# Summary of the Draft Aliso Canyon Gas Storage Field Geologic, Seismologic and Geomechanical Studies and Reports

The Aliso Canyon Natural Gas Storage Facility, operated by Southern California Gas Company (SoCalGas or Company), is located in the Santa Susana Mountains of Southern California. The Facility serves more than 11 million customers, and provides natural gas fuel for electricity generation in California, supporting a flexible power supply system that accommodates use of intermittent, renewable power supplies such as wind and solar. Natural gas is typically stored in subsurface reservoirs and delivered to the market on demand, and thus gas storage facilities such as Aliso Canyon are often located close to these markets.

To promote safe operations of the Aliso Canyon Facility, SoCalGas has engaged in comprehensive assessments of the geotechnical hazards present at the site. Such hazards include the threat of strong ground shaking due to earthquakes, associated displacements on faults that intersect the wells used for gas injection and production, and landslides that might result from earthquakes or severe precipitation events. The goals of these assessments are to:

1) Quantify the level of each hazard at the site; and
2) Determine the impacts that such events might have on the facility

Through these insights SoCalGas can establish plans to further mitigate these risks.

SoCalGas has assembled a team of renowned experts to examine each of these hazards and their associated risks to the Facility. The Company has made available data from the field, and facilitated a series of onsite studies to gather further information. The proposed scope of work and interim results were previously shared with representatives from the California Division of Oil, Gas and Geothermal Resources (DOGGR) and various national laboratories (the National Labs), and their feedback helped to extend and improve these technical assessments.

A central element of this work has been the development of a comprehensive geologic and structural representation of the Aliso Canyon field, including detailed mapping of landslide deposits and subsurface geology. A three-dimensional subsurface model of the Aliso Canyon Field was developed using data constraints from wells, seismicity, and resources such as the Southern California Earthquake Center's (SCEC) Community Fault Model. Together, these datasets and resources support a series of assessments of geologic hazards present at the site, as well as analog and numerical simulations to determine how the wells and reservoir in Aliso Canyon may respond to future seismic or landslide events. Particular attention is paid to the risks of gas leakage to the surface, with the aim of providing recommendations to guide appropriate operating and response strategies to mitigate these risks.

The following sections briefly summarize the technical reports that have been prepared and their major findings.

**Report 1: ALISO CANYON GAS STORAGE FACILITY LANDSLIDE HAZARD REPORT**
The goal of this study is to identify and map the distribution of landslides within the Aliso Canyon facility, and to assess their relative state of activity. This study was conducted by Earth Consultants International and Dr. Roy Shlemon. The effort involved a comprehensive evaluation of previous landslide mapping studies. These maps were then augmented by air photogrammetry and local field investigations, which included mapping, borehole excavations, and trenches.

Dozens of landslides are present at the Aliso Canyon Facility site, with the largest being Late Pleistocene in age (12,000 to 20,000 years old). Based on their geomorphic expression, a subset of these landslides is deemed to be currently active. These active slides appear to have been triggered by large precipitation (El Nino) events as well as ground shaking due to large earthquakes. The 1994 Northridge (M 6.7) earthquake, for example, triggered motion along several of these active slides, including locations where excavations and grading operations associated with past oil production and operation of the gas storage field locally modified surface slopes.

The main conclusions of this study are that:

• Landslides are prevalent at the Aliso Canyon Facility

• Landslides vary in their level of activity, with 17 landslides showing evidence of recent (Holocene or within the last 11,000 years) activity

• Of the 62 gas storage wells operated by SoCalGas at the Facility, only a few are located within active landslide zones

These results will be examined in Reports 2 and 3, which address the stability of slopes and mapped landslides to assess the degree of hazard that they represent. This involves calculating the impact that future landslides may have on wells operating in the field.

**Reports 2 & 3: STABILITY ANALYSIS OF LANDSLIDE-PRONE SLOPES AT THE ALISO CANYON GAS STORAGE FIELD, CALIFORNIA and WELLBORE LANDSLIDE LOADING ASSESSMENT REPORT**
The goals of these studies are to numerically model the stability of landslide deposits at the Aliso Canyon facility and to assess how landslide motions could impact the Gas Storage wells. Report 2 was prepared by Dr. Richard Schultz of Orion Geomechanics, and employed geomechanical methods to quantify the landslide stability and landslide depths. The numerical modeling involved defining the geometry and dimensions of landslide surface slopes at the site, as well as the physical properties of the sediments. Slope stability was assessed under water saturated conditions, attempting to replicate the condition after intense rainfall events when the sediments are weakest. Report 3 was prepared by Stress Engineering Services Inc., under the direction of Dr. Sathish Ramamoorthy, and employed numerical modeling approaches to assess how landslide motions would impact the surface casing, production casing, and tubing for the operating gas storage wells.

The main conclusions of these studies are that:

• Surface slopes outside of known landslide areas are considered to be stable under saturated conditions

• Zones of potential instability are associated with a subset of known landslides.

• The predicted depth of landslides that would result from water saturation of the sediments average 200 ft. deep, with a range from 43 to 265 ft. deep.

• Landslide displacements of more than 9 inches (22.9 cm) are expected to exceed the capacity of tubing in the gas storage wells.

• Significant landslide displacements are unlikely to be supported by a typical well casing in the field, and thus would lead to damage of the well.

• Only a few gas storage wells are at potential risk in active landslide zones.

The risks associated with the limited number of wells impacted by active landslides in the field could be eliminated or reduced by changing the operations of those wells, reinforcing them to resist damage from futures slides, or sealing with cement and abandoning the wells.

**Report 4: ALISO CANYON GAS STORAGE FACILITY GEOLOGIC AND GEOMECHANICAL STUDY**
The goal of this study is to develop a comprehensive geologic and structural model of the Aliso Canyon Facility that can be used to assess the effectiveness of the stratigraphic topseal and fault seals that constrain the natural gas within the Sesnon/Frew Formation gas storage reservoirs. In addition, this model serves as the basis for reservoir simulations to assess gas storage capacity and reservoir pressures, as well as potential gas migration under conditions where well systems are damaged. The study was conducted by Numeric Solutions, LLC, under the direction of John Harris.

The subsurface structural and reservoir model consists of a 3-D model of the Sesnon and Frew Formation gas storage reservoirs, the topseal, and a series of other key stratigraphic horizons up to the surface. In addition, both reservoir-scale and larger regional faults are represented in the model. Several of these structures, including the Ward and Frew faults, limit the extent of the reservoir and thus influence gas containment. Specific focus was paid to defining the geometry of the Santa Susana fault, a tectonically active structure[1] that overlies the gas storage zone. This analysis included evaluation of the fault geometry in the SCEC Community Fault Model (Plesch et al., 2017), which was subsequently refined using additional well data from the field. Reservoir and rock properties were modeled using well logs and defined in the geologic model using

[1] The Santa Susana fault is defined as a class A active structure that has ruptured in the last 15,000 years, based on the U.S. Geological Survey Quaternary Fault and Fold database.

geostatistical interpolation methods. In particular, shale content was used to infer porosity and permeability, which helped to support reservoir flow and storage simulations. Petrophysical properties and values of tectonic stress and fluid pressure were defined using well logs.

The structural and reservoir models, including rock properties, were used to assess topseal and fault seal of the storage reservoir. This included X-Ray diffraction analyses of samples taken from cores, and estimation of the Shale Gouge Ratio (SGR) across faults.

The main conclusions of this study are that:

• The Storage Field is the faulted, southeast plunging Aliso anticline, with a steeper north limb (~60˚) and a gentler south limb (~25˚). These limbs provide north-south closure for the reservoir, along with sealing across the Frew and Ward faults. Closure to the east is due to onlap and stratigraphic pinch out of the Sesnon sands. The Santa Susana fault does not act as a seal for the gas storage reservoir.

• Determined values of vertical stress (1.00 psi/ft.), minimum horizontal stress (≈ 0.60 psi/ft.), and fluid pressure (≈ 0.44 psi/ft., near hydrostatic) were typical for fields operating in this region.

• The Modelo caprock/top-seal sequence has shale contents (Vshale) of 75–100 and low permeabilities, implying good static sealing properties within the Storage Zone.

• The Ward fault is considered to provide a good static seal of the Storage Zone. Cross-fault sealing characteristics of the Santa Susana fault are consistent with those of the Ward fault. The Frew fault may provide a seal of intermediate quality.

The structural and reservoir model will be used in subsequent Reports to assess earthquake hazards, simulate reservoir performance, and assess the impacts of seismic events on well systems and gas storage and migration.

**Report 5: ALISO CANYON PROBABILISTIC SEISMIC HAZARD ANALYSIS**

The goal of this study is to estimate the potential levels of strong ground shaking that could result from future earthquakes that affect the Aliso Canyon facility. The study employs a standard probabilistic seismic hazard analysis (PSHA) approach that incorporates uncertainties in future earthquake occurrence (event locations, magnitudes, and timing), seismic wave propagation and attenuation, and near-site soil response. The study was conducted by Dr. Paul Somerville of AECOM, using OpenSHA software (Field et al., 2003) provided by the Southern California Earthquake Center.

The PSHA analysis used the Uniform California Earthquake Rupture Model (UCERF3) (Field et al., 2014) developed by the U.S. Geological Survey, California Geological Survey (CGS), and SCEC, enhanced with refined alternative representations of the Santa Susana fault presented in Report 4. The study developed probabilistic uniform hazard response spectra (UHS) with average return periods (ARP) of 475 years (equivalent to a 10% probability of exceedance in 50 years), 975 years (equivalent to a 5% probability of exceedance in 50 years) and 2,475 years (equivalent to a 2% probability of exceedance in 50 years) for the rock formations that underlie the ground surface assuming linear behavior. Using ground motions recorded during the 1994 Northridge (M 6.7) earthquake, sets of three component time histories were spectrally matched to the mean uniform hazard spectra and these time histories were used as input into non-linear site response analysis. Ground motions were provided to the well system response team (Report 7) in the form of a vertical array of three component ground acceleration time histories within a soil profile representative of the Aliso Canyon site. This analysis also considered the decrease in forecast ground motions with depth in order to determine values appropriate for modeling subsurface borehole response.

The main conclusions of this study are that:

• The Aliso Canyon Facility is situated in an area of moderate to high ground shaking hazard, comparable to other sites in Southern California near major active fault systems.

• The seismic hazard is dominated by earthquakes that occur on nearby structures, including the Santa Susana fault. Alternative representations of the Santa Susana fault developed with subsurface data from the field are considered in this analysis.

• The mean probabilistic peak ground accelerations with 475, 975 and 2,475 ARPs exceed 1g.

• Recordings of the 1994 Northridge earthquake were spectrally matched to the uniform hazard spectra and non-linear seismic site response analyses were performed on these time histories to estimate the ground motions at 5-foot depth intervals.

• Overall, the 1994 Northridge (M 6.7) earthquake, which was only about 6-7 km away from the Aliso Canyon Facility, provides a direct analog for ground shaking that will result from future large earthquakes in the region.

The study will be used as the basis for the assessment of fault displacement hazards in Reports 6, and the modeling of well system response in Report 7.

**Report 6: ALISO CANYON PROBABILISTIC FAULT DISPLACEMENT HAZARD ANALYSIS**

The goal of this study is to estimate the potential magnitudes of displacements on the Santa Susana fault that could result from future earthquakes that affect the Aliso Canyon facility. The study employs the earthquake rupture forecast presented in the PSHA of Report 5 to calculate likely displacements on the various strands of the Santa Susana fault that are penetrated by wells operating in the field. The study was conducted by Dr. Hong Kie Thio of AECOM.

The Santa Susana fault lies beneath the Aliso Canyon facility and is penetrated by wells operating in the gas storage zone from several hundred to more than 4000 ft depth. The fault consists of two distinct surface splays (upper and lower) which merge to a single fault plane at depth. The Probabilistic Fault Displacement Hazard Analysis (PFDHA) estimates mean fault displacements for the average return periods of 475, 975, and 2,475 years. To date, PFDHA methods have largely been applied to determine the likelihood of surface fault displacements. However, at the Aliso Canyon facility the primary risks associated with fault displacements are at depth where wells penetrate strands of the Santa Susana fault. Thus, this study examines the variations in fault displacement as a function of depth and fault type, and uses an extensive earthquake catalog in Southern California to guide this assessment. Results are comprised of probabilistic hazard curves (rate of exceedance versus displacement) and estimates of exceedance for the 475, 975, and 2,475 annual return periods for individual wells.

The main conclusions of this study are that:

• Exceedance displacements for the 475-year average return period range from zero to 9 cm; for the 975-return period from ≈ 50 to 70 cm; and for the 2,475-return period from ≈ 1.9 to 2.1 m.

• Earthquake distributions in Southern California indicate a reduced likelihood of displacements at wellbore depth for smaller earthquakes.

• Larger magnitude events associated with longer return periods show an increased likelihood of rupturing to the surface and involving significant displacements at the well crossings.

• Estimated exceedance displacements are sensitive to the slip rates inferred for the Santa Susana fault.

The study will be used as the basis for the assessment the impacts of fault displacements to the well systems in Reports 7 & 8.

**Reports 7 & 8: WELLBORE LOADING ASSESSMENT AND SHEAR TESTING AND FINITE ELEMENT ANALYSIS OF 1:10 SCALE PIPE SAMPLES**

The goals of these studies are to define the response of the SoCalGas gas storage and monitoring wells operating in the Aliso Canyon Facility to ground motions and fault displacements that may result from future earthquakes in the region. The intensity of ground shaking considered in the analysis is based on the PSHA of Report 5. Fault displacement scenarios are based on the PFDHA of Report 6, and are focused on the Santa Susana fault. Both analyses use finite-element modeling techniques to numerically represent casing and tubing components; however, the approaches for the analyses differ in terms of the type of elements used and responses that are extracted. The ground shaking assessment uses models of well system components (constructed used beam elements) and determines the resultant loads on the casing and production tubing. The fault displacement analysis uses models of the region of the well in the vicinity of fault crossings (constructed using solid elements) and determines how different magnitudes of fault displacements will impact these systems. This study was supported by a series of scaled (1:10) analog experiments that simulated fault displacements applied to casing and tubing components under a range of conditions. These experiments were used to determine the strength or capacity of casing and tubing components, and thus the magnitudes of displacement that may lead to failure. These studies were performed by Stress Engineering under the direction of Dr. Sathish Ramamoorthy.

The main conclusions of this study are:

For ground shaking:

• At 475 ARP, mean anticipated levels of ground shaking do not exceed the capacities of any surface casing or tubing for any of the 62 operating gas storage wells. For the production casing the mean load exceeds the capacity for one well. When factoring in a range of uncertainties, the capacities of the tubing are still not exceeded, but the capacities of surface casing in 37 wells and of production casing of one well may be exceeded.

• At 975 ARP, mean anticipated levels of ground shaking may exceed the capacities of surface casing for 31 of the 62 wells and the production casing for one well, but do not exceed the capacities of any tubing. When factoring in a range of uncertainties, surface casing capacities may be exceeded in 21 wells, production casing capacities may be exceeded in 10 wells, and tubing capacities in 7 wells.

• At 2475 ARP, mean anticipated levels of ground shaking may exceed the capacities of surface casing for 43 of the 62 wells. The capacities may be exceeded for production casing in 5 wells and for tubing in 7 wells. When factoring in a range of uncertainties, some additional wells may exceed their capacities of surface (18) and production (41) casing, and 5 wells may exceed their capacities for tubing.

For fault displacement:

• At 475 ARP, depending upon well construction practices and fault crossing angles, it is likely that most wells' tubing capacity will not be exceeded. The anticipated levels of fault displacement may exceed the capacity of the production casing for 41 of the 62 wells.

• At 975 ARP, anticipated levels of fault displacement may exceed the capacity of the production casing and tubing for 48 of the 62 wells.

• At 2475 ARP, anticipated levels of fault displacement may exceed the capacity of the production casing and tubing for all wells.

These results indicate that the likelihood of tubing failure for the 475 ARP is low. Given that all wells at the Aliso Canyon Facility are operating under tubing flow only, these results indicate that the integrity of the well system would be maintained as a result of the anticipated ground shaking and most fault displacement levels. For the 975 ARP, ground shaking levels are also not expected to exceed the capacity of the tubing for most of the wells and thus are not expected to lead to well system failure. For the 2475 return period, a limited number of wells may experience tubing failure due to ground shaking. For both the 975 and 2475 ARP's, fault displacements are expected to lead to failure of the majority of well systems. This motivates the analyses presented in

Reports 9 and 10, which will model gas migration in the event that wells systems are comprised to assess the potential for gas flow to the surface.

**Report 9: WELL FLOW MODELING**

The goal of this study is to determine how gas may flow outside of casing in the event that that wells are damaged by faults displacements during a large earthquake associated with the 975 or 2475 ARP's. The first objective of this assessment is to define relationships between reservoir pressure and flow rate at subsurface locations where the well systems cross the Santa Susana fault and may be damaged by fault displacement. The second objective is to define a range of possible flow rates for gas from these leak points along the well system to the surface. This analysis considers a range of different well system and geological parameters that may affect gas flow, and employ a statistical approach to define relationships between reservoir pressure and gas flow. The studies were performed by RPS under the direction of Dr. Ivor Ellul.

The steady state models developed in this study relate pressure at the reservoir to pressures at the fault (objective 1) or the surface (objective 2), and are used to calculate gas flow rates. These models incorporate assessments of the inflow performance from the reservoir to the well, the various components of the well system that control flow to the fault crossings, and a range of potential apertures for damaged well tubing. For assessing gas flow to the surface along the well systems, additional parameters such as depth of the fault crossing, the diameter of the annulus and integrity of the cement bond between the rock and well casing, and the permeability of shallow geologic formations are considered. Given conservative ranges of these parameters considered in more than 2 million simulations, this analysis yields average (P50), low (P10) and high (P90) rates for gas flow. These relationships are provided for 7 type wells that were chosen to be representative of all 62 wells operating in the field.

The main conclusions of this study are that:

• A set of functions effectively describe the relationship between reservoir pressure and gas flow rate at the fault crossing.

• Calculated gas flow rates to surface along the well system show a range of different outcomes that are sensitive to the aperture of the deformed tubing, the diameter of the annulus and cement integrity between the casing and rock formations, and the permeability of the shallow geological formations.

• Many cases show no gas flow to surface because the tubing does not leak or the cement bond between the casing and rock formations is adequate to halt upward gas migration.

• In the set of cases (representing a 975 or 2,475 ARP type seismic event) where gas flows to the surface, average (P50) gas flow rates per well range from a few thousand to one hundred thousand standard cubic feet per day (0.01 to 0.1 MMscf/day). P90 flow cases per well are approximately 10 MMscf/day.

These results provide static, 1D relationships between reservoir pressure and flow that can be used to inform 3D simulations of gas flow over time. These 3D simulations are described in Report 10, and provide a basis to assess both rates and volumes of potential gas flow along all wells and geologic structures.

**Report 10: ALISO CANYON DYNAMIC GAS FLOW ANALYSIS**

The goal of this study is to define potential gas flow rates and volumes through both geologic structures and wells over time in the event that wells are damaged during a large earthquake associated with the 975 or 2475 ARP's. Gas that moves outside of well casings can potentially migrate along the Santa Susana fault or other geologic pathways, as well as upward along the wells. The models presented here dynamically apportion the flow between the Santa Susana fault and the well systems. These calculations consider the evolving state of reservoir pressure, and thus provide for gas flow rates and volumes over time through these potential pathways. The models provide a range of potential flow scenarios employing the P50, and P90 relationships between reservoir pressure and flow derived in Report 9, and a range of permeability values for the Santa Susana fault. The studies were performed by Seismix Reservoir Management, LLC, under the direction of Drs. Ruben Juanes and John H. Shaw.

The gas flow calculations use a dynamic model of reservoir behavior that considers the history of oil production and gas storage in the Aliso Canyon facility. This model, initially developed by RPS and reproduced by Seismix, was calibrated by matching the pressure histories and flow rates observed at the Facility over time. This provided a sound basis to forecast future reservoir behavior under conditions where gas may flow outside the well casing to the surface. Relationships between reservoir pressure and gas flow at the locations where the wells cross the Santa Susana fault were used to simulate gas flow into the fault and to the surface. The analysis incorporated the 3D geometry of the Santa Susana fault based on the Southern California Earthquake Center's Community Fault Model updated with local field data, and properties for the fault defined by well observations and geological constraints.

The main conclusions of this study are that:

• Simulations allowing for gas movement only along the Santa Susana fault do not produce any flow to the surface. This reflects the low values, and discontinuous nature of, the fault permeability structure.

• Simulations allowing for gas flow only along the wells closely match the RPS results described in Report 8 for peak flow rates. However, the gas flow decreases over time as a result of the reduction of reservoir pressures.

• Coupled simulations that physically partition gas flow between the fault and the wells do not produce gas flow at the surface along the Santa Susana fault. Flow to the surface along wells varies as a function of the well types and corresponding P10, P50, and P90 relationships.

• Models that consider all wells damaged when operating at 3,600 psi reservoir pressure (equating to a working gas inventory of approximately 86 Bcf) and with flow governed by the P50 relationships show total gas flow to the surface from all operating wells peaking at 0.25 MMscf/day and declining quickly thereafter. Total gas releases are less than 1 MMscf over five years. Maximum flow cases for all wells using the P90 flow relationship peak at 250 MMscf/day and would release 40 Bscf over five years.

It is worth noting that, as of today, the field overall is operating below full pressure, which would be expected to lessen gas flow totals.

These results provide a dynamic assessment of potential for gas flow to surface along the Santa Susana fault and the operating wells. These models help to identify the behavior of different classes of wells and the field as a whole, and thus serve to quantify the potential hazard and assess means to mitigate the associated risks.

**DISCUSSION**

This series of assessments define and quantify a number of geologic hazards that are present at the Aliso Canyon Facility. Some of these hazards arise simply from living and working in southern California, whereas others are specific to the operations of the facility. The goal of this assessment is to define these hazards and their associated risks to field operations in a way that SoCalGas and the regulatory agencies can define appropriate operating practices and potential mitigation strategies to reduce these risks. Ultimately, these risks cannot be fully eliminated – as they are not for any home, business, or industrial facility operating in the state. Rather, the practical approach is to define the risk levels that are acceptable, and to operate in a manner that conforms to good industry practices, implements relevant safety protocols, and does not exceed appropriate operating limits and standards.

Active landslide zones are present at the Aliso Canyon Facility, and these have been carefully delineated. A majority of the operating wells at Aliso are not threatened by these active landslides. A few other wells lie within active landslide zones. This provides an opportunity to address these risks, either by reinforcement of the wells, installation of subsurface safety valves, or other mitigation strategies. If these methods do not adequately reduce the risks of damage from landslides, the wells could be removed from operation.

Earthquake hazards at the facility take two forms: that of strong ground shaking or fault displacements. Both hazards primarily result from large, infrequent earthquakes. As is common practice, these hazards are estimated using probabilistic assessment (PSHA and PFDHA, respectively). The ground motions and fault displacements are estimated for select probabilities of exceedance in a given time interval, or equivalency, for selected average return periods. For all return periods the well response analyses are performed for the mean hazard levels. For relatively low return periods (ARP 475 years), this study suggests that the threats to the facility due to the mean hazards are minimal. For longer return periods (ARPs of 975 and 2475 years), the well system response calculations show that the mean probabilistic ground motions do not pose a serious threat to the wells systems and gas containment. Stronger ground shaking may pose hazards to a limited number of wells. The limited threats from strong ground shaking reflect the experience of the 1994 Northridge (M 6.7) earthquake, which occurred about 6 to 7 km away at a depth of about 17 km beneath the facility. No gas storage facility similar to Aliso Canyon has experienced such a strong earthquake, and no gas was released to the surface during this event.

The hazards associated with fault displacements at the Aliso Canyon facility result from the fact that all of the operating wells in the field pass through the Santa Susana fault as they extend down to the gas storage reservoirs. The PFDHA estimates the exceedance rates of fault displacement at the Facility. The mean fault displacement exceedances corresponding to 475, 975, and 2,475-year ARPs was provided to the well response team (Reports 7 & 8) in which a series of numerical models and analog tests describe how the well systems are expected to respond to these forces. These assessments indicate that well tubing, through which the gas flows, will likely not be compromised by displacement associated with the 475 ARP. Larger displacements associated with the 975 and 2475 ARP's are expected to impact the majority of wells. Scaled laboratory-based physical tests show that in many cases the well tubing will be flattened and thus gas flow restricted. In other cases, cement bond integrity between the casing and rock formations will limit upward migration of gas. In still other cases, damaged tubing with more limited overlying cement bonds may result in gas release to the subsurface. For these scenarios, a series of models quantify the potential rates and volumes of gas migration to the surface along the wells, the Santa Susana fault, or both. These simulations do not show gas flow to the surface along the fault, even with high subsurface gas flow rates and fault permeabilities. Rather, gas flows toward the path of least resistance along the wells. Rates of gas flow to the surface vary as a function of well design and permeability of the geologic stratum that surround the wellbore. This analysis defines the expected (P50) and higher potential rates of flow, and identifies specific wells that may pose more risk. This provides a potential way to mitigate these risks through selection of operating wells, reinforcement of well casing systems, installation of downhole safety valves, or other strategies.

Dr. John H. Shaw (March 19, 2019)

**References Cited**

Field, E.H., and 2014 Working Group on California Earthquake Probabilities (2015), UCERF3: A new earthquake forecast for California's complex fault system: U.S. Geological Survey 2015–3009, 6 p., https://dx.doi.org/10.3133/fs20153009.

Field, E.H., T.H. Jordan, and C.A. Cornell (2003), OpenSHA: A Developing Community-Modeling Environment for Seismic Hazard Analysis, *Seismological Research Letters*, 74, no. 4, p. 406-419.

Plesch, A., J. H. Shaw, C. Benson, W.A. Bryant, S. Carena, M. Cooke, J. F. Dolan, G. Fuis, E. Gath, L. Grant, E. Hauksson, T. H. Jordan, M. Kamerling, M. Legg, S. Lindvall, H. Magistrale, C. Nicholson, N. Niemi, M. E. Oskin, S. Perry, G. Planansky, T. Rockwell, P. Shearer, C. Sorlien, M. P. Suess, J. Suppe, J. Treiman, and R. Yeats (2007), Community Fault Model (CFM) for Southern California, *Bulletin of the Seismological Society of America*, Vol. 97, No. 6, p. 1793–1802.