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Natural Gas Network Resiliency to a "ShakeOut Scenario" Earthquake

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Abstract

A natural gas network model was used to assess the likely impact of a scenario San Andreas Fault earthquake on the natural gas network. Two disruption scenarios were examined. The more extensive damage scenario assumes the disruption of all three major corridors bringing gas into southern California. If withdrawals from the Aliso Canyon storage facility are limited to keep the amount of stored gas within historical levels, the disruption reduces Los Angeles Basin gas supplies by 50%. If Aliso Canyon withdrawals are only constrained by the physical capacity of the storage system to withdraw gas, the shortfall is reduced to 25%. This result suggests that it is important for stakeholders to put agreements in place facilitating the withdrawal of Aliso Canyon gas in the event of an emergency.

keywords: natural gas, network modeling, ShakeOut Scenario, earthquake damage.

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1 Introduction

Whether natural gas pipelines will rupture as a result of an earthquake is a matter of significant interest and concern. Multiple assessments document how natural gas pipelines and distribution systems performed under seismic stress. These include assessments for the San Fernando (Johnson, 1971), Loma Prieta (Phillips, 1990), and Northridge (Lau, 1995; Strand, 1995; Lindell, 1997) earthquakes. Others have reviewed multiple events to derive important characteristics that impact natural gas pipeline seismic performance (O'Rourke, 1996) and make natural gas infrastructure performance requirement recommendations based on the observed seismic performance (Honneger, 1997).

In contrast, the goal of this analysis is to assess the consequences of the loss of certain natural gas pipelines in a ShakeOut scenario earthquake. The ShakeOut Scenario earthquake is a magnitude 7.8 earthquake on the southernmost 200 miles of the San Andreas Fault, near the Salton Sea. The southern San Andreas Fault has experienced earthquakes of this size every 150 years, on average yet on the southernmost portion, the last major earthquake occurred more than 300 years ago (Jones, 2008).

This study uses a network model to assist in analyzing the consequences of potential natural gas pipeline outages in a ShakeOut scenario earthquake. The approach of using network analysis to analyze the consequences to the overall infrastructure from the failure of components is established in the literature (Duenas-Osorio, 2007). This study applies the network analysis paradigm to a specific earthquake scenario, and aims to both develop a better understanding of how natural gas supplies may be impacted by a ShakeOut earthquake, and to make actionable recommendations for stakeholders based on that understanding.

Engineering assessment work has already been done on the ShakeOut Scenario as it applies to pipelines, allowing this consequence analysis to be based on a detailed pipeline damage assessment. According to this assessment, natural gas lines are likely to rupture at fault crossings at Cajon Pass, Palm Springs, and Palmdale (Ballantyne, 2008). Using this assessment as a starting point, two scenarios were formulated one with less extensive and another with more extensive damage. A map illustrating the natural gas transmission pipeline network overlaid by the San Andreas Fault and the ShakeOut scenario Modified Mercali Index (MMI) shaking intensity map is shown in Figure 1.

Furthermore, we can consider two possible responses to the scenario disruptions one where the Aliso Canyon storage field (which is in the Los Angeles basin, and at about 85,000 mmcf of working storage capacity happens to be one of the largest storage facilities in the country) remains within a historical band for storage levels, and another where Aliso Canyon is allowed to use its full capacity to respond to the disruption.

For both scenarios, the earthquake is assumed to occur on December 1, 2010, and the damaged pipelines are assumed to be disrupted for the entire month. While this is likely more time than it would take to repair pipeline breaks in normal times, the number of breaks likely involved, the state of roads providing access to the pipeline, and general chaos in the aftermath of the event would all

serve to lengthen the time of disruption. This analysis expresses the quantity of gas delivered per day, which remains this same regardless of the duration of the disruption. At the same time, the duration of the disruption is important in considering the use of gas in storage if the disruption is longer than anticipated, there may not be sufficient gas in storage to withdraw for the entire outage.

The less extensive damage scenario (which posits ruptures only at places pipelines cross the San Andreas Fault in areas of high shaking, and consists of the following ruptures:

- Palmdale: two parallel 30-inch SoCal gas pipes
- Cajon Pass: two parallel SoCal Gas 36-inch pipes
- Palm Springs: a single 36-inch and two 30-inch SoCal Gas pipes
- Indio: SoCal Gas 36-inch pipe and two parallel 30-inch pipes rupture

The same pipelines are rupturing in Indio and Palm Springs in this scenario. Since the direction of gas flow is into southern California, the rupture at Indio (which is southeast of Palm Springs) is enough to halt the flow of gas. The additional break at Palm Springs simply adds to the repair work that must be done to restore gas flow along the pipeline. Though not expressly considered in this scenario, it is likely that there would also be multiple ruptures of these same pipelines from Indio to Palm Springs, as they parallel the San Andreas Fault and are likely to experience violent shaking, though the only impact of this would be to increase the repair time of those pipelines.

The more extensive damage scenario would include the ruptures posited in the less extensive damage scenario, and would add segments of pipelines which are likely to experience shaking of MMI 9.5 and above, and which have 10km or more of length in those areas. The additional areas are south of Bakersfield, and are as follows:

- A 30-inch Kern River gas transmission pipe
- A 30-inch Mojave Pipeline Co. pipe
- A 30-inch SoCal Gas pipe
- A 34-inch SoCal Gas pipe

Using a detailed natural gas network model which represents the North American natural gas transmission network pipe-by-pipeline, GPCM (Gas Pipeline Competition Model), we have modeled the scenarios by disrupting links between nodes in the network. For a description of GPCM, please see Appendix A.

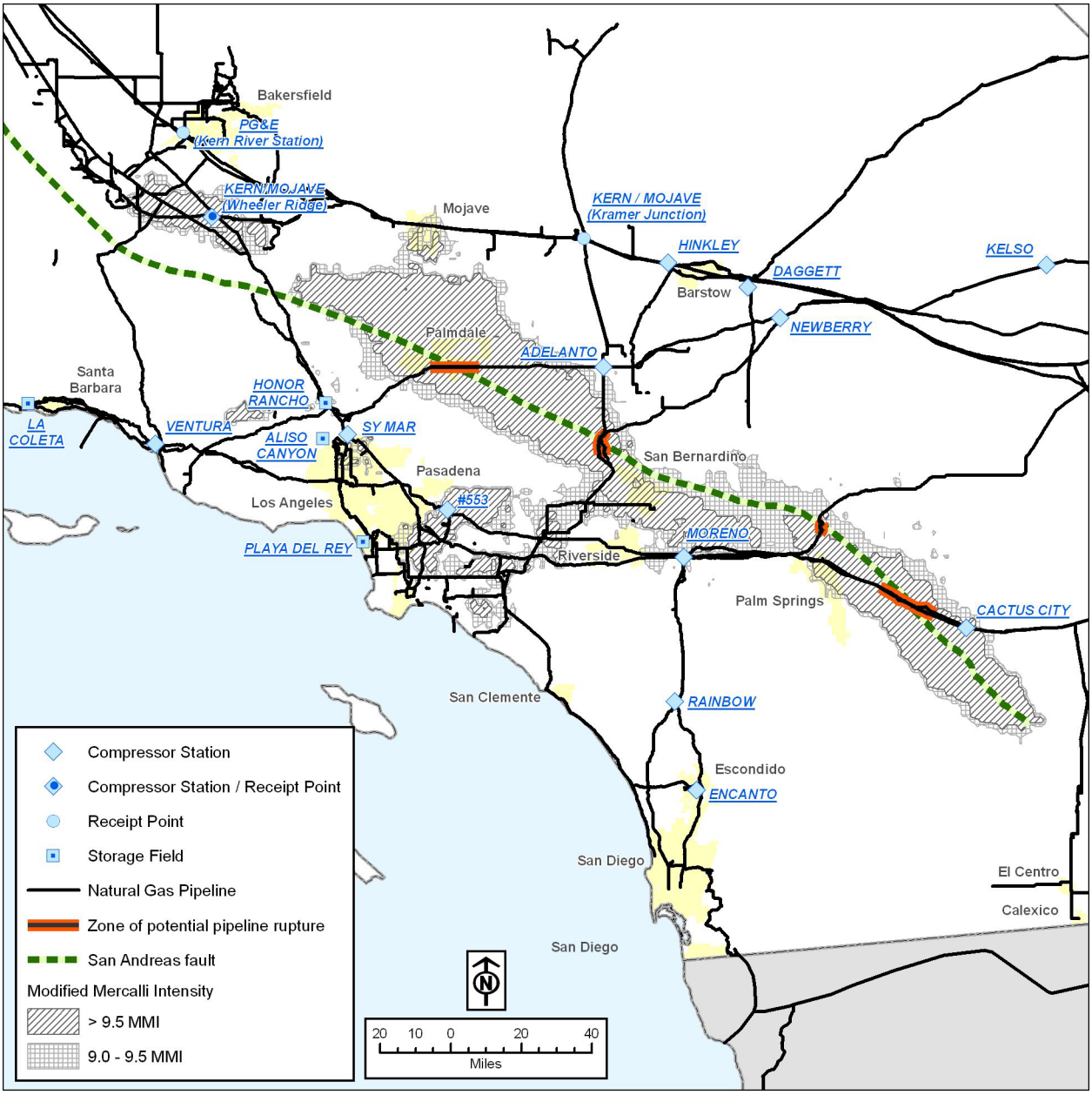

Figure 1. ShakeOut Scenario Earthquake MMI Shaking Intensity Map.

1.1 Discussion of Links and Nodes

As it is important in understanding how the natural gas network is represented, a discussion of what is meant by "links" and "nodes" in GPCM is appropriate. A "node" is an element of the network that can receive gas from storage facilities, pipeline interconnects, or production areas. It can deliver gas to customers, to pipeline interconnects, and to storage facilities. These gas transfers

are considered to take place within a node. Gas can also flow between nodes. This flow between nodes takes place on "links."

A node can be thought of as a segment of pipeline. There is no consideration of geography within a node all flows of gas within a node are simply accounted for as flows within that node. Flows of gas that transit the node (when the node acts as a section of a transmission pipeline, receiving gas upstream and transferring gas downstream) are accounted for differently, as there may be loss of gas in transmission (due to compressor station fuel consumption), and transiting a zone may have implications for the cost of gas transport (such as when a pipeline has zonal tariffs).

Links, therefore, can be thought of as elements which connect the nodes together. What this means physically depends on the specifics of the network. In areas where population is sparse, nodes can be thought of as being short segments of pipe at population centers or pipeline receipt/delivery locations, and links will represent long stretches of pipeline between those areas. Where population is dense, nodes can be thought of as segments of pipe receiving and delivering gas, and links can be considered interconnect points between those segments of pipe.

Disabling a link does not allow gas to flow downstream from a node. Disabling a node also stops gas flow downstream, but in addition does not allow gas transfer within that node. For this study, where there are large distances between population centers, NISAC researchers believe that disrupting links more accurately reflects the nature of the disruption specified in the two scenarios.

2 Study Scenarios

2.1 Base Case Scenario

In the following discussion of the less extensive and more extensive damage scenarios, comparisons will be made with the base case scenario. This refers to consumption levels and flows on a normal, undisrupted network. In this case, since our earthquake disruption scenarios occur in December 2010, our base case scenario will be for a December 2010 without pipeline disruptions.

While there is some production of natural gas within California, the overwhelming majority of gas consumed comes from out of state. Gas for Southern California is transported on transmission pipelines that interconnect with the SoCal Gas network. Therefore, gas primarily flows from out of state into the L.A. Basin and San Diego.

In the base case run for December 2010, natural gas use in the L.A. Basin is about 2,940 mmcf/day. About 1,520 mmcf/day is consumed by residential and commercial users, 730 by natural gas-fired power plants, and 690 by industrial users. It may seem surprising that most of the gas in December is consumed by residential and commercial customers. Even though the climate in southern California is moderate, temperatures are notably cooler in the winter months, and natural gas is the fuel of choice for residential heating in California. Natural gas consumption in southern California is highly seasonal, with most of the use being in the winter period. To illustrate the seasonality, residential and commercial users are projected to demand about 530 mmcf/day in August 2011, as opposed to the 1,520 mmcf/day projected demand in December 2010.

The SoCal Gas network configuration and base case flows that are discussed below are illustrated in Figure 2, where the base case flow volumes are shown in black. In the base case, the L.A. Basin receives gas from the following external sources (which are all part of the SoCal Gas network): 1,290 mmcf/day from the Northern Zone, 655 mmcf/day from Saugus Station, 435 mmcf/day from Moreno Station, and 45 mmcf/day from the North Coastal zone. In addition, the L.A. Basin receives gas from two storage facilities that are internal to the zone: 495 mmcf/day from Aliso Canyon, and 20 mmcf/day from Playa del Rey. The sum of these sources equals the consumption of 2,940 mmcf/day for December 2010.

San Diego consumes about 415 mmcf/day in the base case, receiving all of this from Moreno Station. In the base case, San Diego neither exports from nor imports to Baja California (Mexico) at the interconnect point between SoCal Gas and TGN pipeline (Mexico) at Otay Mesa.

The Northern Zone, which is the biggest single contributor to supply to the L.A. Basin in the base case, in turn receives gas from three sources: Needles (near the border with Arizona), Topock (also at the Arizona border), and Kramer Junction. At Needles, SoCal Gas receives gas mainly from the Transwestern Pipeline, but also from the Southern Trails Pipeline. At Topock, SoCal Gas receives gas from both the Transwestern Pipeline and the El Paso Pipeline. And Kramer Junction receives gas from an interconnect with Kern River.

Saugus Station, which is the second largest contributor to L.A. Basin supply, receives gas from

Wheeler Ridge as well as from the Honor Rancho storage facility, which is located within the Saugus Station zone. Wheeler Ridge supplies roughly 550 mmcf/day, receiving gas in turn from interconnects with the PG&E Baja Path Pipeline, and the Kern River Pipeline. The Honor Rancho facility supplies about 105 mmcf/day.

Moreno Station is the third largest contributor to L.A. Basin supply, and supplies all of San Diegos demand, in the base case. Moreno Station depends on gas from SoCal Gas Blythe station. And at Blythe, SoCal Gas receives gas from its interconnection with Ehrenberg, which in turn is connected to the El Paso Pipeline, the North Baja Pipeline (U.S.), and the Silver Canyon Pipeline.

The supply of natural gas to the L.A. Basin from storage is worth noting. Gas is injected into storage in the warm spring and summer months, when demand is low. It is then withdrawn in the winter months, when demand is high. This is because the production of natural gas does not vary with the seasons, while consumption does. The role of natural gas storage, in general, is to provide a buffer between constant production and the highly seasonal nature of consumption. In this case, Los Angles is fortunate to have the Aliso Canyon storage facility in its backyard. At roughly 85,000 mmcf of working (or usable) gas capacity, this storage facility is one of the largest in the United States. The L.A. Basin also benefits from the Honor Rancho storage facility, which is located immediately north of the L.A. Basin (in the model, it is in a zone called Saugus Station). With a capacity of about 20,000 mmcf, the Honor Rancho facility is a fraction of the size of Aliso Canyon, yet still provides about 105 mmcf/day in the base case (and has the capacity to supply more).

Note that in the discussion of consumption and flows above, many of the numbers have been rounded. This was done to make the string of numbers more user-friendly. We believe that rounding helps the reader focus on the meaning rather than on the specifics of a string of numbers. This practice of rounding numbers to aid in comprehension is followed throughout this paper.

2.2 Modeling of Scenarios

In modeling the less extensive damage and more extensive damage scenarios, it was necessary to translate the projected physical pipeline damage into the appropriate disruption in the model.

In the less extensive damage scenario, the Palm Springs and Indio disruptions were of the same 36-inch and two parallel 30-inch pipelines. This was modeled by disrupting the link from Blythe to Moreno Station on the SoCal Gas network. This disruption halts all flow of gas from Blythe to points westward, but does not impact the flow of gas from Blythe southward to Calexico (U.S.) or Mexicali (Mexico).

Modeling the disruption of the two parallel 30-inch SoCal Gas pipelines south of Palmdale, and the disruption of the two parallel 36-inch SoCal Gas pipelines in the Cajon Pass, is more complicated. In essence, these disruptions deprive the Los Angeles Metropolitan Area (referred to as the Los Angeles Basin or simply L.A. Basin afterwards in this report) of gas flowing on to the SoCal Gas network at the California border at Needles and Topock, and from the Kern

River pipeline at Kramer Junction. Rather than disrupt these three separate routes, the NISAC team disrupted the link from the Northern Zone into the L.A. Basin. Since the Northern Zone is fed from Needles, Topock, and Kramer Junction alone, disrupting the pathway from the Northern Zone to the L.A. Basin halts all flows from these three areas destined for the L.A. Basin, while allowing flows to areas northeast of the disruptions.

For the more extensive damage scenario, four pipelines southwest of Bakersfield are assumed to be disrupted. These pipelines receive gas from in-state producers (SoCal Gas Line 85), as well as from interconnects with other pipelines at Wheeler Ridge, and bring this gas into the L.A. Basin through Saugus Station from the north. Specifically, Wheeler Ridge receives gas through interconnects with Kern River Pipeline as well as with PG & Es Baja Path. In modeling this, NISAC researchers disrupted the link from SoCal Gas Line 85 into Saugus Station, as well as from Wheeler Ridge into Saugus Station. In this case, disrupting the link between Saugus Station and the L.A. Basin would have overstated the damage. This is true because Saugus Station is not merely a waypoint for gas from Line 85 and Wheeler Ridge, but it has a significant natural gas storage facility, called Honor Rancho. Since the damage envisioned is north of Saugus Station, depriving the L.A. Basin of being able to benefit from Honor Rancho in the model would not have been appropriate.

3 Less Extensive Damage Scenario

In this scenario, the two major sources of gas to the Los Angeles Basin from Topock, Needles, and Kramer Junction to the northeast, and Ehrenberg/Blythe to the east are severed. As San Diego is normally served from gas flowing from Ehrenberg/Blythe through Moreno Station, its normal gas supplies are unavailable as well.

Is the natural gas network able to compensate for these lost pathways? How would the network reroute around these damaged pipelines? The answer to these questions can best be found by examining the results of a model run with the less extensive damage scenario disruption, and comparing it to a model run with no disruption (which will be referred to as a base case model run).

As indicated previously, we will discuss the impact of this disruption assuming that the Aliso Canyon storage facility is constrained to remain within historical storage levels during the event, and also with this constraint removed. Figure 2 illustrates December 2010 flows along the regional gas network in the less extensive damage scenario both for constrained and unconstrained Aliso Canyon withdrawals, and compares these with the base case (undisrupted) flows for that same month.

3.1 Constrained Aliso Canyon Withdrawals

The Los Angeles Basin consumes about 1,690 mmcf/day in December 2010 in the less extensive damage scenario with constrained Aliso Canyon withdrawals (referred to in this section simply as the disrupted case), versus base case consumption of about 2,940 mmcf/day. Thus, deliveries to Los Angeles drop by roughly 1,250 mmcf/day, or by more than 40

Comparing the base case with the disrupted case, we see that there is more flow into the Los Angeles Basin from Saugus Station in the disrupted case. The flows into the L.A. Basin from the Northern Coastal zone also increase in the disrupted case. Finally, withdrawals from the Aliso Canyon storage facility in the disrupted case increase by about 100 mmcf/day. These flow differences can be seen in Figure 2. Aliso Canyon thus enters into January 2011 with the minimum level of storage allowed by this scenario (about 65,000 mmcf). The increased flows from the north and from the Aliso Canyon storage facility are evidence of a system using what paths remain in an attempt to compensate for the loss of pipelines.

What would the actual impacts be to customers in the L.A. Basin of the loss of more than 40% of normal supply? Typically, natural gas-fired generators and industrial consumers are more price sensitive than other customer classes, and would therefore choose to not receive gas were the price to dramatically increase (as it would in the case of a severe supply restriction). However, in this case we must take into account that large portions of the natural gas distribution system in the Los Angeles area would likely be damaged and require significant repair. It is likely, therefore, that some fraction of residential and commercial customers will be unable to use gas even if it were available.

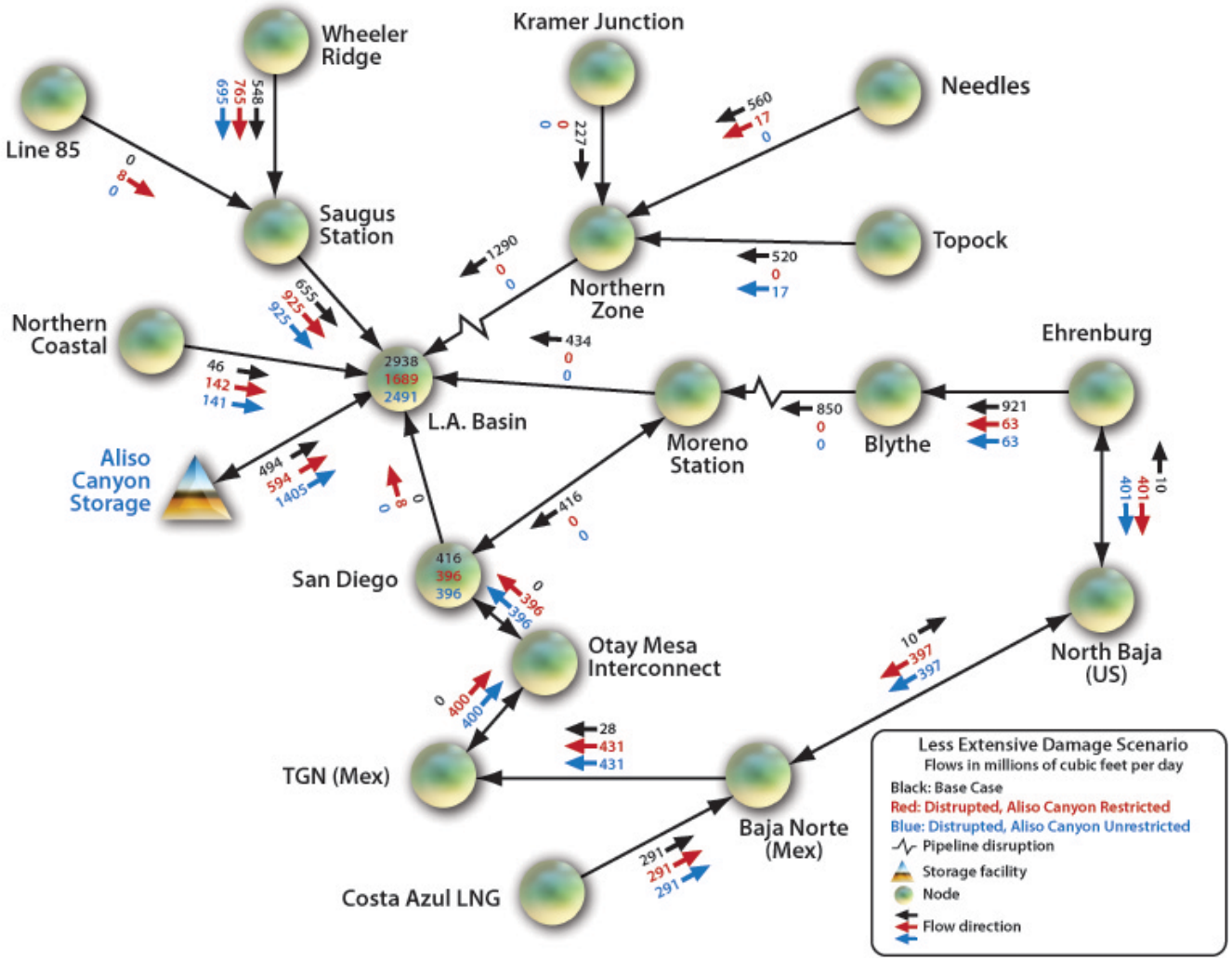

Figure 2. Natural Gas Flows in the Less Extensive Damage Scenario.

In the base case for December 2010, SoCal Edison gas-fired power plants use about 730 mmcf/day of natural gas. If we assume that about 1/3 of the distribution system in the L.A. Basin will sustain significant damage, then this would mean that about 500 mmcf/day (out of a total normal demand of 1,500 mmcf/day) would be available for industrial and power generator use. It is reasonable to assume that most of this would be allocated to power generation, given the immediate need to supply power to the grid. (Of course, we should also consider that the earthquake will likely damage the distribution grid as well, and therefore reduce the amount of power demanded). In any case, gas available for power generation would in all likelihood be significantly below the normal demand of 730 mmcf/day in the base case for December 2010.

In this less extensive damage scenario, San Diego consumes about 400 mmcf/day in December 2010, versus base-case consumption of about 415 mmcf/day. Therefore, deliveries to San Diego

drop by only about 5For San Diego, the way the network reconfigures to meet demand is by importing gas from Baja California at Otay Mesa. In fact, this is the only source of natural gas for San Diego in the less extensive damage scenario. In the base case, all 415 mmcf/day of gas comes from the north, from Moreno Station no gas is imported to or exported from San Diego at Otay Mesa. This flow, and the others discussed in this section, can be seen in Figure 2.

In the disrupted scenario, San Diego imports the maximum allowed from Baja California at Otay Mesa about 400 mmcf/day. Only a very small amount of gas is sent from San Diego to Los Angeles, as after meeting its own demand there is very little left to send elsewhere.

In order to supply the 400 mmcf/day at Otay Mesa, deliveries from El Paso pipeline through the Ehrenburg interconnect and through to the North Baja pipeline increase. North Baja (in the U.S.) connects with the Baja Norte pipeline in northern Baja California (Mexico) near Algodones, Mexico. In the disrupted case, gas flows along Baja Norte to the west, towards the TGN pipeline which interconnects with the SoCal Gas system at Otay Mesa. In fact, there remains additional capacity at the Ehrenburg interconnect with the North Baja pipeline, and within the Baja Norte pipeline itself, to get more gas up to San Diego which could in turn send larger quantities of gas north to the Los Angeles Basin. However, it is the capacity of the TGN pipeline and the interconnect with SoCal Gas at Otay Mesa which prevents these increased flows from taking place.

As can be seen in Figure 2, in the base case there is no flow from the US North Baja pipeline (to the Mexican Baja Norte pipeline. Most of the flow (250 mmcf/day) in the Baja Norte pipeline supplies gas-fired power plants in Baja Mexico, and only 28 mmcf/day flow to the interconnect with the TGN pipeline. The TGN pipeline can flow gas west, to Rosarito, Mexico, where there is a power plant, and it can flow gas north to the Otay Mesa interconnect with SoCal Gas. In the base case, the gas flowing from Baja Norte to the TGN pipeline is used by the power plant at Rosarito. No gas flows to the interconnect with SoCal Gas.

In the less extensive damage scenario, there is a flow of about 400 mmcf/day from the US North Baja Pipeline to the Mexican Baja Norte pipeline. The same 250 mmcf/day supplies power plants in Baja Mexico. However, 431 mmcf/day flows into the interconnect with the TGN pipeline. About 400 mmcf/day of this amount flows north to the Otay Mesa interconnect with SoCal Gas to supply San Diego with its sole source of gas in this scenario.

It can be seen that there is a supply of 291 through an interconnect directly to the Baja Norte pipeline. This represents supply from the Costa Azul LNG import facility near Ensenada, Mexico. This is the only operating LNG import facility on the Pacific coast on the North American continent.

3.2 Unconstrained Aliso Canyon Withdrawals

Historically, the Aliso Canyon storage facility begins December nearly full, since it injects gas starting from the spring through October in preparation for withdrawals in the winter to meet higher demand. In the model run discussed above, Aliso Canyon is almost at 85,000 mmcf in

working gas storage at the end of November 2010. It is not allowed to drop below about 65,000 mmcf in December 2010, however, because this level corresponds with a historical minimum for storage levels entering into January. In fact, in the constrained scenario discussed above, Aliso Canyon responds to the disruption by withdrawing just enough to allow it to enter into January 2011 with the prescribed minimum volume of gas in storage (65,000 mmcf).

In this case, we remove the 65,000 mmcf minimum level constraint for December 2010. The physical constraints on Aliso Canyon that its withdrawal rate is capped at 1,850 mmcf/day and its injection rate is capped at 450 mmcf/day remain. The Los Angeles Basin receives about 2,490 mmcf/day in December 2010 in this unconstrained case about 15% less than the base case consumption of about 2,940 mmcf/day, but much higher than the constrained Aliso Canyon withdrawal case of roughly 1,690 mmcf/day. In this unconstrained case, Aliso Canyon supplies about 1,400 mmcf/day to the Los Angeles Basin, for a total monthly withdrawal of about 45,000 mmcf. This is opposed to the constrained Aliso Canyon withdrawal level of 600 mmcf/day. These levels are illustrated in Figure 2.

We should keep in mind that after this much withdrawal, it would likely take several years to replenish the storage facility to normal historical levels. This is because Aliso Canyons capacity to inject gas is significantly lower than its capacity to withdraw gas, and because large levels of injection would tend to drive up regional natural gas prices. In addition, supplies in January and February 2011 may be tighter (and thus more expensive) than had storage levels not been depleted as much.

4 More Extensive Damage Scenario

This scenario posits damage more extensive than the ShakeOut Scenario Supplemental Study: Oil and Gas Pipelines posited. Though not projected in the Supplemental Study, the project team felt that segments of pipelines which are likely to experience shaking of MMI 9.5 and above and experience that degree of shaking for 10km or more of their length could potentially fail. NISAC analysts therefore created a second scenario that included this additional damage for the sake of having a more stringent test of the natural gas network.

The more extensive damage scenario was modeled by including the line breaks specified in the less extensive damage scenario, and adding two more. Specifically, the link from Wheeler Ridge to Saugus Station and the link from SoCal Line 85 to Saugus Station were severed. This action prevents gas from being received at Saugus Station. This means that gas from the Kern River and PG & E Baja Path pipelines cannot be transported to the Los Angeles Basin.

Figure 3 illustrates December 2010 flows along the regional gas network in the more extensive damage scenario both for constrained and unconstrained Aliso Canyon withdrawals, and compares these with the base case (undisrupted) flows for that same month.

4.1 Constrained Aliso Canyon Withdrawals

The model run shows that the Los Angeles basin receives about 1,460 mmcf/day in this scenario, which is lower than the 1,690 mmcf/day it received in the less extensive damage scenario. However, a reduction of 230 mmcf/day is less than one might expect from the loss of the Kern River and PG & E Baja Path gas (which supplied about 770 mmcf/day to Saugus Station in the less extensive damage scenario).

The reason the loss of supply to the L.A. Basin is mitigated is that the Honor Rancho storage facility is located south of the break (near Saugus Station), and remains operational. In this scenario, it greatly increases its output from about 150 mmcf/day in the less extensive damage scenario to about 630 mmcf/day. At this rate, the storage facility completely exhausts its storage of about 20,000 mmcf in the month of the disruption. It is important to note that here we have allowed the Honor Rancho storage facility to drop down below its historical storage levels, though Aliso Canyons minimum storage level is still constrained. This is because it seemed to the NISAC team unlikely that both storage facilities would adhere to normal storage levels in the immediate aftermath of a disaster.

San Diego again receives almost 400 mmcf/day from Baja California at Otay Mesa. However, it does not use all of this gas it sends a total of about 70 mmcf/day to the L.A. Basin given the extreme shortfall in supply there. Figure 3 illustrates supplies to both San Diego and the L.A. Basin in this scenario.

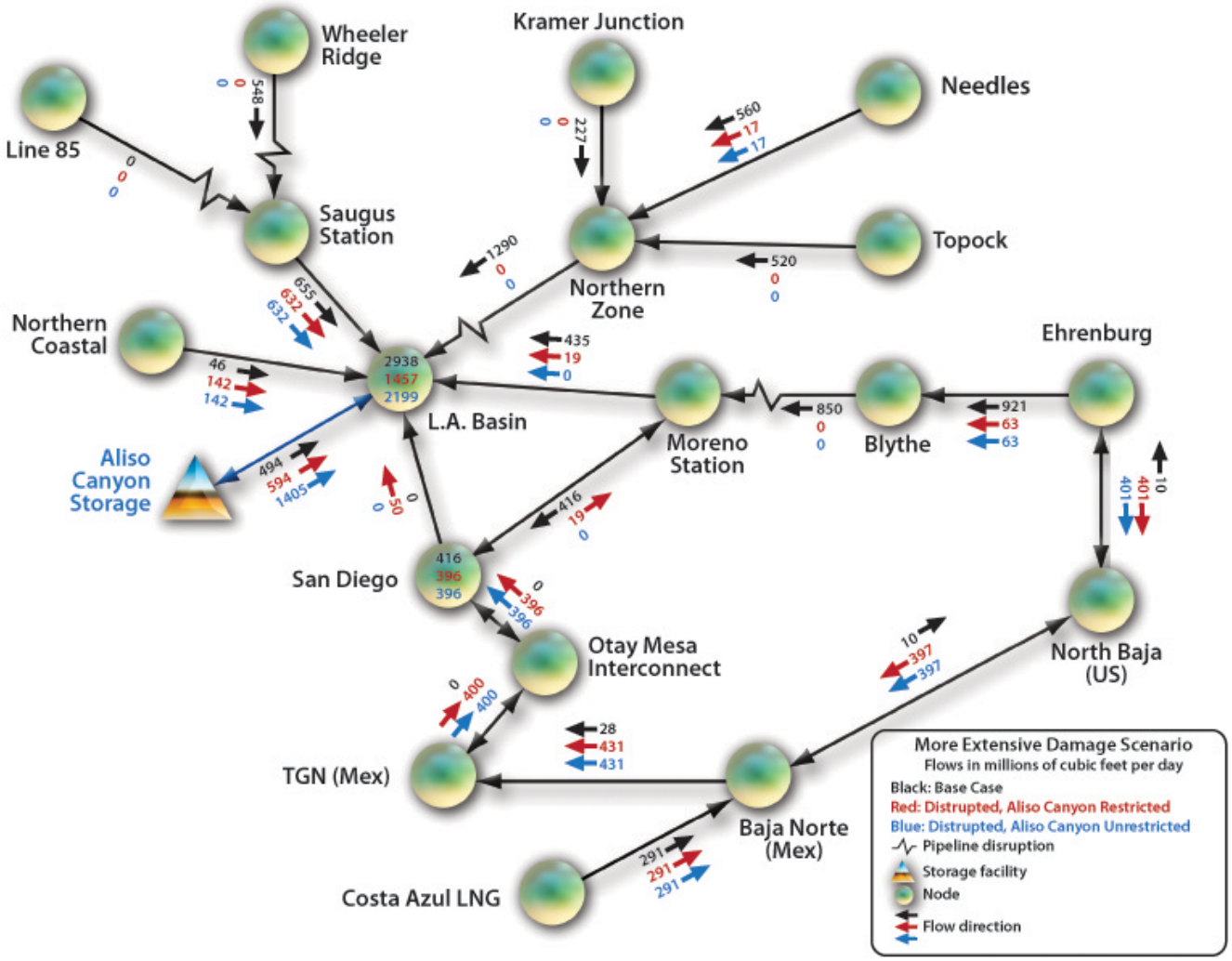

Figure 3. Natural Gas Flows in the More Extensive Damage Scenario.

4.2 Unconstrained Aliso Canyon Withdrawals

Not constrained by historical storage levels, the Aliso Canyon storage facility supplies about 1,400 mmcf/day to the L.A. Basin in the more extensive damage scenario (this is illustrated in Figure 3). Total supply to the L.A. Basin is thus about 2,200 mmcf/day. This is about 25% lower than the 2,940 mmcf/day in the base case, but given the likely distribution network outages, this reduced amount may well be enough to meet demand. Given the loss of the three major arteries bringing gas into the Los Angeles Basin, this level of supply is excellent and is a testament to how resilient the natural gas network can be in face of major shocks.

It is important to note that this level of withdrawal would bring the Aliso Canyon storage facility level down by almost 45,000 mmcf, bringing it to well below historical levels entering into

January. This may mean that supplies are tighter (and more expensive) in January and February 2011. Also, it is likely that gas would need to be injected slowly into the storage facility to bring it back up to its normal level, both because its capacity to inject gas is significantly lower than its capacity to withdraw gas, and because large levels of injection would tend to drive up regional natural gas prices. Therefore, it may be several years before storage levels at Aliso Canyon are back to normal historical levels.

5 Possible Actions to Increase Network Resiliency to a Shakeout Scenario Earthquake

5.1 Actions that Require no Network Modifications

The most important action to increase network resiliency in the face of a ShakeOut Scenario earthquake is to discuss with stakeholders how gas in storage at the Aliso Canyon storage facility might be used in an emergency. If this gas is available to be used, then there should be no shortage of supply in the L.A. Basin. If this gas is unavailable, then the network as currently configured is unlikely to be able to supply sufficient gas to meet demand. Unless this issue is discussed before the occurrence of a ShakeOut Scenario earthquake, and arrangements made to allow gas in storage to be used in such an emergency, there may be no legal way to require that the gas be made available.

5.2 Possible Network Modifications if Additional Aliso Canyon Withdrawals Aren't Possible

Given our findings that about 1,250 mmcf/day in supply to the L.A. Basin would be lost in the less extensive damage scenario (with constrained Aliso Canyon withdrawals), and assuming that 500 mmcf/day of this would not be needed due to damage to the residential and commercial distribution network, this means that network modifications that would allow an additional 750 mmcf/day of supply to the L.A. Basin even when the two major gas supply lines are cut would go far in increasing the resiliency of the network. In the absence of additional Aliso Canyon withdrawals, there are two ways to attempt to compensate for the loss of the major pipelines from the east increase receipts from the south (imports from Mexico into San Diego at Otay Mesa) and increase receipts from the north (primarily into Saugus Station and then into the Los Angeles Basin).

As we have seen, the network as currently configured can import enough gas into San Diego to satisfy the needs of San Diego. There is not enough excess gas left over for San Diego to send appreciable quantities to the L.A. Basin. This is because there is a bottleneck in the current system. That bottleneck is the stretch of the TGN pipeline that links the SoCal Gas system (at Otay Mesa) with the Baja Norte system. While it appears that SoCal Gas could import 700 mmcf/day at Otay Mesa, and that Baja Norte could put up to 800 mmcf/day onto the TGN system, the TGN pipeline connecting SoCal Gas with Baja Norte appears to have a maximum capacity of 400 mmcf/day.

If this could be increased to, say, 700 mmcf/day to match SoCal Gas import capacity at Otay Mesa, then an additional 300 mmcf/day could flow into San Diego, and then from San Diego into the L.A. Basin. (The normal flow is from Moreno Station to San Diego in this case, the normal flow would be reversed). To get this additional 300 mmcf/day into San Diego, El Paso could supply an additional 100 mmcf/day to the North Baja pipeline at Ehrenburg (assuming the capacity of the pipeline to flow gas east-to-west is 500 mmcf/day). (Transcanada, 2010). The remaining 200 mmcf/day would need to come from the only other source available the Costa Azul LNG import facility near Ensenada, Mexico. There could be delay times in getting additional LNG shipments

into the facility, so the additional gas may not be immediately available. At the same time, the expected large increase in price of gas in southern California in the aftermath of the ShakeOut scenario earthquake would provide strong incentive to divert LNG shipments to the Costa Azul facility as quickly as possible.

It is likely, therefore, that this single improvement increasing the capacity of an approximately 10-mile stretch of TGN pipeline connecting Baja Norte with the SoCal Gas interconnect at Otay Mesa would allow an additional 300 mmcf/day of gas to reach the L.A. Basin. However, we still need another 450 mmcf/day of gas to completely compensate for the damaged pipelines. This would need to come to the L.A. Basin from the north.

The capacity from Saugus Station to the L.A. Basin is 925 mmcf/day. This capacity is fully used when the two major natural gas pathways are disrupted by the less extensive damage scenario. Therefore, it would need to be increased to around 1,400 mmcf/day. The question then becomes how the additional gas will get to Saugus Station, given that capacity to transport gas from Wheeler Ridge to Saugus Station is limited to 765 mmcf/day, and from SoCal Line 85 to Saugus Station is limited to 190 mmcf/day. It so happens that Saugus Station is connected to a storage facility called Honor Rancho, which can store up to 19,500 mmcf of working gas (gas available to be withdrawn).

In the less extensive damage case, Honor Rancho contributes about 150 mmcf/day to flows to the L.A. Basin. If capacity to get gas to the L.A. Basin is increased to 1,400 mmcf/day, then Honor Rancho could increase its flows by 450 mmcf/day to roughly 600 mmcf/day. To provide 600 mmcf/day for 30 days, Honor Rancho would need to have 18,000 mmcf in storage prior to the earthquake. Fortunately, the storage facility is likely to be full around December 1, so it is possible that the required amount of gas would be available. Would the scenario earthquake happen in, say, March, there would be much less gas in storage, and it is unlikely that delivering 600 mmcf/day for 30 days from Honor Rancho would be possible. (At the same time, gas consumption in the L.A. Basin is lower in March than in December, so 600 mmcf/day from the storage facility would likely not be needed).

It is important to note that here we assume that the Honor Rancho storage facility will be allowed to drop down below its historical storage levels, though Aliso Canyons minimum storage level is still constrained. This is because it seemed to the NISAC team unlikely that both storage facilities would be constrained to normal storage levels in the immediate aftermath of a disaster. If Honor Rancho is not allowed to drop below historical storage levels, then increasing the Saugus Station to L.A. Basin pipeline capacity would be of little use as additional gas would not be made available. The discussion has so far centered on the less extensive damage scenario. In the more extensive damage scenario, the upgrade of the section of TGN pipeline connecting into the SoCal Gas system at Otay Mesa would still be useful. However, the Saugus Station to L.A. Basin pipeline capacity expansion would not be needed. This is because without the gas from the Kern River and PG & E Baja Path pipelines, the Honor Rancho storage facility can withdraw at its maximum level and not be constrained by the Saugus Station to L.A. Basin pipeline link.

6 Confidence in Results

In any study that asks to what extent the network can reroute flows to adjust for pipeline outages, it is important to have both network connectivity and capacities properly represented in the network model.

We have a high degree of confidence that the network connectivity in the GPCM dataset is a true and useful representation of actual network connectivity for the North American natural gas network. Not only is there a dedicated team that updates the model dataset each quarter, but also there is a substantial user group (including companies from the oil and gas industry) of the model and dataset. Having many users means that discrepancies are more likely to be discovered and corrected than with a database developed in-house with no other users.

In addition, the network as represented for the primary region of interest in this study (southern California) can be compared with the map of the southern California natural gas network in Figure 1. It can be seen that the structure of the network representation in the dataset (see Figures 2 and 3) corresponds to the map of the southern California gas system.

The issue of how well the capacities in the model correspond to actual system capacities is a separate issue. Given the work on the model dataset and the number of users of the model and dataset, it is likely that the North American networks capacities are accurately represented. Even so, given the importance of gas from Baja Mexico in either ShakeOut earthquake damage scenario, it is especially important that capacities along this pathway be represented properly. Therefore, the project team checked the capacities of key portions of the network manually.

We consider that up to 600 mmcf/day can flow east along the Baja Norte pipeline (Mexico) to the North Baja pipeline (USA), that the TGN- SoCal Gas interconnect at Otay Mesa can supply up to 400 mmcf/day from Mexico to the USA , that the total delivery capacity of the TGN pipeline is up to 800 mmcf/day , and that the Baja Norte TGN interconnect allows up to 800 mmcf/day to flow from Baja Norte to TGN. (North Baja, 2010; SoCal Gas, 2010; and TGN, 2010, respectively). The model database was altered to reflect this understanding.

The Baja Norte-TGN interconnect size is an assumption. Since the TGN pipelines capacity is 800 mmcf/day, and their primary source of gas (the other possible source being imports from San Diego at Otay Mesa) is from the Baja Norte pipeline, it seems logical that the Baja Norte-TGN interconnect would be sized at 800 mmcf/day. This, in turn, means that the Baja Norte pipeline must have the capacity to send at least 800 mmcf/day west to the interconnect with TGN. At first glance, it would seem that Baja Nortes capacity to receive 500 mmcf/day from the east (North Baja pipeline) does not match up with an interconnect capacity of 800 mmcf/day with TGN. However, Baja Norte also receives gas from the Costa Azul LNG import terminal near Ensenada, Mexico, which has the capacity to import roughly 1,000 mmcf/day . (Energia Costa Azul, 2010). Therefore, the Baja Norte pipeline has the capacity to supply at least 800 mmcf/day to the TGN pipeline. If this assumption differs from reality, then the results of the model runs will not fully reflect the true capabilities of the system to adjust to the ShakeOut scenario disruptions.

Finally, in discussing potential system modifications, an assumption was made about the capacity of the TGN pipeline to transport gas to the interconnect with SoCal Gas at Otay Mesa. TGNs total capacity is stated at 800 mmcf/day, whereas the interconnect capacity at Otay Mesa was confirmed to be 400 mmcf/day. Given the fact that TGN supplies gas west to Rosarito and connects to the SoCal Gas system at Otay Mesa in the north, and given that the pipeline seems to be a uniform diameter (30-inches), it is logical to conclude that TGN must have the capacity to send 400 mmcf/day to the west and 400 mmcf/day to the north. Given that the capacity of the SoCal Gas system to import at Otay Mesa is likely 700 mmcf/day (according to the GPCM dataset), it would make no sense to have a 400mmcf/day interconnect between a 700mmcf/day and a 800 mmcf/day pipeline. This interpretation of TGN capacities is not critical to the model runs however, when proposing what system modifications might be made to increase the ability of the network to respond to a ShakeOut earthquake scenario, understanding whether the bottleneck lies in the interconnect between TGN and SoCal Gas at Otay Mesa or in the TGN pipeline itself is important.

7 Summary

In the event of a ShakeOut Scenario earthquake, it seems likely that SoCal Gas transmission pipelines bringing gas from the Arizona border into southern California would fail. This would disable the two major corridors bringing gas into southern California for use in the Los Angeles Basin and San Diego. NISAC analysts found that in this event (called the less extensive damage scenario in this report), assuming natural gas storage levels in the Aliso Canyon facility (a major natural gas storage facility located in the Los Angeles Basin) would be constrained to historical levels, the existing network is able to reroute enough gas to fully supply San Diego, but that supplies to the Los Angeles Basin would be curtailed by over 40

This loss in supply is mitigated by the fact that portions of the residential and commercial natural gas distribution system in the L.A. Basin would be damaged, rendering these parts of the distribution system inoperable until extensive repairs are made. Even so, the loss of supply would be severe, and would almost certainly lead to deeply curtailed gas-fired power production and industrial natural gas use in the L.A. Basin.

If we remove the constraint on the Aliso Canyon storage facility to remain within historical levels, then we get a different picture. The Los Angeles Basin receives about 15% less natural gas than in the base case, which is considerably better than the 40% curtailment discussed above. In this unconstrained case, Aliso Canyon supplies about 1,400 mmcf/day to the Los Angeles Basin, as opposed to the constrained Aliso Canyon withdrawal level of 600 mmcf/day.

A greater extent of damage to the network is possible from a ShakeOut Scenario earthquake. The project team posited that segments of pipelines which are likely to experience shaking of MMI 9.5 and above and experience that degree of shaking for 10km or more of their length could fail. This scenario, called the more extensive damage scenario in this report, would mean that natural gas from the Kern River and Mojave pipelines north of the L.A. Basin could not reach the L.A. Basin.

In the case that the Aliso Canyon storage facility is constrained to historical levels, the model run shows that the Los Angeles basin receives about 50% less gas than in the base case (with no earthquake damage). While this is a drop from the less extensive damage case (with constrained Aliso Canyon levels), it is not a steep a drop as originally expected. This is because the Honor Rancho storage facility north of the L.A. Basin increases its withdrawals to partially compensate for the lost pipeline volumes.

Assuming the Aliso Canyon storage facility would not be constrained to historical levels, supplies to the L.A. Basin would be about 25% lower than in the base case. Given the likely distribution network outages, this reduced amount may well be enough to meet demand. Taking into account the loss of the three major arteries bringing gas into the Los Angeles Basin, this level of supply is excellent and is a testament to how resilient the natural gas network can be in face of major shocks.

The most important action that could be taken prior to an earthquake such as this is to discuss

with stakeholders how the gas in the Aliso Canyon facility, one of the largest natural gas storage facilities in the U.S., might be used. If the owners of the gas in storage decline to release it (beyond normal levels), there may be no legal way to require them to do so, and severe shortages (while pipeline repairs are made) could not be avoided with the current network configuration. However, if emergency arrangements could be put in place that would allow the gas in storage to be used, this major storage facility could replace a large fraction of the gas lost due to pipeline damage while repairs are made.

Apart from agreements on the use of Aliso Canyon gas in storage, there are two relatively small alterations to the network that would allow for significantly more supply to the L.A. Basin in the case of ShakeOut Scenario damage. One is to increase the capacity of the section of the TGN pipeline that connects the Baja Norte pipeline in Baja California with the SoCal Gas network at Otay Mesa (near San Diego) from its current 400 mmcf/day to 700 mmcf/day. This would allow enough imports from Baja California for San Diego to send up to 300 mmcf/day to the L.A. Basin. Another is to increase the capacity of the pipeline from Saugus Station to the L.A. Basin from 925 mmcf/day to around 1,400 mmcf/day. This would allow the Honor Rancho storage facility near Saugus Station to increase withdrawals enough to bring an additional 450 mmcf/day to the L.A. Basin.

The North American natural gas network is highly interconnected, providing multiple pathways to supply gas to customers. The natural gas network in southern California is no exception. This interconnectivity not only increases competition among suppliers, but also allows for a more resilient network in the face of natural disasters. In planning for a disaster, usually much effort is placed on determining what will be damaged. In this case, understanding how stakeholders will react to the damage is equally important. Specifically, if agreement can be reached to use the gas in storage at Aliso Canyon to the fullest extent possible in an emergency, then we will have gone a long way towards mitigating the impact of a ShakeOut Scenario earthquake on the availability of natural gas in the Los Angeles Basin.

A GPCM

The Gas Pipeline Competition Model (GPCM) was developed by Dr. Robert Brooks of RBAC, Inc. It represents all of the major natural gas pipelines in North America, as well as gas production areas, storage facilities, and consumption by consumer category. As of May 2009, the model contained: 188 pipelines, 84 supply areas, 110 demand areas with 442 major gas customers, and 430 storage areas.

The model also contains a number of pipelines and storage areas that are planned for the future. These are included in a model simulation starting at the time they are planned to become operational.

Time is resolved to the level of months so that seasonal effects can be modeled (natural gas consumption is highly seasonal because much of it is used for heating). Monthly time resolution means that short disruptions of a few days or weeks cannot be modeled with precision. However, for a disruption caused by a major earthquake, as is being considered in this study, a disruption length of a month or more is reasonable. The spatial resolution of GPCM is very good for resolving the types of disruptions of interest.

The natural gas market is represented as a partial-equilibrium economics model, which balances supply against demand. The model requires a supply curve (price versus quantity supplied) for each supplier and a demand curve (price versus quantity demanded) for each customer, plus capacities and costs for gas transport in each pipeline zone and capacities and prices for gas injection and withdrawal for each storage area. All of these inputs are supplied by RBAC, Inc., along with GPCM, but they can be modified by the user if desired (for example, pipeline capacities can be modified to represent damages caused by an earthquake). The dataset is an important part of the value of GPCM, as putting together a consistent set of all the inputs needed for a model like this is a large effort. Furthermore, GPCM is a respected tool, licensed by over two dozen companies in the natural gas industry.

The heart of GPCM is a network composed of nodes and arcs. There are four types of nodes: supply nodes, demand nodes, storage nodes, and transshipment nodes. Gas is introduced into the network at supply nodes (e.g., producers and importers) and removed from the network at demand nodes (different types of consumers). Storage nodes represent natural gas storage areas and transshipment nodes represent points or sections of pipelines. Each node is treated as a market point, with a price calculated so as to balance supply and demand. Nodes are connected to each other by arcs, which represent the pipes that allow flow between nodes. Each arc is defined by four quantities: the maximum flow (capacity), minimum flow (if any), cost per unit of flow, and efficiency of flow (one minus the fraction of gas burned as compressor fuel or otherwise lost or unaccounted for on that arc).

Prices and flows are calculated by GPCM for all locations and all times simultaneously, using an optimization method called the simplex algorithm to minimize costs. To do this, the network, as described above, is duplicated for each time point (i.e., each month to be simulated), with successive times connected through the storage nodes. That is, a given node, say n_i, is duplicated

so that there is a copy of it for each time: n_{ij}, j = 1,..., J, where J is the number of months in the simulation. The arcs are duplicated as well, so that each n_{ij} has the appropriate connections to other nodes n_{kj} at the same time. Then, the sub-networks for successive times are connected through the storage nodes: If n_i is a storage node, arcs are added connecting n_{i1} to n_{i2}, n_{i3} to n_{i4}, etc. In this formulation, there is no accumulation of gas at nodes, including storage nodes. Rather, storage is represented by a flow from a node to the corresponding node at the next time (for example, gas that flows from n_{ij} to $n_{i(j+1)}$) is gas that is remaining in storage at location n_i from month j to month j+1).

Flows are driven by price differentials, both from location to location (gas is piped from the Gulf Coast to other parts of the country because the price is higher in those other locations) and from time to time (prices are higher during peak demand months, so gas flows to those months by being injected into storage during low-demand months and then withdrawn from storage during high-demand months).

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