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May 8, 2019

Department of Conservation
801 K Street, MS 24-02
Sacramento, CA 95814
RE: Aliso Canyon Draft Seismic Safety Reports

Dear Mr. Harris and DOGGR staff,

While there is no formal public comment forum for the Aliso Canyon draft seismic study, I want to offer some important critical review on the study.

First, I want to commend the study's authors for embarking on a serious and detailed investigation. The study's various authors are distinguished scientists and engineers with the right qualifications for the job. The overall workflow is comprehensive. Their write-up is clear and concise but detailed enough to understand the scope of their work.

The investigation summarized in the reports verifies many of the concerns that I expressed in previous public comment. For example:

- the study confirms that there is about a 5% chance in the next 50 years of an earthquake with sufficient slip to simultaneously rupture the casing and tubing of a substantial number of wells at Aliso Canyon (975-year recurrence).
- The study confirms that wells subjected to earthquake shear are likely to leak. SoCalGas' Risk Management Plan Supplement #2 claimed (without evidence) that the tubing "normally does not" leak in earthquakes (p. 11). But when they actually tested things out, the tubing leaked in 16 of the 18 cases along with complete casing rupture. It is essential that DOGGR continue to require evidence and not simply take the operator's opinion about what will or will not happen.
- The study confirms that scenarios exist in which the flow rate is up to three times greater than the 2015 blowout (Peak flowrates in the P90 scenario of 250 MMscf/day).

The study also claims that the high flow rate scenarios are unlikely, and that the majority of scenarios have flow rates that are very low. I am compelled to write this message because I do not feel that the study accurately characterizes the probability of the different scenarios due to an incorrect assumption about fault permeability. This message pertains specifically to Report 10 of the series that describes the dynamic gas flow analysis of the entire reservoir system.

Summary

The report does a good job of incorporating our current understanding of fault damage zone morphology around large, active faults (e.g., Evans, Forster, and Goddard, 1997). What the report fails to do is account for the changes to the fault permeability after a large earthquake. The quantitative treatment of post-earthquake permeability that the authors used systematically biases the study towards low flow rates and therefore underestimates the risk of high flow-rate scenarios.

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Specific concerns

Permeability changes post-earthquake

Comment: The authors of Report 10 interpret their model by saying, "This reflects the low values, and **discontinuous nature of, the fault permeability structure**." (Report 10). If that's true, then we should be concerned about the validity of their conclusions. One of the key effects of earthquake rupture on permeability structure is to create continuous permeability pathways (e.g., Wang et al., 2016 — the very title of which is "Large earthquakes create vertical permeability by breaching aquitards").

Page 22 of the draft of Report 10 has a thoughtful and accurate discussion of the changes in permeability following earthquakes. While the authors are aware of the permeability changes, their treatment of the effect in their model is not sufficient. They state, "Rather, we suggest that the high permeability fault case that we consider encompasses the likely increase in fault zone permeability associated with such an earthquake" (p. 22). In other words, they feel that the 90% confidence level of pre-earthquake permeability is sufficient to account for the permeability change. Traditionally, the permeability during and following a large earthquake is modeled by a 1-2 order of magnitude increase in permeability in both the fault core and damage zone (e.g., Cappa and Rutqvist, 2011; Miller and Nur, 2000). These changes are caused by sudden stress reductions and are verified in both laboratory experiments (e.g., Uehara and Shimamoto, 2004) and theoretical modeling (Bizzarri, 2012). Even the passage of seismic waves from distant earthquakes has been linked to a factor of 3 increase in permeability in fractured granodiorite (Elkhoury et al., 2006). Importantly, these changes are essentially 'bulk' permeability changes, but the changes might be much more significant locally. It is these local changes that are responsible for creating an interconnected flow pathway through the damage zone and eradicates the discontinuous permeability structure that seems to dominate the flow rates in Report 10's models.

Suggestion: The proper treatment should model at least an order of magnitude increase over pre-earthquake permeabilities. The authors should also model a 'worst case' that includes a two-orders of magnitude increase in permeability that heals over time. The permeability changes following a large earthquake can be long-term. At the Nojima fault zone, one of the best-studied examples of permeability changes within a fault core following a large earthquake, it took a full eight years for the permeability to stabilize, though healing followed an exponential decay (Kitagawa & Kano, 2016). Simply using pre-earthquake permeabilities is *not* an appropriate assumption and dramatically underestimates the expected flow.

Permeability measurements

Comment: The report itself does not articulate how the permeability measurements were obtained (it cites an inaccessible internal report from Numeric Solutions). We've known for decades that measurements at the laboratory scale of core samples tend to significantly underestimate the bulk, field-scale permeability around active faults (e.g., Zoback & Byerlee, 1975; Coyle &

Zoback, 1988). Within phyllosilicate gouge materials, gas permeability tends to be up to an order of magnitude higher than water permeability (Faulkner & Rutter, 2000). In order for us to provide adequate peer review, the authors must provide further information.

Suggestion: 1) Describe how the permeability measurements were derived specifically in the public document. 2) Ensure that bulk/field-scale permeabilities for gas are used.

Modeling timeline

Comment: In Cappa & Rutqvist's (2011) model of CO_2 flow along faults, they found that it took about 10 years for the gas to migrate to the ground surface. Report 10 stops the model after 5 years without any justification for this timeline. Figure 7.5b in Report 10 show a considerable amount of gas within the fault zone and that no additional gas is leaking into the fault. The progression from 2021 to 2025 indicates that there is an upward migration and Figure 7.5a indicates pockets of very high pressure that likely drive continued flow (albeit 'slow'). How long will it take for the gas to reach the surface, and what will the flow rate be when it does?

Suggestion: Carry the simulation out for as long as it takes to determine the peak flow at the surface.

Summary document

SoCalGas' summary of the findings is overly optimistic and ultimately misleading, omitting key information from Dr. Shaw's summary and the reports themselves. Since it is more likely to be read than the individual reports, I want to ensure that it accurately portrays the range of findings and does not mislead policy makers.

Off-fault flow

Comment: The overview states that, "Could only potentially flow to surface along the well infrastructure" (p. 3). This is misleading. Report 10 indicates, "Our current analysis does not consider other potential flow paths, such as fracture zones or stratigraphic units, in the hanging wall of the Santa Susana fault. This simply reflects that we do not have sufficient knowledge of these potential structures to explicitly represent them in our simulations." (p. 23).

Keep in mind that permeability can be enhanced by shaking from large aftershocks that would be expected in the years following a large earthquake. Such permeability changes might be especially important in the shallower sections of the fault where confining pressure is lower. The existing modeling stops right about the time that the gas in the fault core itself is reaching these shallower sections. Faults often exhibit complex flower structures in the near-surface and a new earthquake can significantly modify the fracture network and create new structures. The overall *interpretation* of the simulation must include mention of this limitation.

Report 10 argues that these additional flow pathways are unlikely because of the discontinuous permeability structure in the fault zone, but I mention above that we cannot count on the pre-earthquake barriers to be present after an earthquake.

Suggestion: Change the summary to, "Could flow to the surface along the well infrastructure or other structures that were not included in this simplified model. If gas does flow along these other structures, the amount of leakage could be substantially higher than the simulations indicate."

Fully characterizing the range of scenarios

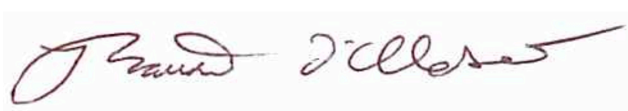
Comment: The summary states, "Even in such an unlikely event, and if all active wells were damaged, the study indicates that the expected release would be approximately 1 MMscf over five years. The studies also define other gas flow scenarios and provide insights that can be used to help address these risks" (p. 3).

First, the event is not all that unlikely – 5% in 50 years. All large earthquakes could be considered 'unlikely', but we will still advocate that people prepare for them!

Second, the word "expected" doesn't really capture the quantitative information given by probabilities within the studies. P50

Suggestion: The authors could say that there is a 50% chance that the leakage will be less than 1MMscf over five years. But the summary shouldn't simply dismiss the 'other scenarios'. There is a 10% chance that the P90 flow scenario will occur, and it is so much worse that the authors really should include it in the summary. Such low probability, high cost events need to be provided to policy makers.

Thank you for your consideration,



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References

Cappa, F., & Rutqvist, J. (2011). Modeling of coupled deformation and permeability evolution during fault reactivation induced by deep underground injection of CO2. International Journal of Greenhouse Gas Control, 5(2), 336-346.

Bizzarri, A. (2012). Effects of permeability and porosity evolution on simulated earthquakes. Journal of structural geology, 38, 243-253.

Elkhoury, J. E., Brodsky, E. E., & Agnew, D. C. (2006). Seismic waves increase permeability. Nature, 441(7097), 1135.

Evans, J. P., Forster, C. B., & Goddard, J. V. (1997). Permeability of fault-related rocks, and implications for hydraulic structure of fault zones. Journal of structural Geology, 19(11), 1393-1404.

Rojstaczer & Wolf (1992) that dynamic strains caused fracturing in the upper 200-300 m that formed a new, continuous flow path.

Kitagawa, Y., & Kano, Y. (2016). Changes in permeability of the Nojima fault damage zone inferred from repeated water injection experiments. Earth, Planets and Space, 68(1), 185. https://link.springer.com/article/10.1186/s40623-016-0566-2

Nicol, A., Seebeck, H., Field, B., McNamara, D., Childs, C., Craig, J., & Rolland, A. (2017). Fault Permeability and CO2 Storage. Energy Procedia, 114, 3229-3236. doi: 10.1016/j.egypro.2017.03.1454

Miller, S. A., & Nur, A. (2000). Permeability as a toggle switch in fluid-controlled crustal processes. Earth and Planetary Science Letters, 183(1-2), 133-146.

Rojstaczer, S., & Wolf, S. (1992). Permeability changes associated with large earthquakes: An example from Loma Prieta, California. Geology, 20(3), 211-214.

Uehara, S. I., & Shimamoto, T. (2004). Gas permeability evolution of cataclasite and fault gouge in triaxial compression and implications for changes in fault-zone permeability structure through the earthquake cycle. Tectonophysics, 378(3-4), 183-195.

Wang, C. Y., Liao, X., Wang, L. P., Wang, C. H., & Manga, M. (2016). Large earthquakes create vertical permeability by breaching aquitards. Water Resources Research, 52(8), 5923-5937.