out a clean-out, and finally placing cement plugs with the minimum thickness required by regulations. However, the integrity of plugged and decommissioned wells might still be compromised due to the failure of the individual or multiple barriers leading to the creation of potential leakage pathways for the migration of fugitive emissions (formation fluids) to hydrologically isolated water-bearing zones. For instance, Boothroyd *et al.*, (2016) examined the fugitive methane emissions from 103 decommissioned wells in the UK, from which 30% indicated signs of soil surface contamination by methane at their proximity as the result of well integrity failure.

In this project, a simple leakage rate simulator for plugged and decommissioned wells will be developed and tailored, implementing the likelihood of the Beetaloo basin shale regarding self-sealing competencies and the creation of natural barriers that significantly reduces the risk of contaminants entering the environmental systems. The simulator will be developed based on the NT decommissioned well components, including the cement plugs, the reservoir conditions, the associated decommissioning strategies, and the NT code of practice requirements.

Prior Research

Literature review on the creep experimental studies

Many studies have investigated the factors that control creep rate and creep deformation magnitude. Creep deformation magnitude is dependent on but not limited to the shale mineralogy, applied temperature, pressure, and environmental chemistry. Mineralogy of the formation and specifically the amount of clay determine whether the formation can act as a barrier completely (the amount should be more than 40%). The formation properties are also influenced by the amount of Smectite (which acts as a bonding agent), quartz, illite, kaolinite, and chlorite. Smectitic clays usually swell more, are less stiff, and, therefore, show more ductility than other types of clay minerals. The creep processes are accelerated as the applied stress and temperature increase. Therefore, the stress state, the imposed differential stress during drilling to decommissioning, and the yield and failure stress are critical to be determined. The closer the stress state to failure, the more creep deformation is observed. Hence, it is crucial to evaluate the stress state near the wellbores. The chemistry of the drilling fluid seems to impact the creep process, too (Skjerve, 2013; Ozan *et al.*, 2018; Fredagsvik, 2017).

Sone and Zoback, (2011) also investigated the visco-plastic properties of gas shales. They suggested that formations are more prone to creep deformations in the perpendicular direction to their bedding (while the loading axis is orthogonal to the long axis of the plug) compared to parallel to their direction (the loading axis is along the long plug axis).

Researchers have also developed techniques and approaches to stimulate shales to form barriers through temperature, pressure changes imposed on the shales, and by utilizing some chemicals to enhance the creep process. The chemical activation technique possibly will be more straightforward in field applications as the chemical solutions are circulated through the annular space by casing perforations with a workstring and packer arrangement (Carpenter, 2021). Incorporating the chemical reduces the near-wellbore shale stiffness, accelerating the creep process to fill up the annulus (van Oort *et al.*, 2020).

Characterizing chemoporomechanical shale–fluid interactions is very important to understand the shale response (i.e., creeping or swelling) while exposed to different annular fluids.

Literature review on developing leakage rate simulators

To the best of our knowledge, only one study has been carried out in relation to quantifying the consequences of barrier failures in decommissioned wells, by Ford et al., (2017), for quick estimation of the leakage potentials. Their model considers three leakage pathways: leakage through the cement bulk, faults and fractures, and micro-annuli.

In this study, the leakage simulator can provide a semi-quantitative assessment of the leakage rate and the associated risks that co-occur with compromising the integrity of the NT decommissioned wells' barrier components. In addition to the well barriers' performance, the creep of the Beetaloo basin shale formations will be taken into account by the simulator, which can benefit the community in terms of providing more assurance and identifying the impacts of decommissioned well leakage rate.
This research will investigate the competency of the shale in the Beetaloo basin to form a natural barrier and create zonal isolation. In addition, the sensitivity of shale specimens (obtained from the Beetaloo basin) to changing the chemistry of the annular fluid and the associated impacts on the shale creep rate will be examined. First, a literature review of the current state-of-knowledge will be performed. Then, a systematic series of downscaled laboratory experiments will be run on cylindrical specimens comprising a steel rod and shale samples under the specified (adapted to the Beetaloo basin characteristics) downhole stress conditions.

Need & Scope

As noted in the Independent Scientific Inquiry into Hydraulic Fracturing of Onshore Unconventional Reservoirs in the Northern Territory (Pepper et al., 2018), communities in the region of the Beetaloo Basin have expressed concerns about whether decommissioned wells could be a potential source of contaminants on long timescales. In other words, the likelihood of any connectivity forming between the target natural gas seam and surface aquifers happening after gas production ceased, and the well was plugged and abandoned is one of their main distresses. Therefore, it is important to assess the long-term integrity of the decommissioned wells in the conditions experienced in the Beetaloo Basin at the temperature, pressure, and stress conditions of the formations underground. It is also important to put the results of this work in the context of the potential risk of contamination of hydrocarbon fluid leakage. Therefore, the project focuses on two aspects:

(1) the sealing competency (chemo-poro-physical characteristics) of Beetaloo Basin shales, and
(2) the expression of these shale characteristics as impacting the potential for fluid flow to the surface over time (given the regulated decommissioning requirements in the NT).

Field observations and analyses in other jurisdictions have shown that shale creeps into the annular space can have the potential to act as a reliable well barrier. It may be possible to utilize this phenomenon in the Beetaloo Basin.

By understanding long-term behavioural interactions between the Beetaloo Basin shales and decommissioned gas wells, this project will highlight the role of creep behaviour in sealing wells and the potential for technological and regulatory development in this aspect of decommissioning processes.

Acceptable long-term integrity performance of decommissioned wells is another issue of community concern around decommissioned wells (Pepper et al., 2018). This project will provide an understanding on how the shale creep behaviour in the Beetaloo basin would potentially impact decommissioned well integrity over the long-term and in doing so inform the development of suitable monitoring programs for decommissioned wells. The development of the Beetaloo Basin well leakage simulator will provide regulators and gas companies the ability to analyse and determine suitable long-term performance behaviour of decommissioned wells.

Objective

Oil and gas wells comprise a linked series of steel casing, cement, and valves to establish multiple barrier envelopes to provide zonal isolation and prevent the movement of hydrocarbon fluids to the outside of the well. However, some concepts regarding maintaining decommissioned well integrity over time have been loosely defined, including the timescale pertaining to well integrity in perpetuity, the extent of contamination, and the associated risks.

The key aspect of this project investigates the self-sealing competency (creep occurrences) of the Beetaloo basin shales, and the potential to create a natural barrier that reduces the risk of contaminants entering the environmental systems. The first step of this aspect investigates the Beetaloo shale mineralogy and its mechanical properties to determine the potential sealing capability (creep rate). However, the creep phenomena in shale formations are time-dependent processes that innately may take decades to fill up the annulus or seal the formation fracture to a sufficient extent to prevent unintended fluid flow. Therefore, the potential for activation mechanisms (mostly changing the chemistry of the annular fluid) to be employed to accelerate the Beetaloo basin creep deformations will also be investigated.

A simple leakage rate simulator for plugged and decommissioned wells will be developed and tailored to the Beetaloo basin characteristics. It will incorporate the impact of shale creep behaviour in acting as a natural barrier as characterised in this project along with other physical processes that impact on well integrity.

Methodology

1. Research inquisitions:

- Literature Review (**Task 1**):

  A literature review of the understanding of shale as barriers during decommissioning, experimental studies, and possible activation mechanisms will be delivered. This review will summarise key aspects of the extensive literature on shale behaviour and its impacts on decommissioned wells. The review will focus on

  - Experimental input data collection for shales and well conditions.
  - The impacts of shale behaviour on well integrity.
  - Shale barrier validation methods.
  - Techniques and approaches to stimulate and activate shale in decommissioned wells.
  - Theoretical and experimental lab investigations to confirm the experimental study design.

- Defining key long-term decommissioned well integrity concepts (**Task 6**):

  A workshop will be conducted with regulators, industry, and technical experts to ground truth the integrity of decommissioned wells and the leakage rate caused by the compromised integrity of the decommissioned wells

- Developing a leakage rate simulator (**Task 5**):

  The main leakage pathways through failed well barrier components will be defined. The leakage calculator will consider all physical processes affecting the potential movement of fluids along possible pathways within a well and to the surface. Subsequently, the leakage rate will be estimated by considering different factors, including well architecture and trajectory, the type of compromised barrier components, the length of the barriers, the driving force, reservoir conditions, and the type of hydrocarbon formation fluids. Independent validation of the leakage calculator will be sought through industry and research peers.

2. Downscaled laboratory experiments:

- Evaluation of the mineral composition (**Task 2**) :

The core mineralogy is acquired by X-ray diffraction (XRD). Major mineral constituents and organic-matter contents are to be quantified prior to the experiments. After the minerals present in the samples were identified, each mineral phase's reference intensity ratios (RIR) values were determined, with corundum (cor). The RIR value relates the intensity of the peak of interest and the standard peak in an XRD pattern. This value allows us to quantify the different minerals in the samples subsequently.

- Evaluation of chemo-poro-elastic properties (**Task 2**) :

In order to identify and foresee the swelling and shrinking response of shales to different chemical solutions in annular fluids, the chemoporoelasticity properties of the shale are to be measured utilizing the MicroRX rig.

- Performing triaxial creep tests (**Task 3**):

This study's main objective is to determine the creep rate and characterize the creep behaviour of shale samples acquired from the Beetaloo basin. This project also investigates the effect of changing the chemistry of annular fluid on the acceleration of creep processes.

Specimens consisting of a cylindrical steel rod and hollow cylindrical shales with a gap between them will be employed to run multistage triaxial creep tests. The servo-controlled triaxial apparatus set-up is to be developed and assembled containing Hook's cell, ISCO-pump to provide confinement pressure, and data acquisition configurations. The vertical strains will be measured with two LVDTs (Linear Variable Differential Transformer), which will be placed 180˚ apart at the top platen. The specimens will be outfitted with a cantilever bridge to measure radial strain deformations. The multistage triaxial creep tests are performed by applying constant confining pressure followed by applying the axial load (deviator stress), which is kept constant for the desired time interval. The axial load will be increased and held constant if required during the following steps. The specimen deformation is monitored and recorded for the complete duration of the test. At first, the time-dependent creep behaviour of Beetaloo shale samples will be examined by performing triaxial creep tests under dry room conditions while no fluid is flowing into the system. Secondly, the triaxial creep tests will be repeated while artificial pore fluid with different brine concentrations enters the system. It is worth mentioning that solutions of Potassium chloride (KCl) solutions will be incorporated into the designed annular fluids to prevent swelling of clay minerals, which also hinders the shale softening and decreases the degradation of mechanical properties. Finally, the creep behaviour of the samples is determined. After this step, the annular fluid will be displaced by a test fluid consisting of different chemicals (i.e., sodium silicate mud, lithium silicate solution). The triaxial creep tests will be performed, and radial and axial strain will be measured over time to identify the effect of changing pore fluid chemistry on the creep rate of the shale specimens.

- Analyses of experimental results (**Task 4**):

Young's modulus (E) is computed from the slope of the stress-strain curves at the loading stages. The data obtained from performing a series of triaxial creep experiments on samples at different applied differential stresses are utilized to describe creep behaviour. The results obtained from changing pore fluid chemistry will be assessed to identify the associated impacts on the creep rate.

In addition, the leakage rate simulator will be updated and tailored based on the findings (Task 3 and 4) specifically applicable to the Beetaloo basin shale.

- Project reporting and outcomes communications (**Task 8 and 9**):

A final report, encompassing the project scope, methodology, assumptions, and experimental outcomes from the running shale creep experiments and developing a leakage rate simulator, will be prepared and communicated through a knowledge transfer session with the government/gas industry and presentations to the community members/groups.

It is worth mentioning that the experimental results and sensitivity to annular fluid chemistry are only applicable to the obtained specific shale type, and it may not be feasible to generalize the results to all types of shales considering that shales are different in terms of mineralogy, particularly in the amount of clay and also the percentage of other constituents including Smectite, Quartz, Illite, Kaolinite, and Chlorite.

3. Project Inputs

Previous Research

Australia's oil and gas industry is at various stages of maturity across different basins and over time all of the petroleum wells will need to be decommissioned. Therefore, well decommissioning operations in Australia will be an inevitable, evolving, and long-lasting process. Subsequently, Australia needs to develop effective strategies and take advantage of local geological features to ensure the long-term risks of decommissioned well leaks are minimised into the future. The previous CSIRO (GISERA) research on decommissioning are as follows:

1) "Decommissioning coal seam gas wells" (project number: S.9)
2) "Improved approaches to long-term monitoring of decommissioned wells." (project number: W.20)

The first research covered the regulatory frameworks and examines the characteristics of successful decommissioning jobs from the perspective of different stakeholders and developed policy possibilities for government regulators and industry operators in coal seam gas (CSG) reservoirs. The latter research examined the available options for monitoring the integrity of petroleum wells after decommissioning in the Northern Territory that are commensurate with the risks of well integrity failure.

Resources and collaborations

This project has two key aspects related to understanding the long-term performance of decommissioned wells. Firstly the project proposes to investigate the self-sealing competency (creep occurrences) of the Beetaloo basin shales during and after decommissioning and estimates the protentional performance of any created natural barrier in preventing contaminants entering the environment. The Beetaloo shale mineralogy will be defined through collaborations with the Mineral business unit in CSIRO to determine the potential sealing capability (creep rate). Secondly, decommissioned well integrity concepts will be captured in a developed a simple leakage simulator. The simulator will quantify the consequences of a compromised barrier or multiple barriers within a decommissioned well, which results in leakage to the surrounding environment and the impact of Beetaloo basin shale creep behaviours.

Researcher	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organization
Elaheh Arjomand	87 days	Well integrity	> 5	CSIRO
James Kear	45 days	Environmental and petroleum engineering	> 15	CSIRO
David Down	80 days	Instrumentation	> 20	CSIRO
Cameron Huddlestone-Holmes	17 days	Geologist	> 20	CSIRO
CSIRO Minerals	10 days	XRD Capability	> 5	CSIRO

Subcontractors (clause 9.5(a)(i))	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
N/A				

Technical Reference Group

The project will establish a Technical Reference Group (TRG) to seek peer-to-peer technical advice on contextual matters and discuss research requirements and outputs as the project progresses. The TRG will most likely be composed of:

- The project team members
- A representative from the Petroleum Branch, NT Department of Environment and Natural Resources
- A representative from the Northern Territory Geological Survey
- Representatives from operating companies in the NT
- A representative from a regulator outside of the NT (South Australia, Queensland or WA.)
- An industry expert on well integrity (consultant)
- An academic expert on well integrity (university-based)

Budget Summary

Source of Cash Contributions	2021/22	2022/23	2023/24	2024/25	2025/26	% of Contribution	Total
GISERA	$0	$266,640	$109,605	$0	$0	80%	$376,245
- Federal Government	$0	$176,649	$72,613	$0	$0	53%	$249,262
- NT Government	$0	$29,997	$12,331	$0	$0	9%	$42,328
- Santos	$0	$29,997	$12,331	$0	$0	9%	$42,328
- Origin	$0	$29,997	$12,331	$0	$0	9%	$42,328
Total Cash Contributions	**$0**	**$266,640**	**$109,605**	**$0**	**$0**	**80%**	**$376,245**

Source of In-Kind Contribution	2021/22	2022/23	2023/24	2024/25	2025/26	% of Contribution	Total
CSIRO	$0	$66,660	$27,401	$0	$0	20%	$94,061
Total In-Kind Contribution	**$0**	**$66,660**	**$27,401**	**$0**	**$0**	**20%**	**$94,061**

TOTAL PROJECT BUDGET	2021/22	2022/23	2023/24	2024/25	2025/26	-	TOTAL
All contributions	**$0**	**$333,300**	**$137,006**	**$0**	**$0**	**-**	**$470,306**
TOTAL PROJECT BUDGET	**$0**	**$333,300**	**$137,006**	**$0**	**$0**	**-**	**$470,306**

4. 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	A fact sheet at commencement of the project which explains in plain English the objective of the project. A factsheet with general information on decommissioning and well integrity, highlighting the role of geology, to provide a resource for the community.	At commencement of the project.
Gas Industry	Industry adopts methods for improving decommissioning technologies	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
Community stakeholders, including land holders and traditional owners.	Presentation of research findings	A range of approaches will be explored to present findings to the community, with close alignment with GISERA communication's activities. This may include, but not necessarily be limited to, plain English documents (e.g., 'The Conversation' articles, fact sheets) and material shared by CSIRO on relevant social media forums. Opportunities for face-to-face forums with stakeholder groups (through NTCA, NLC, CLC for example) will be explored.	At Completion
Regional community/wider public, government, scientific community and industry	To report on key findings	Public release of final report. Plain English factsheet summarising the outcomes of the research. Web based and simplified version of leakage simulator.	At project completion

In addition to project specific communications activities, CSIRO's GISERA has a broader communications strategy. This strategy incorporates activities such as webinars, roadshows, newsletters and development of other communications products.

5. Project Impact Pathway

Activities	Outputs	Short term Outcomes	Long term outcomes	Impact
Define long-term decommissioned well integrity concepts	The project's final report will cover the identified concepts.	Developing a leakage rate simulator will provide a scheme to measure the contamination degree and subsequently estimate the associated risk to the environment. This project helps to raise the NT community's awareness regarding : • Field observations in relation to shale formation behaviour which could creep into the annular space and perform as an acceptable barrier • NT shales considered to a competent well integrity barrier • Beetaloo shale creep mechanisms and the potential activation techniques to expedite the creep strains to seal the reservoir fracture and fill up the annular space within the decommissioned wells.	Assist in informing governments, regulators, and policy-makers regarding the shale mineralogy impact on the performance of the shale formations as a competent barrier. This project could also benefit the industry by improving its decommissioning practice and decision-making processes to optimize its profits and reduce the associated costs. The experimental outcomes could lead to achieving greater trust between industry, government, community and CSIRO by showing the creep behaviour in shale reservoirs and its impact on providing complete zonal isolation and achieving long-term well integrity.	*Environmental Impact:* The NT communities that live in the proximity of shale gas zones and industry will benefit from the outcomes of this research. By raising awareness of the environmental impacts of activating shale to form a natural barrier in decommissioned wells to provide complete zonal isolation and achieve long-term well integrity. *Social Impact:* This project offers knowledge to the community regarding achieving long-term well integrity for decommissioned wells which results in greater assurance and trust between government, industry, and the NT community. *Economic Impact:* The costly decommissioning procedures (i.e. cement plug placement costs, rig time, etc.) could be avoided by activating overburden shales to creep and form an acceptable barrier.
Develop a decommissioned well leakage simulator to bound potential contaminant flux over the long-term	The project's final report will cover a chapter explaining the simulator and the development processes.			
Literature review	The project's final report will cover a literature review on the concept of shale barriers, experimental studies, and possible activation mechanisms.			
Evaluation of Beetaloo shale mineralogy	The final report will incorporate a report reviewing the results of XRD studies to determine the shale mineralogy along with the minerals' quantification.			
Evaluation of the shale chemoporomechanical properties	The chemoporoelastic properties, including hydraulic diffusivity (D_h) and ionic diffusivity (D_c) will be defined.			
Performing triaxial creep tests	The creep behaviour of the Beetaloo shale will be described.			
Investigating the effect of pore fluid chemistry on the creep behaviour	The potential activation techniques to expedite the creep strains will be assessed.			
Results interpretations	Experimental results and observations will be incorporated into the final report, along with data interpretations.			
Project Reporting	This project will be documented and published through CSIRO's internal review processes.			
Communicating with key stakeholders	The project objectives, progress, and results to GISERA stakeholders according to standard GISERA project procedures will be communicated.			

5. Project Plan

Project Schedule

ID	Activities / Task Title	Task Leader	Scheduled Start	Scheduled Finish	Predecessor
Task 1	Literature review of the concept of shale barriers, experimental studies, and possible stimulation mechanisms	Elaheh Arjomand	15 Aug 2022	15 Oct 2022	-
Task 2	Acquire the shale core samples from the Beetaloo basin and quantify the shale mineralogy and chemoporomechanical properties	James Kear	15 Sep 2022	15 Jan 2023	-
Task 3	Perform triaxial creep tests under different downhole conditions to characterize Beetaloo shale behaviour	Elaheh Arjomand	15 Nov 2022	15 Jul 2023	Task 2
Task 4	Results interpretations	Elaheh Arjomand	15 May 2023	15 Aug 2023	Task 2,3
Task 5	Develop a decommissioned well leakage simulator to bound potential contaminant flux over the long-term	James Kear	15 Mar 2023	15 Jul 2023	-
Task 6	Define key long-term decommissioned well integrity concepts such as timescale, and contamination grade	Cameron Huddlestone-Holmes	15 Jun 2023	15 Jul 2023	Task 1
Task 7	Update decommissioned well leakage simulator with Beetaloo shale properties	James Kear	15 Jul 2023	15 Oct 2023	Task 5
Task 8	Project reporting	Elaheh Arjomand	15 May 2023	15 Nov 2023	Task 2,3,4,5,6,7
Task 9	Communicate findings to stakeholders	Elaheh Arjomand	Project duration		

Task description

Task 1: Literature Review

OVERALL TIMEFRAME: August 2022 to October 2022

BACKGROUND: Stimulating and activating the shale can happen through temperature and pressure changes imposed on the shales and also utilizing some chemicals. Chemical activation might be more straightforward than imposing temperature changes in field applications. The chemical solutions are circulated through the annular space by casing perforations with a workstring and packer arrangement.

TASK OBJECTIVES:

The main emphases of the literature review will be placed on:

1.1) Experimental input data collection includes downhole conditions, wellbore characteristics, nominating chemicals
1.2) Shale barriers validations using logging techniques with the intent to qualify the formed shale barrier.
1.3) Techniques and approaches to stimulate and activate shale in decommissioned wells
1.4) Theoretical and experimental lab investigations to confirm the design of the studies in task 3.2

TASK OUTPUTS AND SPECIFIC DELIVERABLES: An internal report summarizing the literature review on the concept of shale barriers, experimental studies, and possible activation mechanisms will be delivered. This internal report will be incorporated into the project's final report.

Task 2: Evaluation of the Beetaloo shale mineralogy and chemoporomechanical properties

OVERALL TIMEFRAME: September 2022 to January 2023

BACKGROUND: Shale mineralogy (mainly the amount of clay and also the proportion of other constituents, including Smectite, which acts as a bonding agent) plays a critical role in the performance of the shale to act as an appropriate barrier. In addition, the response of shale to different annular fluids chemistry influences the time-dependent creep behaviour. In order to study the swelling and shrinkage of the shale, the chemoporomechanical properties, including the determination of chemoporoelastic properties including hydraulic diffusivity $(\mathrm{D_h})$ and ionic diffusivity $(\mathrm{D_c})$ should be measured.

TASK OBJECTIVES:

2.1) Acquiring the shale core samples from the Beetaloo basin
2.2) Determination of core mineralogy by X-ray diffraction (XRD). Main mineral constituents and organic-matter contents will be quantified prior to the experiments
2.3) Commissioning the MicroRX rig
2.4) Sample preparation
2.5) Preparing the fluids test and the chemical solutions

2.6) Measuring the chemoporoelastic properties

TASK OUTPUTS AND SPECIFIC DELIVERABLES: An internal report summarizing the results of XRD studies along with mineral quantifications, rig calibration, and chemoporoelastic properties will be incorporated into the project's final report.

Task 3: Performing triaxial creep tests and investigating the effect of pore fluid chemistry on the creep behaviour

OVERALL TIMEFRAME: November 2022 to July 2023

BACKGROUND: The data obtained from performing a series of triaxial creep experiments on samples under downhole pressure conditions are to be utilized to describe creep behaviour. The set-up is designed in a way to be able to run the tests under dry conditions while no fluid enters the system or run the tests while artificial pore fluid with different brine concentrations flows into the system. In addition, different fluids with different chemical solutions enter the system during each creep test to investigate the effect of changing the chemistry of annular fluid on the acceleration of the creep processes.

TASK OBJECTIVES:

3.1) Running triaxial creep tests under dry downhole pressure condition
3.2) Running triaxial creep tests while artificial pore fluid with different brine concentrations flows into the system
3.3) Preforming the triaxial creep tests under downhole conditions along with investigating the effect of chemical solutions

TASK OUTPUTS AND SPECIFIC DELIVERABLES: The experimental results along with results interpretations will be summarized and incorporated into the final results.

Task 4: Results interpretations

OVERALL TIMEFRAME: May 2023 to August 2023

BACKGROUND: Shale mechanical properties, including young's modulus (E), are computed from the slope of the stress-strain curves at the loading stages. The data obtained from performing a series of triaxial creep experiments on samples at different applied differential stresses and subjected to changing pore fluid chemistry is utilized to define time-dependent creep behaviour.

TASK OBJECTIVES:

4.1) Defining creep behaviour of the Beetaloo basin shale according to the obtained experimental outputs
4.2) Observing the impact of different pore fluid chemistry on the Beetaloo basin shale creep rate

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Experimental results, observations, and data interpretations will be incorporated into the project's final report.

Task 5: Developing a leakage rate simulator

OVERALL TIMEFRAME: March 2023 to June 2023

BACKGROUND: A simple leakage simulator model will be developed to quantify the consequences of compromising a barrier or multiple barriers, which results in leakage from a plugged and decommissioned well to the surrounding environment. The leakage calculator will consider all physical processes affecting the potential movement of fluids along possible pathways within a well and to the surface. Independent review for the leakage simulator will be sought from industry and research peers.

TASK OBJECTIVES:

The main emphases in developing the simulator will be placed on:

- 5.1) Developing a leakage rate simulator for formation fluids flowing from the reservoir to the potential leakage pathways.
- 5.2) Quantifying the contamination intensity due to the well leakage.

TASK OUTPUTS AND SPECIFIC DELIVERABLES: A chapter explaining the simulator and the development processes will be incorporated into the project's final report.

Task 6: Defining the key long-term decommissioned well integrity concepts

OVERALL TIMEFRAME: June 2023 to July 2023

BACKGROUND: The leakage simulator model will be updated based on the findings of the previous tasks.

TASK OBJECTIVES:

- 6.1) Updating (tailoring based on the Beetaloo basin characteristics) the leakage rate simulator for formation fluids flowing from the reservoir to the potential leakage pathways

TASK OUTPUTS AND SPECIFIC DELIVERABLES: A chapter explaining the simulator and the development processes will be incorporated into the project's final report.

Task 7: Updating decommissioned well leakage simulator with Beetaloo shale properties

OVERALL TIMEFRAME: July 2023 to October 2023

BACKGROUND: The leakage simulator model will be updated based on the findings of the previous tasks.

TASK OBJECTIVES:

7.1) Updating (tailoring based on the Beetaloo basin characteristics) the leakage rate simulator for formation fluids flowing from the reservoir to the potential leakage pathways

TASK OUTPUTS AND SPECIFIC DELIVERABLES: A chapter explaining the simulator and the development processes will be incorporated into the project's final report.

Task 8: Project Reporting

OVERALL TIMEFRAME: May 2023 to November 2023

BACKGROUND: Information from this project is to be made publicly available after the 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:

8.1) Preparation of a final report outlining the scope, methodology, scenarios, assumptions, findings and any suggestions/options for future research.

8.2) Following CSIRO ePublish review, the report will be submitted to the GISERA Director for final approval; and

8.3) Provide 6 monthly progress updates to GISERA office.

Task 9: Communicate project objectives, progress and findings to stakeholders

OVERALL TIMEFRAME: Full duration of the project

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

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

TASK OUTPUTS AND SPECIFIC DELIVERABLES: Communicate project objectives, progress and results to GISERA stakeholders according to standard GISERA project procedures which may include, but not limited to:

9.1) Knowledge Transfer session with Government/Gas Industry

9.2) Presentation of findings to Community members/groups

9.3) Preparation of article for GISERA newsletter and other media outlets e.g. The Conversation

9.4) Revision of project factsheet to include final results (a factsheet is developed at project commencement, and another will be done at completion)

9.5) Peer reviewed scientific manuscript ready for submission to relevant journal

Project Gantt Chart

PERIODS Deliverable ◆

Task	OBJECTIVES	DESCRIPTION	ACTOR	15-Aug-22	15-Sep-22	15-Oct-22	15-Nov-22	15-Dec-22	15-Jan-23	15-Feb-23	15-Mar-23	15-Apr-23	15-May-23	15-Jun-23	15-Jul-23	15-Aug-23	15-Sep-23	15-Oct-23	15-Nov-23
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Task 1	1.1	Literature Review	EA	■	■														
	1.2		EA	■	■														
	1.3		EA	■	■														
	1.4		EA	■	■ ◆														
Task 2	2.1	Evaluation shale mineralogy & Evaluation of the shale chemoporomechanical properties	JK+EA+DD		■	■	■	■											
	2.2		JK+EA+DD		■	■	■	■											
	2.3		JK+EA+DD		■	■	■	■											
	2.4		JK+EA+DD		■	■	■	■											
	2.5		JK+EA+DD		■	■	■	■											
	2.6		JK+EA+DD		■	■	■	■											
Task 3	3.1	Performing Triaxial tests	EA+DD+JK				■	■	■	■	■	■	■	■					
	3.2		EA+DD+JK				■	■	■	■	■	■	■	■					
	3.3		EA+DD+JK				■	■	■	■	■	■	■	■					
Task 4	4.1	Results interpretations	EA+JK										■	■	■				
	4.2		EA+JK										■	■	■				
Task 5	5.1	Developing a leakage rate simulator	JK+CHH+EA								■	■	■	■					
	5.2		JK+CHH+EA								■	■	■	■					
Task 6	6.1	Defining the key long-term decommissioned well integrity concepts	CHH											■					
Task 7	7.1	Updating decommissioned well leakage simulator with Beetaloo shale properties	JK+EA+CHH												■	■	■		
Task 8	8.1	Project Reporting	JK+EA										■	■	■	■	■	■	■
	8.2		JK+EA										■	■	■	■	■	■	■
	8.3		JK+EA										■	■	■	■	■	■	■ ◆
Task 9	9.1	Communicate project objectives, progress and findings to stakeholders	EA+JK	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	9.2		EA+JK	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	9.3		EA+JK	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	9.4		EA+JK	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	9.5		EA+JK	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

6. Budget Summary

Expenditure	2021/22	2022/23	2023/24	2024/25	2025/26	Total
Labour	$0	$266,300	$127,006	$0	$0	$393,306
Operating	$0	$67,000	$10,000	$0	$0	$77,000
Subcontractors	$0	$0	$0	$0	$0	$0
Total Expenditure	**$0**	**$333,300**	**$137,006**	**$0**	**$0**	**$470,306**

Expenditure per task	2021/22	2022/23	2023/24	2024/25	2025/26	Total
Task 1	$0	$10,315	$0	$0	$0	$10,315
Task 2	$0	$78,060	$0	$0	$0	$78,060
Task 3	$0	$180,838	$14,696	$0	$0	$195,534
Task 4	$0	$22,714	$10,645	$0	$0	$33,359
Task 5	$0	$26,482	$0	$0	$0	$26,482
Task 6	$0	$9,839	$20,970	$0	$0	$30,809
Task 7	$0	$0	$26,868	$0	$0	$26,868
Task 8	$0	$3,789	$42,810	$0	$0	$46,599
Task 9	$0	$1,263	$21,017	$0	$0	$22,280
Total Expenditure	**$0**	**$333,300**	**$137,006**	**$0**	**$0**	**$470,306**

Source of Cash Contributions	2021/22	2022/23	2023/24	2024/25	2025/26	Total
Federal Govt (53%)	$0	$176,649	$72,613	$0	$0	$249,262
NT Govt (9%)	$0	$29,997	$12,331	$0	$0	$42,328
Santos (9%)	$0	$29,997	$12,331	$0	$0	$42,328
Origin (9%)	$0	$29,997	$12,331	$0	$0	$42,328
Total Cash Contributions	**$0**	**$266,640**	**$109,605**	**$0**	**$0**	**$376,245**

In-Kind Contributions	2021/22	2022/23	2023/24	2024/25	2025/26	Total
CSIRO (20%)	$0	$66,660	$27,401	$0	$0	$94,061
Total In-Kind Contributions	**$0**	**$66,660**	**$27,401**	**$0**	**$0**	**$94,061**

	Total funding over all years	Percentage of Total Budget
Federal Government investment	$249,262	53%
NT Government investment	$42,328	9%
Santos investment	$42,328	9%
Origin investment	$42,328	9%
CSIRO investment	$94,061	20%
Total Expenditure	**$470,306**	**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	Literature review of the concept of shale barriers, experimental studies, and possible stimulation mechanisms	GISERA	Aug-22	Oct-22	2022/23	$8,252
Task 2	2.1	Acquire the shale core samples from the Beetaloo basin and quantify the shale mineralogy and chemoporomechanical properties	GISERA	Sep-22	Jan-23	2022/23	$62,448
Task 3	3.1	Perform triaxial creep tests under different downhole conditions to characterize Beetaloo shale behaviour	GISERA	Nov-22	Jul-23	2023/24	$156,427
Task 4	4.1	Results interpretations	GISERA	May-23	Aug-23	2023/24	$26,687
Task 5	5.1	Develop a decommissioned well leakage simulator to bound potential contaminant flux over the long-term	GISERA	Mar-23	Jul-23	2023/24	$21,186
Task 6	6.1	Define key long-term decommissioned well integrity concepts such as timescale, and contamination grade	GISERA	Jun-23	Jul-23	2023/24	$24,647
Task 7	7.1	Update decommissioned well leakage simulator with Beetaloo shale properties	GISERA	Jul-23	Oct-23	2023/24	$21,494
Task 8	8.1	Project reporting	GISERA	May-23	Nov-23	2023/24	$37,279
Task 9	9.1	Communicate findings to stakeholders	GISERA	Aug-22	Nov-23	2023/24	$17,824

7. 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 13.1)	**Party**		**Commercialisation Interest**	
	CSIRO		Not applicable	
	Santos		Not applicable	
	Origin Energy		Not applicable	

8. References

An, C., Killough, J. and Xia, X. (2021) 'Investigating the effects of stress creep and effective stress coefficient on stress-dependent permeability measurements of shale rock', *Journal of Petroleum Science and Engineering*. Elsevier B.V., 198(November 2020), p. 108155. doi: 10.1016/j.petrol.2020.108155.

Boothroyd, I. M. *et al.* (2016) 'Fugitive emissions of methane from abandoned, decommissioned oil and gas wells', *Science of the Total Environment*. The Authors, 547, pp. 461–469. doi: 10.1016/j.scitotenv.2015.12.096.

Carlsen, T. (2012) 'Formation as barrier during P & A Formation as barrier', in *Wellbore Stability and Drilling Practice*.

Carpenter, C. (2021) 'Using Shale as a Barrier Simplifies Well Abandonment', *Journal of Petroleum Technology*, 73(01), pp. 62–63. doi: 10.2118/0121-0062-jpt.

Cerasi, P. *et al.* (2017) 'Shale Creep as Leakage Healing Mechanism in CO2 Sequestration', *Energy Procedia*. The Author(s), 114(1876), pp. 3096–3112. doi: 10.1016/j.egypro.2017.03.1439.

Feng, W. Q. *et al.* (2017) 'Long-term Non-linear creep and swelling behavior of Hong Kong marine deposits in oedometer condition', *Computers and Geotechnics*. Elsevier Ltd, 84, pp. 1–15. doi: 10.1016/j.compgeo.2016.11.009.

Ford, E. P. *et al.* (2017) 'Leakage calculator for plugged and abandoned wells', *Society of Petroleum Engineers - SPE Bergen One Day Seminar 2017*, 010(2013). doi: 10.2118/185890-ms.

Fredagsvik, K. (2017) 'Formation as Barrier for Plug and Abandonment of Wells Master thesis by Katrine Fredagsvik University of Stavanger', *Master ' S Thesis*.

Kristiansen, T. G. *et al.* (2018) 'Activating shale to form well barriers: Theory and field examples', *Proceedings - SPE Annual Technical Conference and Exhibition*, 2018-Septe(September), pp. 24–26. doi: 10.2118/191607-ms.

Liu, K. *et al.* (2021) 'Creep Behavior of Shale: Nanoindentation vs. Triaxial Creep Tests', *Rock Mechanics and Rock Engineering*. Springer Vienna, 54(1), pp. 321–335. doi: 10.1007/s00603-020-02255-4.

van Oort, E. *et al.* (2020) 'Simplifying well abandonments using shale as a barrier', *SPE/IADC Drilling Conference, Proceedings*, 2020-March. doi: 10.2118/199654-ms.

Ozan, C. *et al.* (2018) 'Assessment of creep potential of gearle formation for Griffin field PP&A planning', *52nd U.S. Rock Mechanics/Geomechanics Symposium*.

Pepper, R. *et al.* (2018) *Final Report of the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory*.

Skjerve, K. M. (2013) 'Evaluation of shale formations as barrier element for permanent plug and abandonment of wells', *Master Thesis Dissertation*, (June). Available at: http://hdl.handle.net/11250/2400752.

Sone, H. and Zoback, M. D. (2011) 'Visco-plastic properties of shale gas reservoir rocks', *45th US Rock Mechanics / Geomechanics Symposium*.

Strand, G. O. (2018) 'On technologies for shale barrier evaluation in the north sea', *Proceedings of the*

International Conference on Offshore Mechanics and Arctic Engineering - OMAE, 8, pp. 1–9. doi: 10.1115/OMAE2018-78309.