Independent High-Level Quantitative Risk Analysis
Schuyler County Concentrated Natural Gas Storage Proposal

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Quantitative Risk Analysis:
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Executive Summary

An independent, high-level quantitative assessment was performed to evaluate the major risks associated with expansion of concentrated natural gas (CNG) storage in dormant Schuyler County solution-mined salt caverns. The risks of events associated with CNG pipe transport and salt cavern storage were evaluated using standard methodology, a twenty-five year exposure interval, and publicly available sources.

Pipe transport events are scored a low likelihood at 11%, but risk reduction efforts should be considered because of possibly serious consequences. Salt cavern storage events are scored a medium likelihood at 35%, and are an unacceptable risk because of extremely serious consequences. The very low likelihood of major brine leak with extreme consequences, and the fact that the salt cavern is located in bedded plane geology rather than in a salt dome, add to that risk.

In aggregate, the likelihood for a concentrated natural gas event of serious consequences within the county in the next twenty-five years is scored at more than 40%; the likelihood of a disaster of extremely serious consequences is more than 35%. From the perspective of community safety based on this analysis, the Arlington proposal carries an unacceptable risk of serious or extremely serious consequences. Because risk mitigation efforts in salt cavern storage have thus far proven unsuccessful in significantly reducing the frequency of serious and extremely serious incidents, an alternative plan should be considered.

Introduction

Risk assessment work starts with a prioritization process, based on the likelihood and consequences of identified untoward events. For events of extreme seriousness and high likelihood, the risk is ordinarily deemed unacceptable, and efforts are made chiefly to reduce or eliminate the risk. For events of minor consequence and low likelihood, the risk may be deemed acceptable, and a response plan is developed. A matrix is commonly used to display the combination of consequence and likelihood:[1] [2]

MATRIX FOR RISK ASSESSMENTS at NTNU

CONSEQUENCE	Extremely serious	E1	E2	E3	E4	E5
	Serious	D1	D2	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Not significant	A1	A2	A3	A4	A5
		Very low	Low	Medium	High	Very high
		LIKELIHOOD				

Principle for acceptance criteria. Explanation of the colours used in the risk matrix.

Colour		Description
Red		Unacceptable risk. Measures must be taken to reduce the risk.
Yellow		Assessment range. Measures must be considered.
Green		Acceptable risk Measures can be considered based on other considerations.

Figure 1 – Sample Risk Matrix

In a high-level quantitative risk analysis (QRA) I have applied this process to evaluate the risk of the Schuyler County concentrated natural gas (CNG) storage proposal submitted by Arlington Storage Company, LLC.

Brief summary of CNG storage proposal:
Arlington's DEC application to expand its Schuyler County CNG storage capacity calls for the conversion of two interconnected bedded salt caverns from which salt is no longer being solution-mined, to increase working gas capacity from 1.45 to 2.00 billion cubic feet.[3]

In this case multiple stakeholders have identified two high-level processes in which a catastrophic event or events might occur. I limited my analysis to these two contingencies. Stated as questions:

(1) Is transportation of CNG by pipeline an acceptable risk?
(2) Is salt cavern storage of CNG an acceptable risk?

Tools and techniques for risk assessment scoring in the petroleum and natural gas industries include guidelines from the International Organization for Standardization (ISO) and other energy sector sources.[2 4 5]

To assign probabilities on the continuum from "very low" to "very high" likelihood I used an ISO risk matrix with an exposure interval of 25 years, which is standard in the occupational health literature[6] and appropriate for longer-term community planning.

RISK ANALYSIS

Pipeline Transportation Risk:

CNG pipeline would occur via the existing network of Schuyler County natural gas pipelines.[7]

The most serious risk in CNG pipeline transportation in 2013 was pipe disruption caused by failure material or welds (43%), excavation damage (23%), corrosion (13%), natural force damage (7%), other outside force damage (7%), incorrect operation (3%) or other cause (3%).[8] In the decade 2004-2013 such disruptions in the United States have resulted in 565 significant incidents with 15 fatalities, 104 injuries, and more than $1Billion in property damage.[8]

These significant incidents were distributed over a natural gas pipeline network of approximately 300,000 miles[9] and depending on the proximity to population centers, the potential for evacuation, and the number of casualties would be scored at **moderate to serious consequence** on the ISO risk matrix. Over a 25-year exposure interval the average risk for Schuyler County's 24 miles of CNG pipeline is approximately 11 percent, or **low likelihood**.[10]

I have therefore placed pipeline events in cell D2. This cell indicates "assessment range," so ways to reduce risk further should be still considered **because of the possibly serious consequences**.

CONSEQUENCE	Extremely serious	E1	E2	E3	E4	E5
	Serious	D1	PIPELINE RISK	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Not significant	A1	A2	A3	A4	A5
		Very low	Low	Medium	High	Very high
				LIKELIHOOD		

Color		Description
Red		Unacceptable risk. Measures must be taken to reduce risk
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Green		Acceptable risk. Measures can be considered based on other considerations

Figure 2 -- Pipeline Risk

Salt cavern risk:

Event rates
As of 2012 there were 414 underground gas storage facilities in the US. Most are in depleted oil and gas fields; a few are in aquifers, and 40 are in “salt cavern” facilities.[11] Most salt caverns have been developed over several decades from naturally occurring, globular, so-called “salt domes” in the Gulf states. Nine have been added since 2007. A few salt caverns are in “bedded salt” deposits like Schuyler County’s, which itself has been used in the past for LPG and natural gas storage. Safety oversight of underground gas storage is performed by both federal and state agencies.

Despite this supervision, between 1972 and 2012 there have been 18 serious or extremely serious incidents in salt cavern storage facilities.[5],[12] With the average number of facilities in operation through most of the last two decades close to 30,[9] the US incidence is about 60 percent (compared to 40 percent worldwide[13]), and the frequency is about 1.4% per year. Causes of failure have included corroded casings, equipment failure, brine erosion leading to breach, leakage into other geologic formations, and human error.[12] Worldwide, the percentage of incidents *involving casualties* at salt cavern facilities as a percentage of the number of facilities operational in 2005 was 13.6 percent, compared to 0.63% for gas and oil fields, and 2.5% for aquifers.[12]

Nine of the salt cavern incidents were accompanied by large fires and/or explosions. Six involved loss of life or serious injury. In eight cases evacuation of between 30 and 2000 residents was required. Extremely serious or catastrophic property loss occurred in thirteen of the 18 cases.[5],[12] The likelihood of a serious, very serious, or catastrophic incident over twenty-five years is 35 percent.[14] This would be initially scored a **medium likelihood**, with the potential for at least **serious** consequences, and possibly **extremely serious** consequences, and thus an **unacceptable risk**.

Salt infiltration
Seneca Lake is the saltiest of the Finger Lakes at 150-170 parts per million chloride, (versus 20 to 50 ppm for the other Finger Lakes), probably because its basin intersects the same salt strata from which the caverns are derived[15].

The geologist responsible for Seneca water quality monitoring has raised a concern that salt-solution mining has been partially responsible for Seneca Lake’s increasingly elevated chloride levels since 1900, that natural gas salt cavern storage may have caused the dramatic spike in lake chloride levels seen in the late 1960s, and that further pressure on the salt caverns could aggravate that process.[16] In that event, remediation for large-scale brine contamination could well take decades or be impossible, jeopardizing the source of drinking water for about 100,000 people.[17] Other long-term water sources could be needed, or else large populations would be obliged to move.

Few salt caverns are adjacent to a large lake. I could find no reported cases of catastrophic brine leakage in fuel storage facilities, but “brine gushers” have occurred in capped brine caverns.[12] While a disaster resulting from accelerated geologic salt infiltration into Seneca Lake would be scored a **very low likelihood**, it would certainly have **extreme consequences**. When considered together with the other extremely serious incidents, it raises the consequence of salt cavern events into the **extremely serious** range.

Geology

Much concern has also been raised about the geology of the solution-mined caverns proposed for natural gas storage. There has been a great deal of discussion over faults, partial roof collapses, rubble piles, undiscovered uncapped wells, and so on. In its detailed and very considered approval of Arlington’s application to increase natural gas, the Federal Energy Regulatory Commission (FERC) acknowledged the serious concerns raised by independent geologists as to the stability of the Schuyler County salt caverns, but chose to support the company geologists’ reassurances and test results, merely requiring the company to monitor for gas leaks, ground subsidence, and the like.[3]

Likewise, the New York State Geologist is obliged by statute to rule on the integrity of caverns used to store hydrocarbons, Earlier this year, an official in that office did vouch for the “long track record” of the salt caverns in a half-page document.[18] I do not have the expertise to evaluate such concerns, reassurances, rulings, or requirements.

However, I would reiterate that it is not necessary to get into such detail for this level of analysis. From the risk assessment perspective it is enough to recall that standard and additional regulatory recommendations, routine mechanical integrity testing, and every other careful industry precaution have failed to prevent the eighteen serious or extremely serious salt cavern incidents. Some have been quite recent, and some have occurred in caverns with long safety track records.[12]

It should also be noted that both oversight and industry literature report that using the salt cavern subset of bedded salt deposits like Schuyler County’s is riskier than using the salt domes common in the Gulf, perhaps for geologic reasons like those mentioned above, and especially when single well-bore holes are used,[12] as planned in this case. The most instructive incident in this connection occurred at the Yaggy salt cavern facility seven miles northwest of Hutchinson, Kansas, a town of 44,000. Gases that escaped from the salt cavern due to human error traveled along sedimentary layers, erupted in the town itself, and resulted in fire, explosion, two deaths, one injury, and more than 250 evacuations. A detailed summary, map, and photos are appended. The unfavorable geology and irregular cavern shapes generally associated with bedded salt deposits[12] probably push the likelihood of salt cavern failure somewhat higher in the **medium likelihood** category.

Risk tolerance

This level of consequences per facility over twenty-five years--major fires, explosions, collapses, catastrophic loss of product, evacuations--is an unusual level of risk. Most other regulated industry sub-segments with a persistent serious to extremely serious facility incident rate of over thirty percent would be shut down or else voluntarily discontinued, except in wartime. Even in the petroleum industry, which is widely known to tolerate higher risks than most others, the rate of events per facility involving casualties is more than 20 times higher in salt caverns than in the alternative--depleted oil and gas fields.[12]

In most other industries, including healthcare, automotive, and nuclear power, to name a few prominent ones, severe regulatory sanctions are imposed for catastrophic failure rates that are many, many times less than in salt cavern facilities. Salt caverns provide less than ten percent of U.S. working gas storage,[9] so even though salt caverns have shorter cycle times and may be closer to market, the depleted oil and gas option alternative is clearly the better safety option from a national perspective.

To be sure, there have been many advances in assessment, extraction, storage, and transportation technology over the years in which salt caverns have been used for natural gas storage. Yet those advances have not yet led to a significant reduction in the rate of serious and extremely serious incidents.[19] This may in part be lag time; the interval from commissioning to events has often been a decade or more. As in oil drilling, however, there may also be an increased tolerance for riskier project selection. Experience from NASA, nuclear power plants, car manufacturing, and healthcare consistently shows that to improve safety the critical requirement is not better technology but cultural change.

There have been scattered other reports and articles praising the safety of underground storage. The flaws and biases in those analyses from the point of view of Schuyler County are not hard to identify.[20]

CONSEQUENCE						
	Extremely serious	TRAIN RISK	E2	SALT CAVERN RISK	E4	E5
	Serious	D1	PIPELINE RISK	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Not significant	A1	A2	A3	A4	A5
		Very low	Low	Medium	High	Very high
				LIKELIHOOD		

Color		Description
Red		Unacceptable risk. Measures must be taken to reduce risk
Yellow		Assessment range. Measures must be considered
Green		Acceptable risk. Measures can be considered based on other considerations

Figure 3 – Pipeline and Salt Cavern Risks

Other risks:

Diesel air pollution, noise pollution, loss of jobs in tourism and wineries from "industrialization," and many other risks have been discussed widely in community forums. They are not included in this analysis because they are unlikely to require emergency response, but they may well have health or other consequences that are more difficult to quantify.

Risk summary and Conclusion:

Neither of the two possible types of events--pipelines and caverns--is contingent on either of the other events, so for probability purposes they are considered "independent" risks. Combining the two independent probabilities, **the likelihood for a CNG event of *serious* consequence within the county in the next twenty-five years is more than 40%**[21]**, and the risk of a CNG salt cavern event *of extremely serious* consequence within the county is more than 35%.** Most of this risk, of course, comes from the possibility of serious or extremely serious salt cavern events as described above.

CONSEQUENCE						
	Extremely serious	E1	E2	CNG STORAGE RISK	E4	E5
	Serious	D1	D2	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Not significant	A1	A2	A3	A4	A5
		Very low	Low	Medium	High	Very high
				LIKELIHOOD		

Color		Description
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Figure 4 – CNG Storage Proposal Risk

Worst case scenarios are not hard to imagine. They would involve some combination of loss of life, loss of the lake as a source of drinking water, and/or temporary or permanent evacuation. Each of these scenarios has happened in other salt cavern facilities. Fortunately for the nation, but of no help to Schuyler County, most of the other events occurred in locations more isolated from population centers than ours.

By its very nature, there are large uncertainties in any risk assessment estimate. For the sake of argument, though, even if each of the two probabilities has been overestimated by 75 percent, the likelihood for serious or extremely serious consequences over twenty-five years is still approximately 25 percent.[22]

From the perspective of health safety, based on this independent analysis, I conclude that the Arlington proposal carries an unacceptable risk of extremely serious consequences.

Plans should always be made for acceptable risks. And some unacceptable risks can be made acceptable through mitigation. Other municipalities have reduce rail accidents, for example, by enacting ordinances to regulate train speed within their borders.

It is not yet clear, however, that any regulatory or mitigation effort to date has been effective in reducing serious and extremely serious salt cavern incidents frequency to a significantly lower level. Strong consideration should therefore be given to an alternative course of action.

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[1] Matrix risk analysis is used worldwide and in many industries. This typical

[2] *Guidelines for Chemical Transportation Safety, Security, and Risk Management*, Center for Chemical Process Safety, John Wiley & Sons, 2008.

[3] 147 Federal Energy Regulatory Commission ¶ 61,120: Arlington Storage Company, LLC, May 15, 2014.

[4] ISO 17776:2000(en)Petroleum and natural gas industries--guidelines on tools and techniques for hazard identification and risk assessment at:
https://www.iso.org/obp/ui/#iso:std:iso:17776:ed-1:v1:en
(emphasis on off-shore, but much still applicable)

[5] Hopper, John M., *Gas Storage and Single Point Risk,* in Natural Gas, at
www.documbase.com/Gas-Storage-And-Single-Point-Failure-Risk.pdf

[6] Mullai, Arben, *Risk Management System—Risk Assessment Frameworks and Techniques*, DaGoB publication series 5:2006.

[7] National Pipeline Mapping System map for Schuyler County, New York, at:
https://www.npms.phmsa.dot.gov/PublicViewer

[8] Significant pipeline incidents by cause, Pipeline Safety Stakeholder Communications, Pipeline and Hazardous Material Safety Administration, U.S. Department of Transportation at:
http://primis.phmsa.dot.gov/comm/reports/safety/SigPSIDet_2013_2013_US.html?nocache=7539#_ngtranson

[9] U.S. Energy Information Administration at :
http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/index.html

[10] calculation: 57 significant incidents/yr/300,000 miles pipeline x 24 miles Schuyler County pipeline x 25 years = 0.113

[11] www.eai.gov

[12] Health and Safety Executive of the United Kingdom*, An appraisal of underground gas storage technologies and incidents, for the development of risk assessment methodology,* at:
http://www.hse.gov.uk/research/rrpdf/rr605.pdf

[13] The lower world-wide incidence is thought by some to reflect under-reporting in Europe and the former Soviet Union.

[14] Calculation: 1.4% incidence per year x 25 yrs = 35%

[15] Limnology and Water Quality—*Seneca Lake at:* http://www.gflrpc.org/Publications/SenecaLakeWMP/chap6a.pdf

[16] Concern reported in 147 Federal Energy Regulatory Commission ¶ 61,120: Arlington Storage Company, LLC, May 15, 2014.

[17] Halfman, John D. *Water Quality of Seneca Lake, New York: A 2011 Update* at http://people.hws.edu/halfman/Data/2011%20Seneca%20Report.pdf

[18] Andrew Kozlowski, Acting Associate State Geologist, to Peter Briggs, Director, NYSDEC, March 15, 2014.

[19] Industry sources cite a reduction in incident frequency in the 1990's, but this reversed with a spate of incidents in the early 2000's.

[20] Such flaws include:

- failure to separate out salt caverns from other forms of underground storage
- among salt caverns, failure to separate out bedded salt geology from salt domes
- claims that salt cavern storage is safer than above-ground storage, which may be true but is beside the point
- claims that the total number of casualties in underground storage incidents is lower than the corresponding number for other parts of the petrochemical distribution chain, without calculating incidence or frequency rates per facility, per mile, etc.
- claims that human error and technology failures because they are potentially correctible, should be discounted from the risk analysis
- failure to include transportation risks and other risks in analysis
- desire to promote other types of underground storage
- petrochemical industry funding

[21] Calculation: (1-((1-0.11)*(1-0.35)) = 42.1%

[22] Calculation: 1-((1-0.06)*(1-0.2))= 24.8%

An appraisal of underground gas storage technologies and incidents, for the development of risk assessment methodology, Health and Safety Executive, United Kingdom, 2/2008, pp 161-164:

Hutchinson – aka Yaggy, Kansas (USA)

The town of Hutchinson, with a population of around 44,000, lies around 11 km (7 miles) SE of the Yaggy Storage Field (Figs. 25&35), and provides the location for perhaps the most publicised and notorious UGS incident. The area is underlain by the Hutchinson Salt Member, which has been mined and extracted at Hutchinson since the 1880s and in which caverns had been created for storage purposes. At the time of the incident, the Yaggy storage facility played a key role in the supply of gas in central Kansas and was thus of national importance. It was one of 30 "hubs" in the USA national gas distribution system and one of 27 such cavern storage fields in the USA. The incident has been extensively reviewed elsewhere and so will only be outlined here, with emphasis on the history of the facility to illustrate the background to the disaster.

The Yaggy field was originally developed in the early 1980s to hold propane. The storage caverns were formed by salt dissolution using brine wells, drilled to depths between 152 m and 274 m in the lower parts of the Lower Permian Hutchinson Salt Member of the Wellington Formation (Fig. 35). The top of each cavern was located about 12 m below the top of the salt layer to ensure an adequate caprock that would not fracture or leak and the wells were lined with steel casing into the salt. The Wellington Shale Formation is overlain by the Ninnescah Shale, both of which dip to the west and northwest and form the bedrock to 15 m or more of the sands and gravels of the Equus Beds. These unconsolidated deposits underlie (Fig. 35) and provide the municipal water supply for the city of Hutchinson, and the city of Wichita to the east.

Decreasing financial viability eventually led to the closure of the propane storage operations in the late 1980s. The wells were cased into the salt and later plugged by partially filling them with concrete. In the early 1990's, Kansas Gas Service, a subsidiary of ONEOK of Tulsa (Oklahoma), acquired the facility and converted it to natural gas storage. The existing caverns were re-commissioned, which required drilling out the old plugged wells, whilst further wells were drilled to solution mine additional caverns.

Mention is made of the Yaggy Storage Field consisting of 98 caverns in the Hutchinson Salt Member at depths greater than 150 m. It appears that at the time of the 2001 incident, the facility had about 70 wells, of which 62 were active gas storage caverns, at depths greater than 152 m. More than 20 new wells had been drilled and were being used to create new caverns for expansion of the facility (Allison, 2001a). The wells, with 90-120 m spacing, are located on a grid. A group of wells are connected at the surface via pipes and manifolds, allowing gas to be injected or withdrawn into all the caverns in the group simultaneously. The capacity of the Yaggy field was circa 90.6 Mcm (c. 3.2 Bcf) of natural gas at around 600 psi.

The incident at Hutchinson occurred on the morning of January 17th, 2001, when monitoring equipment registered a pressure drop in well S-1, which connected to a cavern being filled. The cavern could hold 1.7 Mcm of gas at an operating pressure of about 4.65 MPa (675 psi). This could, however, range from 3.8 to 4.7 MPa (550 to 684 psi). Later that morning a gas explosion occurred in downtown Hutchinson, around 11 km (7 miles) away and was followed by a series of gas and brine geysers, up to 9 m high, erupting about 3.2 km (2 miles = c. 9 miles from the storage site) to the east along the outskirts of Hutchinson (Fig. 35). The following day (18th January), a gas explosion at the Big Chief Mobile Home Park killed 2 and injured another (Fig. 35). The city promptly ordered the evacuation of hundreds of premises: many not returning to their homes and businesses until the end of March 2001.

An investigation into the incident led by the Kansas Geological Survey (e.g. Allison, 2001a&b), found the leak was the result of a large curved slice in the casing of the S-1 well at a depth of 181.4 m, just below the top of the salt and 56 m above the top of the salt cavern. The damage to the casing resulted from the re-drilling of the old cemented well when re-opening the former propane salt cavern storage facility. Furthermore, ONEOK computer operators in Tulsa had overloaded the storage field caverns with natural gas, causing the initial leak. For at least 3 days the casing leak allowed natural gas at high pressure to escape and migrate upwards through the well cement and fractures in rocks above the salt. On reaching a permeable zone formed by a thin bed of micro-fractured dolomite near the contact between the Wellington Formation and the overlying Ninnescah Shale at around 128 m, the gas was trapped by overlying gypsum beds, preventing further vertical movement. The dolomite was fractured in the crest of a low- amplitude, asymmetric, northwesterly plunging anticlinal structure and the pressure of the escaping gas induced parting along the pre-existing fracture system. The gas migrated laterally southeastwards up-dip along the crest of the anticline towards Hutchinson, where it ultimately encountered old abandoned and forgotten brinewells that provided pathways to the surface (Allison, 2001a; Nissen et al., 2003 & 2004).

Geological investigations of the area suggest that the fractures in the dolomites were related to deep seated fractures that caused faulting in the overlying strata. These fractures then appear to have permitted undersaturated water to penetrate down and dissolve the Hutchinson salt, causing variations in thickness of the halite beds. Faulting in strata overlying the halite beds is greatest where dissolution has taken place and the edge of this dissolution zone trends NW close to the crest of the anticlinal structure. The dissolution of the halite appears to have locally enhanced structural relief, which led to further stresses, fracturing and preferred zones of weakness in the overburden, providing pathways for gas migration along the trend of the anticline (Watney et al., 2003a; Nissen et al., 2004b). Shut in tests on vent and relief wells following the incident revealed that with reduced gas pressures, fracture apertures were reduced and closed as pore pressures declined.

Basic volumetrics of the fracture cluster were calculated (Watney et al., 2003b):
· Length – 14 km (8 miles)
· Width – 300 m (1000 ft)
· Height – 0.9 m (3 ft)
· Porosity – 2%
· Fracture volume – 78,000 m^3 (2.8 Mcf)
· Estimated volume of gas released – 4.04 Mscm (143 Mscf) = 99,109 m^3 (3.5 Mcf) at 4.14 MPa (600 psi), 12°C (54°F)

Other storage facilities exist around Hutchinson and provide some useful information on storage pressure gradients. In late 1996 to 1997, Western Resources Inc. who operated a hydrocarbon storage well facility to the west of Hutchinson, submitted requests to the Kansas Department of Health and Environment (KDHE) to increase the maximum storage pressure gradient at their facility. KDHE regulate gas storage operations and operated a 'rule of thumb' that the maximum storage pressure gradient at such facilities in the Hutchinson area was limited to 0.75 psi/foot of depth. This was in order to prevent fracturing of the salt deposit. Following tests on rock cores, Western Resources Inc. requested increasing the pressure from 0.75 psi/foot of depth to a pressure gradient of 0.88 psi/foot of depth, which was actually close to the average fracture pressure gradient of 0.89 psi/foot of depth. One rock sample actually had a fracture pressure gradient of 0.72 psi.foot of depth (KDHE, 1997).

The original downtown explosion site was related to a mineral water well in a basement that had provided mineralized waters for a hotel spa. The second explosion occurred at the site of an old abandoned brinewell. Images of a blazing well in the ruins of a building are available on the Kansas Geological Survey website (http://www.kgs.ku.edu/Hydro/Hutch/CUDD/2nd/set01.html). The same was found to be true for the numerous gas and brine geysers to the east of the city and the explosion at the Big Chief trailer park. When drilled, most old brine wells were only cased down through the shallow Quaternary "Equus beds" aquifer. The deeper parts of the wells were open-hole and thus provided ready pathways for the gas to escape to the surface. As many as 160 old brinewells are thought to exist in the Hutchinson area, either buried purposely or by subsequent development. It is unlikely that the well casings of these wells, if they exist, are sufficiently gas tight to prevent gas escapes and would present problems if future leaks were to occur.

Following the operations to trace and deal with the January leak incident, a second event occurred around six months later on the afternoon of Sunday, July 7, when one of the vent wells (Deep Drilled Vent well 64) suddenly started venting gas at high pressure (Allison, 2001c). The following day, the flare was reported at about 4 m in height and a pressure of 2.3 MPa (330 psi). Mechanical modifications to the surface pipework were made with the result that the flare reached an estimated 9 m - 30 to 12 m in height by Monday evening. Pressures had dropped to only 0.04 MPa (6 psi) by the following Wednesday; when the well was temporarily shut in. However, the pressures then increased quickly again.

Three possible causes for the flare-up were identified (Allison, 2001c):

· formation or near-well-bore damage – this is caused by the flow of water and gas through the near-well-bore environment. The permeability of the rock near to the well is reduced by the plugging the rock with fine materials, chemical alteration, or by changes in relative permeability as the volume of gas drops relative to the volume of water. Such "damage" routinely occur in oil and gasfield wells and is readily corrected.

· segmented pockets or fractures of gas remained - when the gas first entered Hutchinson it was under sufficiently high pressure that it may have forced open previously closed fractures in the rock layers or pushed its way into areas of 'tight rocks', i.e. less permeable rocks. As pressures dropped, it is possible that some fractures would have closed up again, isolating small amounts of gas in separate pockets, which over time, could have worked their way back into the main accumulation and into the vent well.

· another source of gas besides the Yaggy field exists – a scenario thought to be unlikely as well DDV 64 sits in the midst of a swarm of vent wells and it is hard to project a new source of gas that would affect only this one well.

The causes of the resurgence of gas were still being investigated in late 2001/early 2002. However, the results of this investigation, although it is likely that they have been published, have not been found during this study.

The incident in 2001 was not the first time that there had been problems with a cavern and well at the Hutchinson storage facility. On September 14, 1998, a shale shelf collapsed inside the field's K-6 cavern, trapping a gamma-ray neutron instrument that had been used for monitoring purposes. Downhole video surveys revealed the casing on the verge of collapse at about 183 m, with the camera unable to go below 205 m, due to the blockage. In October 1998, a plan was established to remove gas from the cavern over the winter. In the spring of 1999, the radioactive tool was buried under 1.2 m of concrete and the cavern's main pipe was relined with bonding cement to block any possible leaks. The cavern is still monitored for radiation leaks.