United States Department of the Interior

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MEMORANDUM

To: Manager, Western Colorado Area Office
Attention: WCG-EWarner (Ed Warner)

From: Lisa Block, Geophysicist
Geophysics and Seismotectonics Group

Subject: Paradox Valley Unit Second Well Site Investigation Consultant Review Board

A Consultant Review Board (CRB) meeting for the Paradox Valley Unit (PVU) was held in Grand Junction, Colorado, on December 16 - 19, 2012. This CRB was convened to review the information that is currently available for selecting the location of a potential second PVU injection well and to make recommendations for additional data that could be acquired or analyses that could be performed to aid in the site selection process. The board was also asked to provide feedback on the proposed criteria to be used to select the second well site. The specific questions posed to the CRB are attached.

Members of the CRB documented their recommendations in a final report to the Bureau of Reclamation in April, 2013 (Dusseault et al., 2013). The CRB members made many specific recommendations, which are summarized in the attached table. For simplicity, the individual CRB recommendations are grouped based on similar topic; these topics do not correspond directly to the questions posed. The perceived benefits to PVU and Reclamation's responses are included in the table.

Based on the CRB recommendations, we are proposing a series of tasks that should be considered in order to select a location for a potential second PVU injection well. The major steps are outlined in the attached "Second Well Site Investigation Flowchart". Specific actions, based on CRB recommendations, which should be considered for each step are described in the attached "Second Well Site Investigation Roadmap". The roadmap also summarizes related work that has already been performed or is in progress and includes proposed near-term tasks.

Much of the work recommended under the first step, "Determine whether the pressure build-up in PVU well #1 is due primarily to near-wellbore flow impairment or far-field reservoir pressurization", has been completed. The analyses performed to date indicate that the pressure build-up is most likely a far-field reservoir pressurization effect. Hence, we anticipate that much of the near-term work for determining a second injection well site location should focus on step 2B, performing analyses and acquiring geophysical data to look for fault blocks in the vicinity of the current PVU injection well that are hydrologically isolated from current injection operations.

If you have any questions, please contact Lisa Block at 303-445-3171 or via e-mail at lblock@usbr.gov.

Attachments:

cc: 85-833000 (Block, Wood, Yeck, King, files)
UC-240 (Jacobson)
WCG- (Dunn, Stroh)
WCD- (Nicholas, Artichoker, Uilenberg)

Questions to the CRB

Paradox Valley Unit – Second Injection Well Location
Consultant Review Board (CRB) Meeting No. 1, December 16-19, 2012
Grand Junction, Colorado

1. Are existing studies adequate to determine the feasibility and optimum location of a second injection well?
2. Regarding the technical *criteria* considered by the existing studies for evaluating second injection well sites:
    a. Are the identified criteria appropriate and sufficient?
    b. Is their relative importance identified and correctly evaluated?
    c. Should additional or alternative criteria be considered?
3. Regarding the *data* and *approach* considered by the existing studies, and their applicability to finding a suitable site for a second injection well:
    a. Are the existing geologic and geophysical studies adequate to reasonably characterize the local geologic structure?
    b. Do existing seismic reflection data provide sufficient resolution and areal coverage?
    c. Does information from existing wells provide sufficient stratigraphic control for interpreting the subsurface geologic structure?
    d. Have characteristics of potential reservoir formations adequately been considered, such as ultimate capacity, fracture and flow properties, pressure limits, and availability of suitable confining layers?
4. Do the existing studies and documentation adequately consider the feasibility of drilling and maintaining the structural integrity of a second injection well? Have available technologies been considered fully, such as directional drilling, horizontal drilling, or methods for drilling and completing a well through thick sections of salt?
5. If existing studies are found to be inadequate, what additional studies should be considered, and what are their likely relative benefits and costs?
6. Are there other issues, opportunities, or concerns the CRB believes are appropriate to raise concerning the determination of an optimum location for a second injection well?

Second Injection Well Site Selection CRB - Recommendations following December 2012 Meeting

Recommendation	Sub-Recommendations	Benefit	Reclamation Response
Evaluate the condition of the existing wellbore	Determine whether there is any ellipticity in the production casing developed through the Paradox Salt interval above the Leadville.	There has been no entry into the hole since 2001, so there is little information about the current condition of the well. Early detection of developing problems that may eventually impair PVU #1 would mean that mitigation actions could be planned in advance, or bear on how soon a new well is needed. Furthermore, if such effects are detected, it may have implications for the location or design of a potential second injection well.	Evaluating the condition of the borehole would be beneficial if it could be done without substantial risk. There is a severe casing constriction at the depth of the upper Leadville Formation, and possibly shallower (Subsurface, 2001), so the risk of putting tools into the hole increases greatly if going below the salt. There was no indication of scale or other problems above the constriction from the 2001 caliper survey. The 2001 static temperature survey indicated no upward migration of brine above the Leadville formation. Any work near or below the constriction(s) would be a very high risk.
	Determine if there is any shear distortion indicating slip along any bedding plane interface between lithologies.		
	Determine if there is any other distortion of connections or casing that would indicate that the hydraulic integrity of the cased wellbore could be impaired in the future (10-20 years).		
	Assess other issues such as the corrosion state of the Hastalloy and the CYS 95 casing, the presence of any scale or other debris, etc.		
	Perform a cement bond log of the production casing, and an assessment of well integrity.	See if the production casing shows good bond integrity. If possible, evaluate whether there is any significant current leakage of saline injectant upward behind the casing of the well.	
Acquire additional reservoir data in the existing wellbore	Perform a walk-away VSP.	Combined with microseismic data, can help refine stratigraphic model and possibly identify zones of higher porosity and permeability, and could also help locate the cross-cutting strike-slip faults with greater precision in the NW-SE directions, or the locations of the normal faults in the directions to the SW and NE of the PVU #1 well.	Obtaining high-resolution surface-to-borehole seismic data would be useful, if it would provide additional information to constrain the geologic model for the deep formations and faults below the Paradox salt. However, obstacles to being able to obtain the data needed include the high topographic relief in the surrounding area and the risk associated with lowering tools below the borehole constriction(s) at or near the Leadville formation. We should further evaluate the cost and potential benefits of performing a VSP survey in light of these issues.
	Consider installing a high-T wall-locking triaxial borehole accelerometer array into the PVU #1 well .	Collect the decay of microseismic activity as the pressure gradually equilibrates soon after commencement of the shut-in period, which combined with VSP, can help refine stratigraphic model and possibly identify zones of higher porosity and permeability.	Because of the change in injection operations following the January 2013 earthquake, we no longer have long shut-in periods, so this would interrupt production. Also, because of the current relatively low injection pressures, seismicity rates have decreased markedly in the near-well area. This type of survey would likely generate more useful data if done after the reservoir has re-pressurized, which may take two years or longer.
	Execute behind-the-casing logs in sections of the production casing where it is considered appropriate and valuable.	Assess the strata for any changes in the near-wellbore environment; characterize the Leadville and other formations.	These borehole surveys would provide useful information if they could be done below the salt, in the injection horizons. However, because of the constriction(s) in the borehole casing at the depth of the Leadville formation, the risk of running these logs in the zones of interest is high.
	Perform spinner flow surveys.	Find out in which intervals the formation is taking the fluid, and how much. Knowing the injection profile will give insight into the potential injectivity of a second well, which could, for example, help decide where to place a horizontal well injection section to achieve maximum efficacy.	
	Determine if there is merit to obtaining a temperature profile in PVU #1 after a period of non-injection.	Could provide information about where fluid is entering the formation. Could also provide data to indicate the degree of reservoir cooling that has taken place (which helps to hold fractures open).	

Recommendation	Sub-Recommendations	Benefit	Reclamation Response
Perform a workover of the existing wellbore	Clean out bottom-hole junk.	May open up the lower horizons. If opening up the lower horizons opens new flow paths, the well injection capacity may be sustained while the rate of pressure increase is reduced somewhat.	If the increasing pressures in the current injection well are a result of skin effects or clogging within the wellbore, then such a workover may postpone the need for a second injection well for a considerable length of time. However, if the increasing pressures are due mainly to far-field pressurization of the reservoir, then a workover of the existing well may have limited benefit. Analysis of data (pressure-flow data, earthquake data) relevant to determining whether the pressure build-up is due mainly to near-borehole conditions or far-field pressurization should be completed and reviewed prior to considering a work-over of the existing well to increase injectivity.
	If considered desirable, and this must be assessed by experts once the workover is partially underway, perform hydraulic fracture stimulation and the placement of high strength proppant. Additional perforations may also be considered.	Increase the injectivity of the PVU #1 well.	
	Consider re-completing the PVU #1 well with an inclined section directed in an appropriate azimuthal direction.	Intersect a greater length of permeable rock, and perhaps intersect an adjacent block (such as to the northeast or to the southwest) that remains partially hydraulically isolated; increasing the injection capacity of the well and therefore decreasing the rate of pressure build-up.	Ideally, this option would be considered after a second injection well or other salinity control alternative is in place. The risk of re-completing PVU Injection Well #1 - which is currently a critical component of the only salinity control infrastructure in PVU - would be easier to assume at that time. Also, if this were done after a second injection well were in place, then PVU would have 2 wells into which injection could alternate.
Re-enter the Union Well	Assess whether inter-formational leaking of saline injectant is taking place through the Union Well pathway (up or around the casing or in the damaged rock zone surrounding the wellbore). If there is evidence that the Union Well is a conduit for saline injectant migration into other zones, rectify the situation by an appropriately executed sealing program.	Ensure that injected brine remains confined below the Paradox salt.	A review commissioned by the Bureau of Reclamation in 1988 indicated that re-sealing of the nearby Union Oil well was not necessary because "the combined effects of the cement plugs, the mud-laden fluid left in the wellbore, the natural wellbore closure adjacent to the salt, and the cemented casings left in the well will prevent any migration of injected or connate waters into a usable source of drinking water" (Davis, 1988). However, re-entering the Union well and performing the other tasks recommended could produce multiple benefits, as indicated by the CRB report and summarized here. We should assess the cost and risk associated with re-entering the Union wellbore (which penetrates formations that are currently under high pressure) and make a decision about whether to pursue this recommendation based on an analysis of the relative costs, risks, and benefits.
	See if there has been any borehole deformation or other evidence of salt mobilization.	Such evidence would indicate concern for a second well location around the PVU #1 injection well.	
	Assess the temperature change and the stress state in the Leadville Formation.	Provide a data point to help constrain any reservoir modeling or other calculations.	
	Perform wireline geophysical logs for open-hole logging.	Velocity log would help constrain the velocity model used to locate induced earthquakes. Lithology logs (such as density, natural gama, resistivity) would help constrain the subsurface geologic model.	
	Perform a walk-away VSP in the Union Well in conjunction with collecting 6-12 months of microseismic data during continued injection into PVU #1.	Develop more refined stratigraphic model, which will be of great value in deciding where to place the completed zone of the injection well (assuming the Union Well is not deemed suitable for use as a kick-off point) because they will more clearly delineate the fault block structure and give additional insight as to the pressure condition of the surrounding blocks. If the Union Well is deemed suitable as a kick-off point, help choose the optimum trajectory for the deviated wellbore and the best locations for perforations.	
	Evaluate whether the Union Well could be re-habilitated and re-completed as a second injection well, and if so, evaluate the use of the Union Well as a deviated injection well accessing a region of the surrounding rock mass that is currently not experiencing significant effects from the PVU #1 injection activity, and could take a sufficient volume of saline injectant. If the adjacent blocks are already subject to pressure increases, consider a sidetrack from the Union Well involving a horizontal well segment to access the strata in the vicinity of the Conoco Well (under the salt diapir).	Retrofiting an existing well for a second injection well may reduce drilling costs. Locating a second injection well near the existing pumping plant eliminates the need to construct a separate injection facility, thereby reducing initial installation cost and long-term PVU operating expenditures.	
	If drilling the second well is considered to be the best alternative, convert the Union Well into a monitor well for pressures in several horizons (e.g. above the salt) as well as installation of geophysical instrumentation (e.g. downhole accelerometers).	More precisely delineate the locations and evolution of induced seismicity; help understand the flow and stress evolution.	

Recommendation	Sub-Recommendations	Benefit	Reclamation Response
Analyze existing pressure-flow data	Perform pressure-time analysis on PVU #1 pressure build-up data and the pressure fall-off data dating back from the beginning of injection and done on all the high quality data since that time.	Determine whether there is a strong mechanical skin effect, whether the presence of purported sealing faults can be identified and verified, and whether the flow regime has evolved over time; evaluate whether the gradual pressure-build up is indeed a far-field pressurization process, or is more related to near-field flow impairment processes that might be rectified more economically.	We have performed pressure-time analysis of the PVU data recorded since the start of long-term injection in 1996. Results are presented in Technical Memorandum No TM-86-68330-2013-12 (Wood et al., 2013). This analysis was done, in part, to help formulate a response to the January 2013 M_L 4.4 earthquake. Additional studies are in progress, including analysis of data recorded during the 3-month shut-in period following the January earthquake. Because of the change in injection operations following the January 2013 earthquake, we no longer have long shut-in periods, so any additional extended shut-in would interrupt production.
	Consider a careful analysis of the pressure decay after a shut-in for several days or weeks (a well-test expert should be consulted in this regard). Determine if this information is valuable enough to warrant a shut-down of PVU #1 for a period of (for example) three weeks while carefully monitoring the pressure decay and the alterations in the microseismic response.	Understanding the pressure response of the far-field and how it affects the microseismic activity level (magnitude, frequency, location, and motion) may give quantitative insight as to the propagation of the pressurized region.	
Analyze existing earthquake data	Analyze the microseismic data using tomographic techniques to refine the 3D velocity model, which would in turn refine the microseismic locations .	Obtain insight into whether adjacent faults are sealing or non-sealing, refine the location and throws so that more guidance to future drilling can be given, locate zones of higher permeability through detailed analysis of the seismic attributes of a superior seismic model, and guide the decision on which direction to drill a deviated wellbore.	We have been analyzing the microseismic data using tomographic techniques since the mid-1990s. We continue to improve our methods and integrate interpretation of the seismicity data with geologic and pressure flow data. Results of this work will be presented at a future consultant review board meeting.
	Assess the spatial and magnitude evolution of the microseismic data in terms of the probability of length flow paths (distant pressurization phenomena).	Provides insight about far-field pressurization of the reservoir, which is relevant to interpreting the increasing injection pressures at the well.	
	Provide images that allow the assessment of the time and space migration of the microseismicity, tied to the stratigraphy as much as possible. Pseudo 3-D images with microseism magnitude (size of bubble) location and time (color coded) could be developed.	Visual aid for interpretation of induced seismicity.	
Analyze other PVU data	Consider performing more in-depth study of core and drill cuttings.	Potentially identify additional permeable zones for injection. Use for calibration of well logs or regional stress analysis?	We should review the costs and potential benefits of additional studies of the existing core samples.
	Consider re-analysis of existing seismic reflection data, but only if these data are enhanced through the addition of supplementary data such as a tomographic analysis of the microseismic data, and perhaps some new seismic information such as Vertical Seismic Profiling (VSP) data near the PVU #1 well.	Modern analysis techniques may improve the quality of the seismic reflection sections and in turn improve the accuracy of the subsurface geologic models.	Analysis of the microseismic data has recently led to a new interpretation of the subsurface geologic structure. As a result of this work, we have identified specific seismic reflection lines, some already owned by Reclamation and some available for purchase, that could provide confirmation or refinement of the new model. Re-analysis of these seismic reflection lines may provide significant benefit at modest cost.
	Develop a simple volume balance model. Inputs to this model would be average porosity, location of assumed sealing faults (and hence areal extent of fluid displacements), displacement efficiency of the invading fluid, assumptions as to the vertical extent of the sweep, and so on.	Study (estimate) the lateral extent of the zone that has been invaded by injected brine.	Similar analysis has been performed in the past. We should review that work and update the analysis.
	Perform some simple convective heat transfer calculations.	Estimate the volume of rock that might have been cooled because of the lower temperature of the injection water. This can then be compared to the assumed thickness of the Leadville formation that is taking brine, and a few simple thermoelastic calculations can be done.	This analysis could provide new insight at relatively low cost.
	(Not strong recommendation) Consider commissioning a geomechanics simulation expert to carry out some preliminary (first-order) calculations of the changes in the poroelastic stress field arising from the increased pressure and the convective-conductive heat transfer effects around PVU #1, assuming that the BoR injection block is sealed to the NE and SW by bounding faults and that pressure transmission and flow is dominantly to the NW and SE.	Although this will be a rough model, it may, in combination with the microseismic data and with the refined stratigraphic model from the VSP, microgravity survey, and other activity, give insight to the changes taking place in the stress fields and therefore the evolution of the microseismic activity.	The benefits of pursuing these types of modeling efforts should be evaluated in light of the results from the simple pressure-flow modeling (which is nearing completion) and the data available to constrain more sophisticated models.
	Request an opinion of a reservoir engineer as to the feasibility of a simple (single-phase flow) reservoir simulation of the PVU #1 injection geo-system at depth.	Estimate the spatial extent of brine intrusion into the reservoir and pressurization of in-situ fluid.	

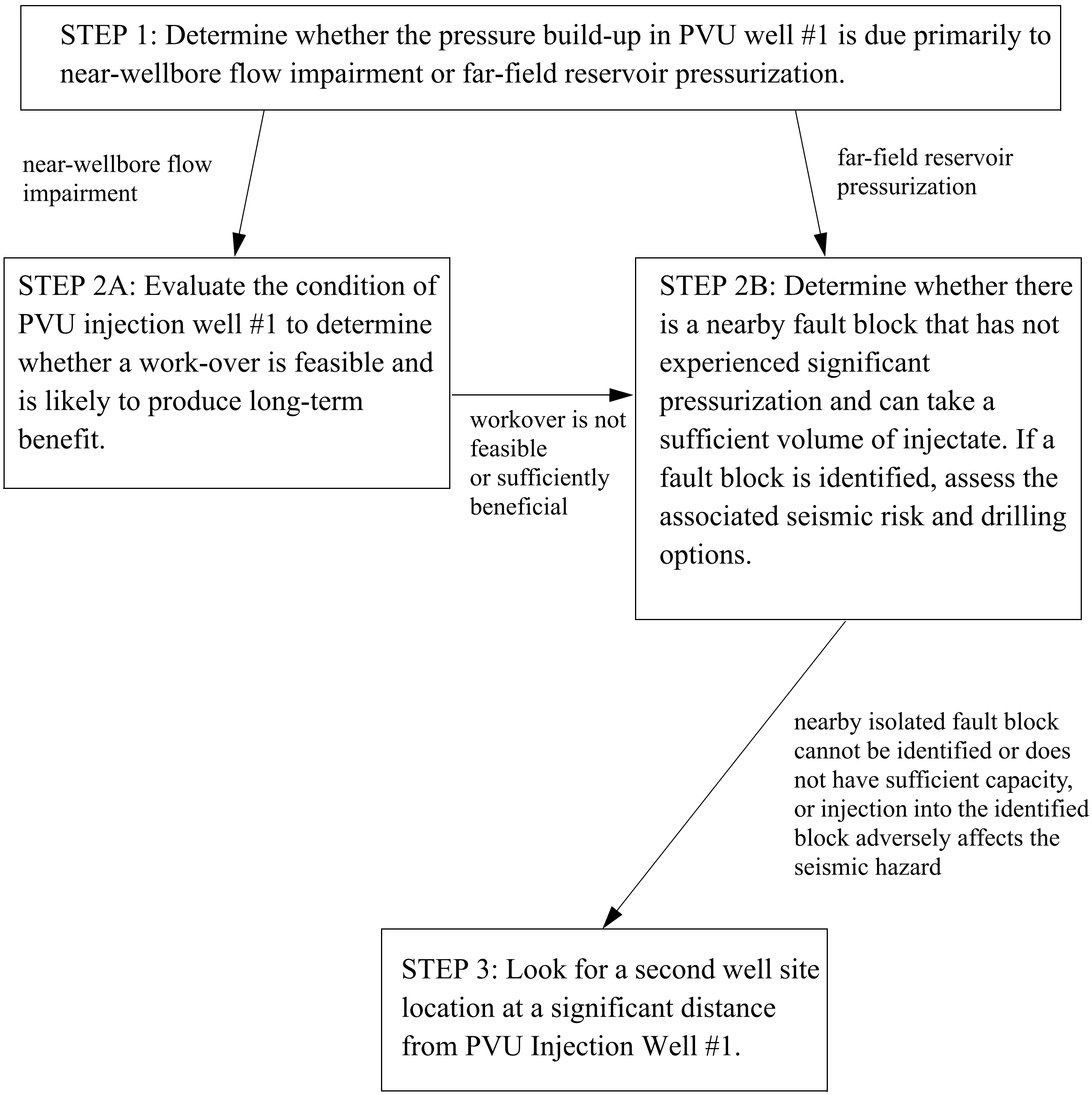
Recommendation	Sub-Recommendations	Benefit	Reclamation Response
Perform new geophysical surveys	Perform a microgravimetric survey.	Could provide more detail on the distribution of salt because of the sharp density contrasts between salt and the other lithologies at depth; help extend the value of the existing seismic and borehole information and help identify superior targets for the trajectory of a second well or a Union Well side-track.	We should consider acquisition of gravity and/or magnetic data. In additional to the benefits identified by the CRB, it may help confirm recent geologic interpretations based on analysis of the microeathquake data.
	Perform an aeromagnetic survey.	Provide better constraints on the locations and throw of the faults at depth; help extend the value of the existing seismic and borehole information and help identify superior targets for the trajectory of a second well or a Union Well side-track.	
	Evaluate other nearby well locations for possible installation of downhole accelerometers arrays.	Would improve depth constraints on earthquake locations and provide additional data for the velocity model.	We should evaluate the feasibility of re-entering abandoned boreholes, the cost of installing downhole accelerometer arrays, and the benefit of the additional seismic monitoring capability. If the feasiblity and cost are acceptable, we can perform computer modeling to evaluate the extent to which downhole accelerometers in existing wellbores would improve the subsurface velocity model and earthquake locations. We could then evaluate the extent to which that improved accuracy would enhance our overall understanding of subsurface conditions or earthquake occurrence.
	High-resolution 3-D seismic reflection survey is not likely to give a great deal of additional structural information because of the rugged topography - NOT recommended.	Likely to have small benefit and high cost.	At this time, we should not pursue acquisition of high-resolution 3-D seismic reflection data.
Evaluate existing area well & geologic data	Examine drilling logs and records of the nearest offset wells (at least the Union 1-0-30 and the Conoco wells, perhaps also the Chicago 1) for any evidence of lost circulation, drilling problems, or other information that could be valuable.	Assess conditions at depth and the approach to future drilling at a selected site	This is a low-cost recommendation that could potentially provide some useful data. We should download all available well data for nearby wells from the Colorado Oil and Gas Commission online database. It may be prudent to retain someone knowledgable in drilling to review them for pertinent information.
	Examine other plugged and abandoned wells in the region for possible re-entry and use, including the possibility of deepening the existing wellbore, drilling a deviated well from an intermediate depth, and horizontal section installation for the injection portion to increase injectivity (only if other options deemed unsuitable)	May reduce drilling costs. Also, if the existing well was previously drilled through the Leadville formation, then we would have apriori information about the reservoir characteristics at that location. This would reduce the risk of selecting a site with poor reservoir potential.	We should evaluate whether re-use of existing wells is feasible and whether it would substantially reduce installation costs (which may depend upon the location, age, and condition of individual wells).
	Examine Lisbon Oilfield, where there exist far more detailed structural data and geological studies, for geologic analogues	May aid in the geologic interpretation of the existing well, seismic reflection, and earthquake data. A better understanding of the subsurface geology would be beneficial for the site selection for a second injection well.	This is a low-cost recommendation that may provide insights useful for our geologic interpretation of existing data, so we should do a literature search of relevant technical papers from the Lisbon Oil Field.
Recommendations for site selection criteria	Seek ways of reducing surface facilities costs and avoiding duplication of surface facilities, such as locating a second well-head nearby so that short-distance pipelining of pressurized brine can be used, and so on.	Reduce the cost of a second injection well.	These recommendations will be kept in mind as the second injection well site selection process moves forward.
	Down-grade injection sites that would increase the induced seismicity level near to populated areas in terms of suitability.	Reduce seismic risk to local population.	
	If a second injection well is deemed necessary but the Union Well cannot be re-used, the second well should be drilled relatively close to PVU #1 and deviated laterally to intersect the most appropriate fault blocks and high permeability zones as delineated by the additional investigation activities that have been recommended.	The drilling and wellhead can be located close to existing facilities, create a lower level of disturbance in the region, reduce NEPA and land management costs, and be easier to manage. Long-term PVU expenditures would be lower for maintaining one injection facility rather than two.	
	Deviated and horizontal trajectories from existing wellbores are likely to be considerably less costly than new wells.	reduce cost.	

Recommendation	Sub-Recommendations	Benefit	Reclamation Response
Approach to site selection	Develop a comprehensive ROAD MAP, based in part on this report and on input from the experienced professionals of the BoR.	Would help to make most effective decisions and lead to a final site selection more efficiently. Keep focus on tasks providing greatest benefit to site selection process. Aid in coordination of activities among different groups.	An initial "roadmap" has been developed and is included as an attachment to this accountability memorandum.
	Implement a semi-quantitative cost-benefit approach. Evaluate the cost-benefit of gravimetric, aeromagnetic, and related geophysical surveys in the context of refinement of the geological models for site selection of the second well .	Assess what actions are the most likely to reduce uncertainty incrementally and sequentially in a series of logical steps.	

ADDITIONAL RECOMMENDATIONS (OUTSIDE SCOPE OF CRB):

Recommendation	Sub-Recommendations	Benefit	Reclamation Response
Evaluate alternatives to increasing injection capacity	Consider installing a designed row of groundwater wells that can inject fresh water.	Create barriers to flow through the reduction of hydraulic head and, in the long term, increase the flow rate by increasing the magnitude of the sink, therefore contributing to the dissolution rate of the salt at depth, which could result in less saline water to inject and delay the time at which additional deep drilling activity is required.	An alternatives study has been underway for several years and is already addressing these issues.
	Fully evaluate alternatives to second well, including evaporation ponds and land use, pumping or diverting fresh groundwater to reduce deep saline dissolution rates, solar desalination to generate fresher water, or some optimized combination of these alternatives.	Reduce the continued injection rate demands on PVU #1 well.	
	Perform a detailed hydrological study of the Paradox Valley to the northwest of the Dolores River, including modeling to allow sensitivity analyses and impact assessment.	Assess the possibility of reducing the amount of saline brine coming into the system through redirection and pumping, by groundwater management using shallow wells at the surface.	
Recommendations for injection operations	Evaluate the option of increasing the injection pressure limit in PVU #1 by perhaps 1000 psi .	This would effectively extend the life of the well for a number of years, given current behavior, and there is a reasonable possibility that the increased pressures will have favorable flow capacity effects on the available flow paths by increasing the transmissivity of fractures and faults because of increased pore pressures and lowered effective stresses.	A consultant review board for considering this recommendation has been planned for some time and is likely to convene in mid-2014. The benefit of increasing the MASIP must be balanced against the risk of inducing more and larger earthquakes. The same CRB will also consider this associated increased seismic hazard.
	Consider the merits of filtering to 3 micrometer particle size.	Reduce cost.	At this time, the relatively small cost savings of not filtering is not deemed to be worth the risk of potentially clogging the fracture network surrounding the existing well.
Recommendation for well completion	Consider the possibility of using new casing materials such as carbon-fiber reinforced plastics instead of hyper-expensive metal alloys.	Reduce the cost of a second injection well.	If a second injection well is drilled, drilling experts, familiar with the new casing materials, will be retained to determine the optimum design of the well.
Rcommendations for data analysis	Continue to perform forward-looking probabilistic analyses of the evolution of seismicity magnitude and location.	Assess the impact of injection on the local community and land use.	We will continue to perform all appropriate analyses of the induced seismicity data.
	View PVU as a long-term experiment (applied science project) and consider undertaking more explicit cooperation with appropriate research organizations and universities .	Use PVU's activities to train highly qualitifed personnel for the scientific community. PVU could become a case study for future seismic methods and modeling methods. PVU can serve as a template and case history with ramifications for other areas. Leverage the value of the PVU data and long-term analyses.	Collaboration with research organizations should be considered when it provides direct benefits to the project and does not re-direct funding or staff time away from our project responsibilities. Reclamation should publish PVU analyses for the benefit of the scientific community.

Second Well Site Investigation Flowchart



Second Well Site Investigation Roadmap

STEP 1: Determine whether the pressure build-up in PVU Well #1 is due primarily to near-wellbore flow impairment or far-field reservoir pressurization.

Recommended actions:

1. Perform simple pressure-flow modeling of existing PVU injection data. (Look for evidence of: a strong mechanical skin effect, and changes in the skin effect over time; changes in the flow regime over time (infer presence of impermeable faults); changes in permeability over time.)

2. Analyze the spatial and magnitude evolution of induced seismicity over time. (Look for evidence of: lengthy flow paths; far-field pressurization; impermeable faults; hydraulic connectivity between the upper Leadville and lower target intervals - is there evidence that fluid is still getting into the lower target intervals even though the lower perforated zones are blocked within the wellbore?)

Work to date:

Substantial analyses relevant to whether the pressure build-up in the injection well is due to near-wellbore flow impairment or far-field pressurization have been performed. The results of these analyses indicate that the increasing injection pressure is most likely **not** due primarily to near-wellbore flow impairment, but rather represents the far-field reservoir response to the applied flow rates.

The pressure-flow modeling completed to date suggests that the gradual increase in injection pressure is simply a result of injecting into a low-permeability reservoir for an extended period of time. Modeling of the pressure-flow data from the last 10 years shows no indication that the flow regime has changed in recent years or that a strong mechanical skin effect has developed over time. In addition, correlation of the occurrence of induced earthquakes with long-term trends in injection pressure suggests that pore pressures are considerably elevated to at least a distance of 2 km from the injection well, where the majority of the largest-magnitude (M3.5+) events occur.

Spatial-temporal analyses of the induced seismicity data suggest that pore pressure changes may propagate relatively quickly along a network of pre-existing faults from the injection well to distances of several km from the well. The onset of seismicity 6 to 8 km northwest of the injection well (in the NW cluster) soon after the start of continuous injection (July 1996) suggests that a relatively high-permeability flow path may exist from the vicinity of the injection well to the northwest. The occurrence of the local magnitude M_L 4.4 earthquake 8 km northwest of the well in January 2013, as well as the significant decline in seismic activity in that area a few months after injection was suspended following the earthquake (and then resumed at a reduced flow rate), suggest that the hydraulic connectivity between the injection well and the NW cluster has become stronger over time. The increased occurrence rates in distant seismicity clusters (SE cluster and northern-valley clusters) and the occurrence of shallow seismicity (~5 to 6 km deep) beneath central Paradox Valley observed in recent years also imply that far-field reservoir conditions are changing.

The distribution of earthquake hypocenters in the near-well area (within 4 km of the well) shows that the earthquakes occur over a depth range exceeding one kilometer. Substantial seismicity occurs both several hundred meters below and several hundred meters above the elevation of the perforated zones in the Leadville formation in the injection well. The vertical distribution of the seismicity appears to be largely controlled by the locations of northwest-trending normal faults, with the earthquakes generally becoming shallower toward the southwest away from the well. In addition, the hypocenters appear to be distributed along near-vertical pre-existing faults that may allow vertical propagation of pore pressure across sub-salt formations. Assuming that the locations of the induced earthquakes have some correspondence with the distribution of pore pressure increase and fluid flow, these analyses suggest that blockages in the injection well across the deeper perforated zones are not preventing fluid from reaching the deeper target formations.

Proposed near-term tasks:

The pressure-flow modeling should be finalized. Results from the pressure-flow modeling and earthquake analyses relevant to the determination that the injection pressures are due to far-field reservoir response should be documented, either in separate reports or in a combined technical memorandum.

STEP 2A: If the pressure build-up is due primarily to near-wellbore flow impairment, evaluate the condition of PVU injection well #1 to determine whether a work-over is feasible and is likely to produce long-term benefit.

Recommended actions:

1. Examine all relevant reports to determine known conditions within the wellbore.

2. Determine whether the risk of re-entering the wellbore to further assess borehole conditions is acceptable.

If risk of wellbore re-entry is acceptable:
3. Enter the wellbore and assess conditions to determine whether a work-over of the well is advisable – is the wellbore in good enough condition to last another 10 to 20 years? (Look for ellipticity or distortions of casing; run cement bond log; assess corrosion state of casing and degree of scaling.)

If wellbore is in sufficiently good condition to last another 10 to 20 years:
4. Perform further surveys to determine whether a work-over is likely to be beneficial – can near-well flow impairment be identified? (temperature log; spinner flow survey; geophysical borehole logs)

If surveys indicate near-wellbore flow impairment, consider improving the near-well flow by doing one of the following:
5a. Cleaning out the lower section of the borehole; performing hydraulic fracture stimulation and possibly the placement of high strength proppant.
OR
5b. Re-completing the lower section of the borehole, possibly with an inclined section to intersect a greater length of permeable rock. If this option is chosen, then additional surveys should be considered to better define the nearby stratigraphy and determine the optimum location for the new bottom of the borehole prior to re-completion (vertical seismic profiling (VSP) survey; passive microseismic survey with borehole accelerometer array; analyses of core samples).

Follow-up: Monitor pressure over time to determine whether a second injection well is still needed.

Work to date:

A report written subsequent to the last borehole evaluation, performed in 2001, has been reviewed (Subsurface, 2001). This report indicates a diameter restriction in the borehole casing in the upper Leadville, at and below a depth of 14,138 feet. A review of logging attempts from 1988 to 1994 indicates that the borehole diameter below this depth became progressively smaller with time, to less than 4.25 inches in 1994 (Subsurface, 2001). A caliper survey run in 2001 indicates a second potential casing restriction above the Leadville Formation, at a depth of 14,043 ft. However, the presence of a magnetic marker at this depth may have biased the results. The report also indicates lost tools in the borehole and sulfur filling the hole up to 14,070 feet depth. At the time of the last borehole entry in 2001, only the upper Leadville Formation perforations were clear and not covered with fill. Risk of performing any type of borehole surveys near the depth of the Leadville is considered very high, as the loss of additional tools in the borehole could cause further blockage of the perforated zones. Since no other salinity control measure is currently in place, a loss of production in PVU Well #1 in the near future would be very detrimental to the project.

Proposed near-term tasks:

None. Based on the analyses completed to date (described under STEP 1), we do not believe that the pressure increase in the injection well is due primarily to near-wellbore flow impairment. Hence, a work-over of the well to increase injectivity is not likely to produce substantial long-term benefit. In addition, because of the condition of the borehole, the proposed borehole surveys and potential work-over procedures would also pose substantial risk to current operations. The borehole investigations proposed above may be re-considered at some later date after an alternative salinity control measure is in place, the pressures in the injection target formations in the vicinity of PVU Well #1 have had sufficient time to decline, and additional injection into this well is being considered.

STEP 2B: If the pressure build-up is due primarily to far-field pressurization, or a work-over of the existing well is not feasible, determine whether there is a nearby fault block that has not experienced significant pressurization and can take a sufficient volume of injectate.

Recommended actions:

1. Analyze earthquake data using tomographic techniques. Use the earthquake locations and associated velocity model to enhance the subsurface geologic interpretation from seismic reflection and well data.

2. Re-process existing PVU seismic reflection data and/or purchase additional seismic reflection data, if considered beneficial based on the results of the earthquake analysis. Field acquisition of additional seismic reflection data, which would be considerably more expensive than purchasing existing data, should only be considered after existing datasets have been reviewed. Acquisition of new seismic reflection data may be considered if: the existing data are of poor quality and data acquired with newer methods are expected to have substantially improved quality; the existing data do not extend to areas of interest; the microgravimetric and aeromagnetic data proposed in item 3 below do not provide adequate subsurface information..

3. Determine if microgravimetric and/or aeromagnetic data are likely to enhance the subsurface geologic models and, if so, collect and analyze such data.

4. Perform a simple volume balance model to estimate the lateral extent of the zone that has been invaded by brine.

5. Perform simple conductive heat transfer calculations to estimate the volume of rock that has been cooled.

If one or more nearby fault blocks that have not experienced significant pressurization have been identified:

6. Calculate initial, rough estimates of the identified fault block(s) reservoir volume, and evaluate whether the anticipated volume is sufficient to make injection into any of the identified blocks economically viable. The initial estimates of reservoir volume would be calculated using the final subsurface geologic interpretation from the geophysical methods described above and assumed ranges of potential reservoir thickness and effective porosity. Economic viability would also need to be defined; a proposed viability threshold might be 25 to 30 years of near-continuous injection at flow rates comparable to those attained in the current well.

7. Evaluate the seismic hazard associated with injecting into the identified fault blocks. [Would new seismicity likely be induced closer to or farther from populated areas? Could a geographical expansion of the seismically-active area increase the probability of

inducing a larger magnitude earthquake (if, for example, injection were to be alternated between a new, relatively nearby second well and the existing well at some point in the future)?]

If injecting into the nearby fault block(s) is judged to be economically viable and would not substantially increase the seismic hazard:

8. Assess strategies for drilling into the identified fault block(s), and drill an exploration well and/or the second injection well if an acceptable drilling strategy can be implemented.

Initially, an exploration well is needed to determine local reservoir characteristics in the targeted fault block. Because of the spatial variability in Leadville porosity, fracture permeability, and thickness, the initial estimate of reservoir capacity determined in step 6 would contain substantial uncertainty. Evaluation of the reservoir capacity would need to be refined after an exploration well is drilled into the targeted fault block(s) and geophysical well logs, core samples, and flow test data are analyzed. If tests performed in the exploration well confirm the presence of a good reservoir formation for brine disposal, then either this well could be completed as the second PVU injection well, or a separate well could be drilled for long-term injection.

Many factors would need to be considered when assessing strategies for drilling the exploration and long-term injection well(s). These include land use and access, and the relative costs, risks, and benefits of vertical and diagonal drilling methods. The CRB specifically recommended, if possible, installing the wellhead for the second injection well near the current pumping plant, using one of the following drilling strategies:

- Re-completing the lower section of PVU Injection Well #1, diagonally drilling to access the identified adjacent fault block(s). In this scenario, PVU will only have one injection well rather than two.

- Re-entering the Union well and re-completing the lower section, diagonally drilling to access the identified adjacent fault block(s).

- Drilling a new well in the near vicinity of the current injection well and pumping plant, and diagonally drilling to access the identified adjacent fault block(s).

Installing the wellhead near the current pumping plant would eliminate the need to construct a second pumping plant, which would reduce both initial installation cost and long-term operating cost. It would also greatly simplify the Environment Impact Study process. Potential drawbacks might include: complications with drilling through pressurized rock; increased cost and complications associated with drilling diagonally (rather than vertically); and potentially reduced reservoir capacity compared to locating a second injection well at a greater distance from the first well. Reclamation would need to hire experts in drilling methods to evaluate these and alternative drilling strategies for the exploration and injection well(s).

Work to date:

We have been analyzing the earthquake data using tomographic techniques since the mid-1990s. Methods have been gradually improved over the years, to refine the subsurface velocity models and improve the earthquake hypocenter estimates. We have used the spatial distribution of earthquake hypocenters in the near-well area and NW and SE clusters to infer the locations of NW-trending normal faults. Recent analysis of the hypocenters also indicates that the NW-trending normal faults may be offset by a major shear zone south of the injection well. If this interpretation is correct, then there may be fault blocks southeast of the well that have not experienced substantial pressurization and may be potential targets for a second injection well. Additional work is in progress to try to improve the spatial resolution of the subsurface velocity models (computed from the earthquake data) and determine whether the presence of the interpreted shear zone can be confirmed by analysis of the velocity structure. In addition, surface seismic reflection lines, some already owned by Reclamation and some available for purchase, have been identified that may help confirm this geologic interpretation.

Proposed near-term tasks:

Complete the high-resolution velocity analysis using the induced seismicity data. Evaluate whether re-processing and/or purchasing of selected existing surface seismic reflection lines is beneficial. An expert on seismic reflection data processing may need to be consulted to evaluate the quality of the existing datasets prior to making a decision.

After analyses of the earthquake and seismic reflection data are complete, determine whether acquisition of microgravimetric and/or aeromagnetic data is advisable. Results from the earthquake analysis and seismic reflection analysis may help judge whether additional confirmation of the subsurface geologic interpretation is needed. Also, insights gained from analysis of the existing earthquake and reflection data may aid in determining the acquisition parameters of the gravity and/or magnetic surveys. Because experience with these types of methods is limited within Reclamation, one or more experts on these methods would likely need to be retained to evaluate their costs and benefits and to aid in design of the surveys.

The simple volume balance and heat transfer calculations proposed by the CRB (recommended actions 4 and 5 above) could be performed at any time. Simple volume balance calculations have been done by PVU in the past and could be updated fairly easily. Simple heat transfer calculations could also be done in-house at relatively small expense.

Evaluation of the seismic hazard associated with drilling into adjacent fault blocks (action 7) should be addressed through a consultant review board process. A CRB is already planned for later this fiscal year for reviewing the seismic hazard associated with PVU fluid injection, and this would be an appropriate topic to include in that review.

STEP 3: If a nearby fault block that has not experienced significant pressurization cannot be identified, or if it is determined to have insufficient reservoir volume, or if pressurizing it would adversely impact the seismic hazard, look for a second well site location at a greater distance from PVU Injection Well #1.

Recommended actions:

1. Review existing well and seismic reflection data in SE Paradox Valley for usefulness. (SE Paradox Valley has lower population than NW Paradox Valley and has not experienced induced seismicity from PVU Injection Well #1.)

2. Consider whether acquiring microgravimetric and/or aeromagnetic data is likely to provide additional constraints for selecting the well site and, if so, collect and analyze such data.

3. Drill an exploration well. Acquire geophysical well logs, perform core analysis, and perform injection flow tests to assess reservoir quality in the new well.

If reservoir quality is good:
4. Acquire new surface seismic reflection data and possibly vertical seismic profiling (VSP) data in the vicinity of the exploration well. These surveys should aid in estimating the capacity of the proposed reservoir (by identifying the locations of sealing faults, for example), to verify that the new well will have an acceptable lifespan. Results from these surveys could also potentially be used to optimize the bottom hole location prior to completing the well.

Work to date:

A potential site for a second injection well has been identified in East Paradox Valley approximately 6 miles southeast of the existing injection well. The site was chosen by virtue of its proximity to the brine well field and being private land, with no geologic or other considerations. Additional geologic and geophysical data collection and analysis of this site would be required.

Proposed near-term tasks:

Acquire existing or new geophysical data and analyze to aid in determination of suitability of the potential site in East Paradox Valley mentioned above. Geophysical methods that might be useful include microgravimetric, aeromagnetic, and seismic reflection surface surveys.

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