Assessment of Underground Storage in Oil and/or Gas Reservoirs

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1.0 EXECUTIVE SUMMARY

Salt caverns are currently used to store large quantities of hydrogen. Porous media, such as oil and gas reservoirs, can offer greater volume, be found more abundantly, and are often furnished with infrastructure that could be potentially be repurposed. This makes them an attractive solution should the need for larger scale hydrogen storage develop, as is predicted through the energy transition.

This report aimed to assess the oil and gas reservoirs in Southern California to identify potential hydrogen storage sites. Starting with pool of 314 existing oil and gas fields, these were screened for proximity to key locations identified by SoCalGas. The remaining [redacted] candidates were entered into a spreadsheet model and populated with key attributes to determine their suitability. Following examination, [redacted] candidates remained which were then filtered quantitatively based on location, geological and commercial factors. [redacted] passed all filters and were further scrutinized manually resulting in several adjustments. Some sites were removed which had undesirable features not captured by the prior screens and filters, while some sites were added which may, for example, have performed exceptionally well against one of the filters, but not passed in another category. A shortlist of [redacted] candidates were then ranked to identify the top [redacted] candidates for hydrogen storage: [redacted].

A more detailed geological assessment was conducted on the top candidates with [redacted] initially identified as the site with most potential for hydrogen storage. [redacted] Despite passing all screening and filters, [redacted], which highlighted that selection can be guided by filters and screening and ultimately an in-depth assessment is necessary. [redacted]. With this revised criteria, [redacted] and [redacted] were now identified [redacted] was also revisited [redacted] as was [redacted] due [redacted]

Ultimately [redacted] was identified as [redacted]

[redacted] was selected early in the process as a case study to investigate the likely scope and cost of a re-development into a hydrogen storage site. To fully characterize a site geologically, understand the minerology, address the need to abandon and re-abandon old wells, and drill new wells designed specifically for hydrogen service, the cost was estimated to be at least [redacted] with further costs expected dependent on the level of reservoir characterization and resolution of land and mineral rights.

[redacted]

2.0 INTRODUCTION

As the energy transition in California gathers momentum, an increased need for hydrogen storage and carbon dioxide sequestration is expected. Hydrogen can be produced using excess renewable energy at peak production times as a method to store energy for later use. It can also be sold for other applications as a raw product. Another method of producing hydrogen is to use natural gas, the methane produces both hydrogen and carbon dioxide from the process. If the carbon dioxide is permanently sequestered, the conversion of the methane to hydrogen has a smaller environmental footprint.

Hydrogen has been stored underground in salt caverns for decades. However, these caverns may not be large, plentiful, or located conveniently enough, for the demand for hydrogen storage that is anticipated from the energy transition. Porous media, especially depleted oil and gas reservoirs have been touted as a potential alternative to expand storage capacity for hydrogen as well as a solution for the permanent sequestration of carbon dioxide.

This project aims to identify potential candidates in Southern California for hydrogen storage, [redacted] InterAct PMTI (InterAct) has performed a preliminary assessment using location, geological and commercial filters. From the shortlisted candidates, a field development plan is proposed to understand the likely scope and cost of future work to re-purpose a site.

This report briefly discusses the desirable properties for both hydrogen and carbon dioxide storage reservoirs as summarized from available literature. The California Geologic Energy Management Division (CalGEM) dataset of known Californian oilfields is used as the starting population. Candidate sites that are clearly unsuitable for the given project parameters are eliminated before remaining candidates are subject to quantified filters that screen out further unsuitable sites. These filters are explained in detail and culminate in an initial shortlist of [redacted]

The screening process was necessarily done at a very high level, and it is emphasized here that passing the filters is not a guarantee of suitability, but a guide to sites that may warrant further investigation. [redacted]

3.0 HYDROGEN AND CARBON DIOXIDE STORAGE

3.1 Need for Storage

One of the drivers for large scale hydrogen storage is a result of the energy transition. Hydrogen production and storage is a convenient solution to store energy for phase shifting energy demand as well as decarbonizing current hydrocarbon energy sources.

Renewable energy is produced with variability that does not always match demand e.g. solar power is produced when the sun shines but electricity is needed for lighting when the sun has set. More energy may also be produced than demand consumes at certain times. A method is required to store the excess energy when it is not needed and reuse it when there is demand. Commonly, batteries have provided the answer which work well on a small scale and for short-term storage. Hydrogen, however, is touted as a storage medium for larger scale, and longer term (i.e. seasonal) storage which can enable effective load shifting. Excess energy is used to create hydrogen which can then be used in its pure form or by blending it with natural gas for power generation or supply. Alternatively, it can also be used to create more valuable products.

Hydrogen is an element which does not plentifully exist naturally in commercially useful quantities; although efforts are underway to discover so called ‘Gold Hydrogen’[1]. More frequently, hydrogen must be manufactured by some process from other compounds. In the context of the energy transition, the method used to manufacture hydrogen is coded a with a color.

One method is to generate hydrogen from natural gas (methane) by a process such as steam reforming. As part of this process, carbon dioxide is also created. If that carbon dioxide can be permanently sequestered, the method is termed ‘Blue Hydrogen’. Therefore, blue hydrogen generation will require storage of both hydrogen and the carbon dioxide by-product. The focus of this project is hydrogen storage although sites for carbon dioxide sequestration will also be considered. If the carbon dioxide is not be captured, the method is termed “Grey Hydrogen” which is currently the most common method of hydrogen production.

In the context of this project, it is also feasible that “Green Hydrogen” is manufactured. This process produces no harmful greenhouse gas emissions. Renewable energy is used to produce hydrogen directly, usually by electrolysis of water. In this case, no carbon dioxide is produced and so only hydrogen storage would be required.

[1] https://www.durham.ac.uk/research/institutes-and-centres/durham-energy-institute/research-profile/current-projects/gold-hydrogen/, *Accessed 09/15/2021*

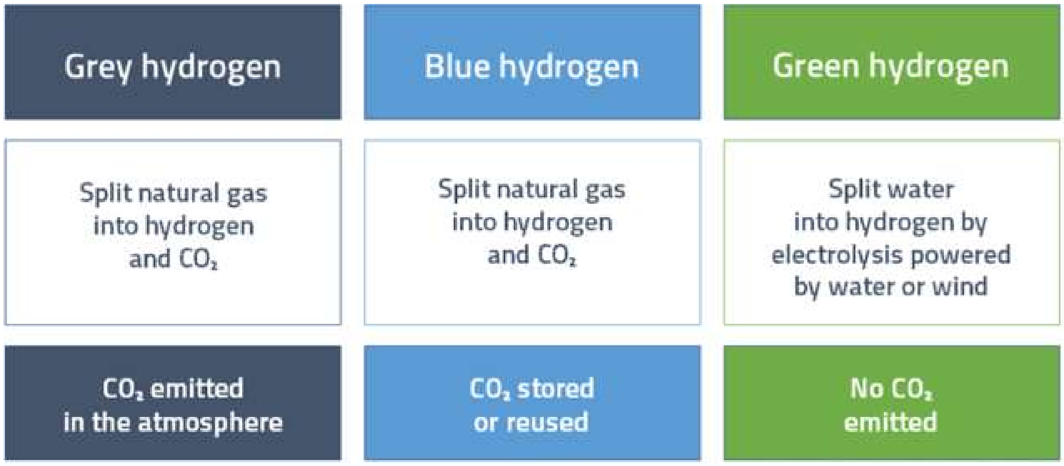

Figure 3-1, Different Hydrogen Types[2]

Hydrogen storage sites should be suitable for cyclic loading from injection and withdrawal cycles while carbon dioxide storage needs to be permanently and demonstrably sequestered for an indefinite period. Preferable minerology here would promote carbonate precipitation to solidify the carbon dioxide, assuring permanent sequestration.

These different requirements along with different behaviors (chemical and physical) of the gases themselves, can lead to different sites being suitable for hydrogen or carbon dioxide.

3.1.1 Storing Hydrogen

Commercial underground storage of hydrogen has historically occurred in salt caverns with notable sites in the UK, as well as Texas. Another large facility is currently planned near Salt Lake City, UT. At present, salt caverns offer the lowest cost storage solution and simplest method of retaining hydrogen purity. However, suitable sites are limited both in terms of size and frequency, and none are known of in Southern California. In contrast, the prevalence of aquifers and oil and gas reservoirs make such structures good potential storage sites. The concept of such is borne from historical experience in storing 'town gas' which was natural gas with up 25-60% hydrogen.

[redacted]

[redacted]

[2] https://aureliaturbines.com/articles/for-the-green-deal-hydrogen-also-needs-to-be-green, *Accessed 8/20/2021*

3.1.2 Storing Carbon Dioxide

While storage of carbon dioxide is not a focus of this project, it is worth pointing out the differences compared to storing hydrogen. Firstly, the objective is that it is intended to be permanent sequestration with no need for cycling, therefore mechanical properties of the media may differ from what is required for hydrogen storage. Also, prominent issues in hydrogen storage such as microbial consumption of the product is not as important for carbon dioxide. The CO_2 molecule is also large, more akin to natural gas, meaning current flow models are more representative, and pathways more predictable. Furthermore, Carbon Capture and Sequestration (CCS) is not such a new concept as hydrogen storage, with several pilot projects already underway and a more developed understanding of the technology. As such, the supply chain is already much better equipped with products available to combat known challenges. For example, carbon dioxide has a detrimental effect on portland cement but resistant cements have been developed. Similarly, elastomers for downhole components such as packer seal elements, and safety valves have carbon dioxide rich environment variants.

4.0 STORAGE SCREENING

The storage site candidates were identified from the 314 onshore oil and gas fields listed in the California Oil and Gas Fields, Volume 1 (Central California, 1998) and Volume II (Southern California, 1992) publications from CalGEM. An additional 151 fields in northern California and 33 offshore fields were rejected due to the location being beyond the project scope area. Next, [redacted] This left [redacted] potential sites. Additional fields were rejected due to having undesirable characteristics identified from prior experience. [redacted]

A further [redacted] sites were rejected in this manner. The remaining [redacted] potential storage candidates were then subject to the three filter categories which can be classified as follows.

1) Location
2) Geological Criteria
3) Commerciality

[redacted]

Using the filters, [redacted] potential sites were identified for hydrogen storage and [redacted] using screening parameters adjusted for the application.

The process is summarized in the following figure with filters (in grey) set for hydrogen storage criteria.

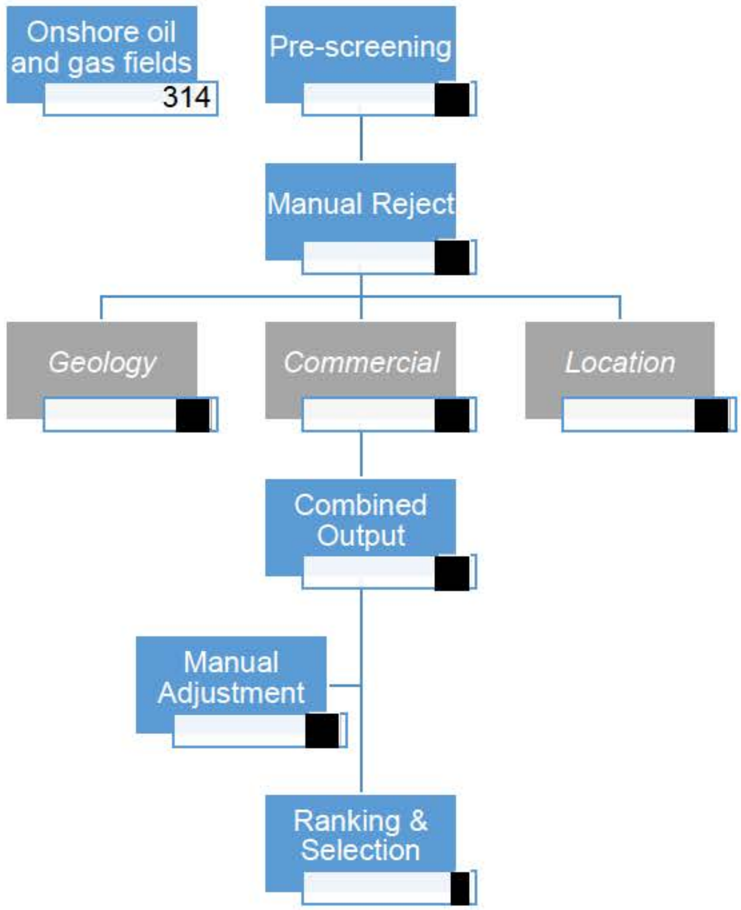

Figure 4-1, Summary of Screening Process

4.1 Pre-Screening

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

5.0 STORAGE CANDIDATES

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[5] CA Department of Conservation (2008). *California Oil and Gas Fields, Volume 1, Central California*

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

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[redacted]

[redacted]

[redacted]

5.4 [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted] [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

5.6 [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

5.7 [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

5.9 [redacted]

[redacted]

[redacted]

6.0 FIELD DEVELOPMENT SCOPE

Having identified the most likely hydrogen storage candidates from initial screening and analysis, there is still considerable investigative and development work required prior to confirmation of the suitability of the site for hydrogen storage. The subsections below discuss the work that is recommended for any leading candidate.

6.1 Field Study

The first step should be to characterize the reservoir in depth to fully understand the trap and seal mechanism, the effort for which will vary depending on existing offset well and/or seismic data. [redacted]

The existing reservoir fluids should be characterized. The low viscosity and high diffusivity of hydrogen make the gas less favorable for displacing in situ fluids, especially brine. This could result in pockets of unrecoverable hydrogen. A flow model of hydrogen migration through reservoir should also be attempted although the comparably low viscosity means commonly applied viscosity models may not be applicable to hydrogen. It is favorable for enabling faster injection and withdrawal of the reservoir. However, lower injection rates could help limit lateral spreading of the hydrogen for more stable, in situ brine displacement. Lower production rates will reduce coning and the rise of fluid interface resulting in less water production and a reduction of gas pressure. While hydrogen will be stored in the gaseous phase, the Ideal Gas Law can be used to describe its behavior at low pressures (<1800 psi) but this becomes less valid at higher pressures[7].

Mineralogy is of great importance, since reactions with hydrogen can change the physical properties of the reservoir (strength, porosity, etc.). Mineral precipitation can lead to reduced injectivity and recovery. This may be expected with clay minerals, although swelling has historically been correlated with freshwater content. Alternatively, dissolution may enhance injectivity but could also lead to migration pathways through the caprock as well as altering the mechanical properties of the formation. Subsurface sandstones have shown dissolution of carbonate and sulphate cements leading to an increase in porosity during hydrogen exposure. This can also affect the long-term integrity of the reservoir. Clay swelling minerals may induce swelling related stresses and conversely repetitive cycling of dry hydrogen may cause clay minerals to dry out and compact, leading to cracks and leak pathways. Framework materials such as quartz and feldspar remain unaffected by hydrogen[8].

Hydrogen consuming microbes can also develop with methanogens, sulphate-reducers, homoacetogenic bacteria and iron-reducers having been identified as major consumers in sub-surface formations. Hydrogen may also be unrecoverable after being converted into products such CH_4 and H_2S. Abiotic pyrite reduction can produce H_2S while generation may be inhibited

[7] Stone, H.B., et al. (2009), *Underground Hydrogen Storage in the UK,* Geological Society, London.
[8] Heinemann, N., et al., (2021), *Enabling Large-Scale Hydrogen Storage in Porous Media*, Journal of Energy and Environmental Science, Royal Society of Chemistry

by the presence of carbonate materials[8]. Assuming the presence of sulfur will allow the potential for H_2S, to form, candidates can be screened for sulfur content as a proxy for H_2S potential. [redacted]

6.2 Well Assessments

As discussed in the screening criteria, [redacted]. All remaining wells in the field will require analysis to ascertain technical risks and economic implications.

- **Abandoned wells:** These wells should be assessed for compliance with current well P&A regulations and objectively assessed through barrier element identification and verification to determine that they are fit for gas storage, and especially for hydrogen. Should wells be deficient, re-abandonments can represent significant technical risk with highly variable costs. If the quality and composition of the cement across the cap rock is uncertain, measures should be taken to re-enter the wells to ensure proper isolation of the storage zone.
- **Active and Idle wells:** The condition of existing wells' cement and casing will need to be analyzed to determine suitability for storage operation. This may include assessment programs similar to those conducted at natural gas storage sites which consist of casing wall thickness measurements, pressure testing and cement bond log analyses.

[redacted] Prior to this date the American Petroleum Institute (API) had not standardized plugging procedure and cement composition meaning cement was often contaminated with mud and failed to harden into an effective seal[9].

It is likely that injection and withdrawal requirements for hydrogen storage will require construction of new wells. Tests should be run on tubulars and cement for such wells to ensure they are suitable for hydrogen service to avoid hydrogen embrittlement of tubulars and potential failure of cement to isolate in a hydrogen environment.

[redacted]

[9] Ide, S.T, et al., (2006), *CO_2 Leakage Through Existing Wells: Current Technology and Regulations,* Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies, Trondheim, Norway 19-22 June, 2006

7.0 FIELD DEVELOPMENT COST ESTIMATE

In order to transition from an oil and gas reservoir to a hydrogen storage facility, some cost is inevitable. In order to give an indicative cost, the [redacted] was selected to in order to illustrate potential costs. These costs are estimated below. Surface facilities are not included in this report.

7.1 Acquisition Costs

[redacted] This is likely to be made up from the following.

- [redacted]
- [redacted]
- [redacted]

Compensation has been estimated based on an estimate of remaining reserves in line with the method described in Section 4.4. For [redacted] this totals [redacted]

[redacted]

[redacted]

The total cost to access the site is estimated to be [redacted] with additional cost for [redacted] and thus not included.

7.2 Remedial Well Work

[redacted]

[redacted]

[redacted]

[redacted] Costs, and indeed risk, for re-abandonments will vary hugely on a per well basis, depending on when the abandonment occurred, and the records of such.

An average order of magnitude cost of re-abandonment is estimated to be [redacted] per well. This estimate is based on recent well re-abandonment work done in the [redacted] Such [redacted], or [redacted], is

[10] https://maps.conservation.ca.gov/doggr/wellfinder/#openModal/-118.59506/34.45918/14, *Accessed 8/19/2021*

[redacted] The estimate also includes [redacted] Detailed cost estimate is shown in Appendix B.

All [redacted] active or idle wells are recommended [redacted] if the field is to be used for hydrogen storage. [redacted]

The order of magnitude cost of abandoning a typical well at [redacted] is estimated to be [redacted] per well. While these wells do not require new wellheads or drilling out of existing cement, they will require clean out and plugging of zones below the caprock.

7.3 New Well Work

Initial new well work may be required to better characterize the reservoir. This could come from sidetracking existing wells prior to abandonment, or new wells may be required. Cores may need collecting to understand mineralogy and/or infill wells may be required to further characterize the reservoir extent and trap features, if not well understood.

If initial investigative work confirms the suitability of the site, new wells will also be required to meet injection and withdrawal requirements. Drilling of new wells rather than conversion of existing wells allows the opportunity to design specifically for hydrogen service.

Material selection in the design of the well will be critical. [redacted] It is estimated that the leak rate of hydrogen over natural gas from steel pipe may be up to three times greater[12].

Hydrogen embrittlement of steel, which may affect well tubulars, is reasonably well understood. Stronger steels (tensile strength >145ksi) and operating temperatures above 300°F are more conducive for hydrogen embrittlement[11], both conditions which are unlikely in typical tubular selection and well placement. However, fatigue properties in high stress, low cycle loading is strongly affected by hydrogen embrittlement. High pressures (2000 psi), which are feasible for injection, can cause hydrogen induced cracking[12] Some experiments designed to replicate downhole environments have however, shown no hydrogen embrittlement in samples of N80,

[11] https://en.wikipedia.org/wiki/Hydrogen_embrittlement, *Accessed 2/8/2021*
[12] Melaina, M.W., et al. (2013) *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*, NREL – National Renewable Energy Laboratory.

K55 and J55 milled steel sections. These were placed in a high salinity brine and exposed to hydrogen at 100°C (212°F) and 100 bar for a period of 4 weeks.[13]

Based on current well density in the [redacted]

[redacted] **The estimated order of magnitude cost for a new well for hydrogen storage is estimated at [redacted] as shown in Appendix B.**

7.4 Cost Estimate

The total cost to develop [redacted] depends on whether the dry holes are determined to be connected to the storage formation. The cost is estimated both without and with the dry hole plugging operations as follows:

Well Type	Number of Wells	Cost/Well	Total Cost
Existing Wells-Plug	[redacted]		
Abandoned Wells-Re-Plug			
New Wells-Drill			
Total w/out Dry Holes			
Plugged Dry Holes-Plug			
Total w/Dry Holes			

Table 7-1, Well Work Total Cost Estimate for [redacted]

[13] Boersheim, E.C., et al. (2019) *SPE-195555-MS Experimental Investigation of Integrity Issues of UGS Containing Hydrogen,* Society of Petroleum Engineers.

8.0 CONCLUSIONS

From the preliminary assessment of oil and gas reservoirs in Southern California, [redacted] appears to be the best candidate for hydrogen storage based on geological parameters. [redacted] Additionally, further investigation would still be required to assuredly confirm geological suitability with literature showing the added complexities of storing hydrogen over natural gas.

The following table summarizes the key features of the top candidates identified from this study.

[redacted]

Table 8-1, Summary of Top Candidates

** Low figure in range based on InterAct volumetrics; high (or single figure) based on cumulative gas production*

*** Conversion of existing wellbore usage possible*

**** Shallowest of multiple zones*

Generally speaking, although the [redacted]

[redacted]

[redacted] As shown through the initial screening process employed in this report, the process may be useful in determining a shortlist of potential candidates, but ultimately each field will need to be studied in depth and on a case-by-case basis to fully understand the geology and mineralogy. This represents a significant investment early in a projects' feasibility stage.

[redacted]

For any hydrogen storage project, it is apparent that site selection is of utmost importance. The geology and environment of the reservoir will be the primary factor in site selection for any project. Proximity to infrastructure, manufacturing or demand centers should be of lesser concern although it is recognized that a project may ultimately be rendered unviable if costs to access that location exceed allowable budget.

[14] Benedictus, T. et al. (2009) *Long Term Integrity of CO_2 Storage – Well Abandonment*, IEA Environmental Projects Ltd.

APPENDIX A

[redacted] WELL LIST

[redacted]

Table 8-2, Well Inventory of [redacted] (Excluding dry holes)

APPENDIX B

WELL COST ESTIMATES

Cost to Drill Hydrogen Storage Wells		
Location	$	[redacted]
Mob & demob	$	
Rig cost	$	
Cement	$	
Fuel	$	
Mud Sys/Disposal	$	
Directional/Logging	$	
Drill Bits	$	
Tools	$	
Misc	$	
Contract Labor	$	
SoCalGasLabor	$	
Fishing	$	
Casing/Liner	$	
Production Equip	$	
Wellhead	$	
10% Contingency	$	
Estimated TOTAL	**$**	

Table 8-3, Cost Estimate to Drill Well at [redacted]

Cost Estimate to Abandon		
Location and Permits	$	[redacted]
Waste Disposal	$	
Completion Rig	$	
Mud and Trucking	$	
Bits	$	
Cementing	$	
Rentals	$	
Trucking	$	
Wireline/Perforating	$	
Milling/Fishing	$	
Contract Labor	$	
Supervision	$	
Engineering	$	
Miscellaneous	$	
Estimated TOTAL	**$**	

Table 8-4, Cost Estimate to Abandon Well

Cost Estimate to Re-Abandon		
Location and Permits	$	[redacted]
Waste Disposal	$	[redacted]
Completion Rig	$	[redacted]
Mud and Trucking	$	[redacted]
Bits	$	[redacted]
Cementing	$	[redacted]
Rentals	$	[redacted]
Trucking	$	[redacted]
Wireline/Perforating	$	[redacted]
Milling/Fishing	$	[redacted]
Contract Labor	$	[redacted]
Supervision	$	[redacted]
Engineering	$	[redacted]
Miscellaneous	$	[redacted]
Estimated TOTAL	**$**	[redacted]

Table 8-5, Cost Estimate to Re-Abandon Well