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THE HUTCHINSON GAS EXPLOSIONS: UNRAVELING A GEOLOGIC MYSTERY

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I. GAS EXPLOSIONS PANIC HUTCHINSON

A. Fires burn downtown businesses

Natural gas exploded in two businesses in downtown Hutchinson on the morning of Wednesday January 17, 2001. Although the force of the explosion blew out windows in nearby buildings and was heard over many square blocks, injuries to store employees and customers were minor. Within minutes both the Décor Shop and Woody's Appliance store were engulfed in flames.

B. Fires can't be extinguished

Officials cut off natural gas supplies to the downtown area on the assumption that the explosion and fire were due to a pipeline leak. By the end of the day, even though there was little of the two stores left that was burnable, the fire department reported to city officials that the fire could not be put out.

C. Gas geysers erupt around town

Wednesday evening geyser-like fountains of natural gas and salt water started bubbling up in a number of locations primarily on the east side of town, about 2 to

3 miles east of the downtown fires. Some geysers reached heights of 30 feet. Contractors hired by the city found that geysers were coming out of abandoned brine wells that had been drilled as long ago as the 1880's for salt production.

D. Two die in mobile home explosion

The next day, January 18, natural gas exploded under the mobile home of John and Mary Ann Hahn in the Big Chief Mobile Home Park on the east side of town near where most of the geysers occurred, severely burning both of them. Both died from their injuries.

E. City orders evacuation

Emergency response teams evacuated residents from 191 homes on the east side of Hutchinson, including those in the mobile home park and surrounding neighborhoods, and from neighborhoods near the geysers. Forty-three businesses in the affected areas were also evacuated.

II. NATURAL GAS LEAK AT YAGGY STORAGE FIELD

A. Catastrophic leak in well S-1 day of explosion

Also on the morning of January 17, technicians at the Yaggy natural gas storage field northwest of Hutchinson noticed a dramatic drop in pressure in the "pod" of 16 underground "jugs" that they had been filling with natural gas during the previous few days. Kansas Gas Service (KGas) officials notified city officials of the leak sometime later, and the coincidence of the leak and the explosions and fires in Hutchinson was noticed.

Upon review of pressure records, KGas realized that the S-1 jug likely had been leaking at a low level at least since its pod of jugs had been refilled on January 14. At the time, technicians did not think much of the minor pressure drop, as it was a routine situation. When the jugs are pressurized, the gas is compressed, raising its temperature. Once in the jugs, the gas begins to cool and condense, resulting in a slight pressure decrease. It is apparently common practice then to "top off" the jugs with additional gas to fill the pod of jugs to the final pressure.

B. Field developed in 1980's for propane storage

The Yaggy field was originally developed in the early 1980's to hold propane. Wells were drilled to depths of about 650-900 feet, into the lower parts of the Hutchinson Salt Member. The wells were cased with steel casing into the salt.

The company had difficulty making a financial success of the operation and eventually ceased operations. All of the storage wells were then plugged by partially filling them with concrete.

C. Converted to natural gas storage in early 1990's

KGas acquired the facility in the early 1990's and converted it to natural gas storage. KGas is a subsidiary of Oneok Corporation, an oil and gas company headquartered in Tulsa, Oklahoma. The Yaggy field is operated by a wholly owned subsidiary of KGas as the Mid-Continent Marketing Center. The wells had been plugged with concrete that needed to be drilled out to return the wells and jugs to use. Each jug is a man-made cavern in the Hutchinson Salt Member, formed by drilling into the salt, pumping down fresh water and removing salty brine. The top of each jug starts about 40 feet below the top of the salt layer to ensure an adequate cap that will not fracture or leak.

The S-1 jug held about 60 million cubic feet of natural gas when fully pressurized. Each jug was developed from a separate well drilled into the salt. Surface wells are 300 feet apart, and each jug is intended to be separate and unconnected to other jugs in the subsurface. A pod of wells is connected at the surface via pipes and manifolds, allowing gas to be injected or withdrawn into all the jugs in the pod simultaneously.

At the time of the crisis, Yaggy had about 70 wells, of which 62 were active gas storage jugs. More than 20 new wells had been drilled and were being used to create new jugs for expansion of the field.

The field could hold 3.5 billion cubic feet (Bcf) of gas at pressures of about 600 pounds per square inch (psi). The advantage of salt cavern storage is the ability to move large amounts of gas in and out quickly compared to gas stored in depleted oil and gas fields where the gas is in the tiny pore spaces between rock grains. This allows the facility to serve as a rapid response source of gas when peak demands occurs. The Yaggy field could supply about 150 MMcf (million cubic feet) of gas per day.

Yaggy is the only gas storage field in salt caverns in the state. Other salt caverns in Kansas are used for storage of liquid hydrocarbons, such as propane, at much lower pressures than the natural gas at Yaggy. Thirteen abandoned oil and gas fields are also being used for underground natural gas storage but at much lower pressures than at Yaggy. All underground storage of natural gas is regulated by the Kansas Department of Health and Environment (KDHE).

D. Hole in casing of well S-1

Records show that when KGas drilled the concrete out from the well casing in S-1 to return the well to operation, they encountered a steel casing coupler that had fallen into the concrete in the well during the plugging operations. The object may have deflected the drill bit against the side of the well casing damaging and weakening it. A down-hole video in S-1 shows a large curved slice in the casing at that depth. The city's geological consultant described it as looking "like a kitchen knife cutting into a can."

E. Geologic hypothesis - gas moved 8 miles underground, came up abandoned brine wells

During the first two days of the crisis, our working hypothesis was that high-pressure gas leaked out of well S-1 as a result of casing failure. The gas moved vertically through the geologic section, possibly through the cement that was supposed to bond the well casing to the surrounding rock. It then traveled laterally along a geologic layer under pressure in all directions. Some of the gas moved "updip" (up slope to the highest point on the rock layer) due to density driven flow, to Hutchinson where it found old, abandoned, brine wells that had been drilled down into the Hutchinson Salt. These wells were only cased down through the shallow "Equus beds" aquifer. The deeper parts of the wells were open-hole and provided paths for the gas to escape to the surface.

III. EMERGENCY RESPONSE IN HIGH GEAR

A. Gas company workers blanket city

KGas mobilized more than one hundred workers to check Hutchinson for gas leaks. Workers went door-to-door, street-by-street checking for any traces of gas using hand-held and truck-mounted “sniffer” devices. Temporary soil-gas detectors were deployed around the city.

Excavations at Woody’s Appliance shop found a long-forgotten brine well in the remains of the basement. The store had been built originally as a hotel and the well drilled to provide brine waters for the hotel spa. The wellhead was replaced and the gas diverted into an aboveground pipe to flare the gas safely. The site was cleared of all the building debris and left to vent gas.

B. First vent wells are dry

The other response effort by KGas, developed in consultation with KDHE and the City, was to drill wells to find and vent underground gas to the surface. Oil and gas rigs were brought in from a number of contract drillers. The first wells drilled were close to many of the geysers on the east side of Hutchinson. They were drilled well into the salt layer but encountered no gas.

Out of the first 36 wells drilled in and around Hutchinson, only eight found gas, one of which was in the parking lot of the KGas building downtown.

C. Gas confined to thin layer 200 feet above the salt layer

The early wells were drilled into the salt horizon on the assumption that the gas was traveling through an informally described “rubble zone” thought to directly overlay the Hutchinson Salt Member. KGas’s drilling strategy was to put wells wherever open space was available on an approximately 160-acre spacing. After some of the wells encountered gas zones, a pattern became clear that everywhere gas was present it was in a relatively thin zone about 200 feet above the top of the

Hutchinson Salt. What was unclear was why the gas was not prevalent in a sheet-like distribution in the layer of rock under Hutchinson.

Samples were examined from a well drilled in 1970 by the Atomic Energy Commission to the north in Rice County, as part of the investigation into using the Hutchinson Salt for storage of high-level nuclear waste. This well had been cored over the entire drilled depth, providing the only comprehensive samples in the area. No layers were found that seemed to be capable of carrying large amounts of natural gas over long distances in a short time. The rocks in the zones of interest were composed of relatively impermeable shale. Fractures, commonly filled with gypsum or anhydrite, occurred throughout the shale layers but there was no zone that stood out as a potential gas conduit.

D. Geological Survey mobilized by Governor:

Survey scientists contacted KDHE on January 18 to offer our services and to provide oil and gas data and geology of the region. As KGas encountered difficulties in finding gas with their early vent wells, discussions centered on the need to use shallow, high-resolution seismic reflection technology to explore for the possible narrow geologic pathways that appeared to being carrying gas selectively under parts of the city.

The Survey's geophysical team is widely recognized as one of the best in the country in this field. The crew was preparing to deploy to Arizona to carry out a long-planned cooperative research project with the U.S. Army. The trucks were loaded with equipment and supplies. Both Survey staff and temporary field crew members were packed and prepared to leave the next day when the decision was made that they were needed in Hutchinson. The Army had committed significant resources in preparation for the Arizona project. For the Survey to back out at the last minute could jeopardize the Army's commitment to the $900,000 project. KDHE officials informed the Governor of the situation and on January 30, the Governor issued a proclamation mobilizing the Kansas Geological Survey and directing us to aid the citizens of Hutchinson. In addition, Senator Roberts' office offered to call the Secretary of the Army on our behalf, if needed. However, with the order in hand, we asked the Army to postpone the field project, which they graciously agreed to.

The Survey committed its geologists, geophysicists, and engineers to the crisis with four goals: (1) Make Hutchinson safe from leaking gas, (2) Find abandoned brine wells for proper plugging, (3) Determine if Yaggy field can be reopened and under what conditions, and (4) Determine what the impacts are for natural gas storage in salt caverns nationwide.

Resolving the crisis at Yaggy had quickly become dependent on unraveling a geologic mystery.

E. Seismic survey detects two potential "gas conduits"

The intent was to find the geologic pathways that seemed to be carrying gas from Yaggy into Hutchinson along some unknown narrow conduits within a thin layer of rock.

The Survey geophysics crew ran its main seismic reflection line along Wilson Road, which runs north-south and lies between the Yaggy field and the city proper. Seismic reflection data are collected by sending shock waves into the ground and recording the signals that bounce off the geologic layers back to the surface. The shock waves were sent into the ground with a truck-mounted vibrator. The reflected signals were recorded by extremely sensitive geophones laid out in long cables.

Data were collected along a 4-mile-long section of Wilson Road, running from just north of the Arkansas River past the Willowbrook subdivision. In order to collect data in the detail necessary to delineate what was likely an extremely small and obscure target, each vibration location was repeated multiple times to build the most noise-free response possible. Recording of seismic data continued for about five days. A second, short line was "shot" across Rice Park on the west side of Hutchinson because we could collect data adjacent to a flaring vent well in the park. We hoped that we could use the Rice Park data to calibrate the Wilson Road data. Altogether, 60 gigabytes of data were collected, filling 100 CD-ROMs. The data were shipped in batches to the Survey offices in Lawrence for computer processing. Interpretation began on the preliminary processing of the data and allowed us to focus more sophisticated processing on smaller areas of interest.

A team of geophysicists and geologists finally identified two anomalous zones that could not be explained by surface noise or interference. The northern anomaly is about 150 feet wide; the southern anomaly is about 200 feet wide. In both cases, the anomaly was defined by a dimming of data relative to the adjacent areas. The team speculated that the dimming indicated that the seismic waves traveled from water bearing rock layers into a gas-bearing layer then again into underlying water-bearing zones. In the areas where the seismic waves did not encounter gas, there was little or no change in the density from one zone to the next and thus no anomalous seismic signature.

F. Geologic vent wells hit gas

The Survey identified the two anomalous zones as likely gas-bearing conduits and recommended to KGas that they be drilled. At that time, KGas had drilled 36 vent wells, of which 8 found natural gas. KGas drilled both seismic anomalies and both found gas at the predicted location and depth. Both wells, DDV 53 and 54, were among the largest gas producers of all the vent wells eventually drilled. The conduits had the characteristic shapes of old river channels, and buried by mud and clays, about 250 million years ago. It appeared to many observers that we had solved the mystery.

G. Ground water monitoring

Officials with the Equus Beds Groundwater Management District (GMD) were concerned that the brines and gas erupting in the geysers would contaminate the shallow ground water supplies. By the end of January, a coordinated ground water monitoring plan was developed. An array of existing wells in the Hutchinson area belonging to the city, the GMD, and KDHE, was sampled on a regular basis for inorganic chemistry (chlorides and other brine components), and for natural gas.

H. Survey web page goes online

The tremendous amount of data coming out of the crisis and the reference materials being compiled made it difficult to keep everyone informed of new information and developments. The Survey set up a web page to post all the Hutchinson-related materials in one location (www.kgs.ukans.edu/Hydro/Hutch). The site incorporates one of the first uses of the new ArcInfo Internet Map Server software that allows users to zoom in and out on maps of the area, select what layers to view, and click on specific locations to get more information. The web site receives thousands of hits per month from around the world. Many megabytes of files have been downloaded. Interestingly, during one period when we looked at who was using the site, we found that nearly two-thirds were companies, with government making up only a few percent of users.

IV. TRACKING THE PATH OF NATURAL GAS

A. Tracing the "channels"

The Survey organized a one-day review in Hutchinson of all the technical and scientific data with KGas, KDHE, and city officials. Following that meeting, KGas solicited the Survey's suggestions on what additional wells and data we wanted. Our requests were for cores into the producing zone and additional geophysical logs in wells. KGas drilled additional vent wells along the seismic line on the north and south ends of Wilson Road. Both wells were dry holes as predicted. They cored the geologic zone laterally equivalent to the producing zone and found shale with veins of anhydrite or gypsum and similarly filled fractures. None of the cored material had the obvious permeability and porosity needed to carry large amounts of natural gas a long distance in a short time.

KGas drilled DDV 67 within a few tens of feet of DDV 53 specifically as a core hole to capture a sample of the producing zone. A visual inspection of the core as it came out of the hole (but before it was sent off to a commercial laboratory in Texas for quantitative analysis), recognized several thin dolomite layers at the equivalent depth of the gas bearing interval in DDV 53. Dolomite is a carbonate rock, similar in many ways to limestone. Dolomite is a magnesium carbonate whereas limestone is a calcium carbonate. Dolomite forms in a marine environment generally similar to that of limestone. It does not form sedimentary channels like sandstone can. Our channel theory did not pan out. We were back to square one in explaining the gas pathways.

B. The fractured tidal dolomite theory

Survey geologists examined the gamma-ray curves of the geophysical well logs run in the vent wells. These logs detected the naturally occurring amounts of radioactivity in the various layers of rock in the well bore. Shales tend to contain relatively more radioactive minerals; sands and carbonates generally contain fewer. Thin dolomite beds in the cored well DDV 67, that offset the gas-bearing well DDV 53, correspond with lower gamma ray values. The gamma-ray logs showed gradational increases in the gas zone from southwest to northeast across the Hutchinson area.

The trend of the gamma-ray bands roughly runs parallel to the band of vent wells that produced gas. This led to a revised theory that the gas pathway was composed of fractured thin dolomite layers that originally were deposited in a shallow marine environment that occupied much of the Hutchinson area. Shallower water and proximity to the basin margin led to increased proportions of impermeable shale. Since the general dip of the rocks is to the west, gas from Yaggy could have moved eastward (updip) through the more permeable rocks until it ran into the permeability barrier created by the shale. The dolomite is more brittle than the surrounding shale and would more likely fracture when bent or stressed. Thus, fractures may have been formed over geologic time in the dolomites but not as extensively or at all in the adjacent shale. Laboratory tests indicate that the dolomites and surrounding strata have minor permeability in the rock matrix. Thus, the only significant permeability would come from the fractures, which were not directly observed in the core.

C. The conduits remain enigmatic

Updated maps prepared from geophysical well logs obtained from lastest half of the vent wells show that while the general gradient of northeasterly increase in the gamma-ray persists, the boundary between the cleaner formation and the shalier unit is more irregular than initially mapped. Gas wells are still located on the northeastern edge of the region of low gamma-ray that passes through the City of Hutchinson.

At this time, we cannot say with certainty that we have correctly identified the conduit or know what it is geologically.

V. NASA JOINS THE EXPLORATION

A. Subsidence concerns

During the first days of the crisis, we thought the gas-charged brine coming to the surface in the numerous geysers around town may have resulted from the gas drawing brine from the century-old salt caverns. If the salt caverns were emptied of the brine that filled and stabilized them, we considered the possibility of cavern collapse leading to land surface subsidence.

As we learned that the gas was apparently moving only within a layer about 200 feet above the salt layer, this concern diminished. However, Hutchinson has been subjected to subsidence due to collapse of old underground salt mining for decades. In addition, natural dissolution of the Hutchinson Salt occurs about seven miles to the east of town where it becomes shallow enough to interact with fresh aquifer waters. The dissolution of the salt has created low topographic areas that have filled with water, creating numerous ponds along the "dissolution front." State highway 50 noticeably dips, and the nearby overpass is damaged, where it crosses the dissolution front.

The Reno County Courthouse had to be relocated in the 1920's due to subsidence over a many-block area of downtown Hutchinson. In 1974, a 300-foot diameter sinkhole developed at the Cargill salt mine southeast of town due to collapse of underground mine workings.

The Survey approached NASA scientists to inquire about the use of radar interferometry technology to monitor potential surface subsidence. The experimental technique, using airborne and satellite interferometry, has been successfully used, recently in Las Vegas, to detect and measure subsidence.

NASA was called on, in part, because they had recently completed a Memorandum of Understanding with the Association of American State Geologists, to encourage collaboration between the two groups and find new ways of employing NASA technology and data to state and local government needs.

B. NASA methane detection

Although NASA identified a variety of sources of existing interferometry data and what would be needed to acquire new data, their more surprising news was that new sensors were being tested that could detect methane directly. It was possible that one of the sensors could be deployed to fly over the greater Hutchinson–Yaggy area to search for trace amounts of gas that had been missed or overlooked. After all, the vent wells had all been in the city or between the city and the storage field. Could there be pockets of gas outside the city that were seeping to the surface but not noticed because of the rural nature of the area?

In fact, there was one occurrence of gas bubbling at the surface about a mile south of Yaggy near the farming area known as Yaggy Plantation. There is no known well or other man-made explanation for the gas to seep here. KGas placed four plastic pipes in the ground to vent the gas to the air at this location.

Among other reasons to conduct a broader airborne survey was KGas's continued assertion that the gas coming up in Hutchinson had not been conclusively connected with the gas lost at their Yaggy facility. They continued to urge us to consider alternative sources of gas. The Survey focused on Yaggy as the gas source, as the only theory that we were pursuing.

Perhaps one of the most important reasons for the NASA mission was to reaffirm to the long-suffering citizens of Hutchinson that every step was being taken to find and vent the gas that had disrupted their lives and their community.

C. University of Wisconsin high-altitude mission

NASA surveyed its contractors and labs around the country to find an appropriate instrument that could be deployed as soon as possible. An investigator from the University of Wisconsin was about to deploy to Oklahoma on a long-planned mission using a High-resolution spectral Imaging Spectrometer (HIS) instrument mounted in an ER-2 aircraft (civilian version of the U-2 spy plane). It would be easy to divert from scheduled flights to make a single pass over the Hutchinson area. Survey geologists laid out a simple flight plan that went from northwest of Yaggy, southeast over the city to the Barton oilfield. The limitation of the HIS is that it has a ground footprint of about 2 kilometers on a side, in part because it typically flies at altitudes over 60,000 feet.

The mission took place over Hutchinson on March 31, and results were reported on April 20. In short, they found no significant amounts of methane above normal background levels in the study area.

D. Jet Propulsion Lab deployment to Hutchinson

An Airborne Emissions Spectrometer (AES), at Caltech's Jet Propulsion Lab (JPL) in Pasadena, California, was available but needed the proper aircraft to deploy. All the NASA aircraft generally used were committed to other missions around the world. JPL leased a Twin Otter aircraft out of Las Vegas and shipped the AES there, where it was mated to the plane. The Twin Otter is a twin-engine plane designed for freight or up to about 20 passengers with the ability to fly "low and slow" and land on short runways. The JPL AES instrument usually flew on significantly larger aircraft like the DC-8. In order to fit the AES into the Otter, it was mounted backwards from normal installation and special modifications had to be made to the fuselage.

The AES instrument is another experimental device that was being tested as an analogue for a satellite expected to be launched in a few years. It had never been used in this kind of operation. Although the footprint was just tens of feet on a side, NASA and JPL cautioned that this was not an emergency response operation but rather an opportunity for them to test the instrument in a unique environment. Everyone was concerned about raising expectations too high.

A mobile weather van from the National Severe Storms Lab in Oklahoma arrived to launch daily weather balloons during the JPL flights to calibrate atmospheric conditions. Corrections to the AES readings needed to be made especially for wind speed and direction.

Field checks were made, with the flight crew and science team, of the larger venting wells and geysers. The initial flights targeted the vent wells in Yaggy and the west part of the city. Detailed grids were flown on multiple days over selected areas.

Because of the unusual flight configuration and rapid deployment, the processing and interpretation of the collected data has taken much longer than anticipated. Methane was definitely detected in the atmosphere over Hutchinson, but whether it was above the normal background level has not yet been determined.

VI. "HUTCHINSON IS SAFE"

Prior to the Hutchinson town hall meeting on March 29, officials from KDHE, KGas, the City, and the Survey met and reviewed our progress and status. For a number of weeks, KGas had contacted the Survey and asked if we had any locations for vent wells we wanted or recommended be drilled and our answer had been "no." We could not identify any areas of potential gas that had not already been drilled.

Gas flow rates and pressures continued to decline. We believed we had at least a framework understanding of the geologic mystery, even if we did not know all the details.

That night the Survey told the town meeting that from a "geological viewpoint, the city is safe." Company and city officials reported on their progress as well. The next day, the city announced that the Big Chief Mobile Home Park was authorized to re-open. The last of the evacuees would be allowed to return home. The message heard by citizens and reported by the newspaper was that the crisis was over.

VII. JULY RESURGENCE OF FLARING GAS

A. Sixth-month surprise

Deep Drilled Vent (DDV) well 64 suddenly started venting gas at high pressure on Sunday afternoon, July 7. The flare on Monday was reported at 14 feet in height and the pressure as 330 psi. KGas made some mechanical modifications to the surface piping and the flare reached an estimated 30 to 40 foot height by Monday night. Pressures dropped to only 6 psi by Wednesday; when the well was temporarily shut in, however, the pressures increased quickly.

The resurgence of pressurized gas caught everyone by surprise. KGas sought to sooth public anxiety by noting that the more gas flared meant the less gas left under the city. The Survey noted that DDV 64 had been shut in two weeks earlier for a pressure build-up test.

B. Investigating the causes

Three possible causes were identified. The first of these is formation or near-wellbore damage. The flow of water and gas through the near-wellbore environment can effectively choke off the permeability by plugging the rock with fines materials, chemical alteration, or by changes in relative permeability as the volume of gas drops relative to the volume of water. These kinds of "damage" routinely occur in oil and gas fields. It generally requires the well operator to stimulate the well to restore flow.

Our guess was that DDV 64 had been experiencing some form of near-wellbore damage. A pressure shock might have occurred upon completion of the pressure build-up test when the well was put back on production. Additional tests and data collection are necessary to determine if near-wellbore damage is operative and what form it is taking.

The second possible source of the resurgence of pressurized gas flow is from segmented pockets or fractures of gas. When the gas first entered Hutchinson it was under high enough pressure that we speculated it could have forced open previously closed fractures in the rock layers or pushed its way into areas of tight rocks. If this were the case, as pressures dropped, it is possible that some fractures would have closed up again, isolating small amounts of gas in separate pockets. Over time, the gas in one of these small pockets could have worked its way back into the main accumulation and into the vent well.

The third possibility is that there is another source of gas besides the Yaggy field. Yaggy had shipped substantial amounts of gas out since the crisis began in January no new gas has been pumped into the field. Pressure in some pods at Yaggy was being reduced to a cushion level, intended to keep the salt jugs from collapsing. Some gas was stored at slightly higher pressures to use in case of emergency demand from customers.

The problem with this possibility is that no other wells gave any evidence of increased pressure or volume. DDV 64 sits in the midst of a swarm of vent wells. It is hard to project a new source of gas that would affect only this one well.

C. More surprises?

All three of the possible causes listed above could apply to the entire gas zone underground. On that basis, it is possible that the other wells could experience a resurgence similar to DDV 64. It is important to determine the cause of the re-pressurization and implement measures to keep the wells venting without being plugged or having small pockets becoming isolated.

VIII. LOCATING THE OLD BRINE WELLS

A. As many as 160 wells buried under Hutchinson

The brine wells that carried gas to the surface from 200 to 300 feet below ground were drilled by farmers, small businesses, and corporations starting in the late 1800's. Typically, they cased only the upper part of the drill hole through the shallow aquifer then drilled into the upper part of the salt layer with an open hole. Thus, a 500-foot deep hole might only be cased in the top 200 feet or less. When these wells were abandoned, the procedures varied greatly. Some were filled with whatever materials happened to be handy – rocks, bricks, dirt, etc. Some had caps welded on the tops of the surface casing. Some were just left as they were, open all the way to the salt layer.

The city and KDHE are reviewing title records and aerial photos taken in the 1930's prior to urban development in the area, to try to locate many of the old brine wells. Estimates of the number of wells vary widely, but there may be about 160. Some are readily visible at the surface, but many were buried purposely or by subsequent development. A concern is that some may lie under buildings and foundations and may be almost impossible to locate.

The city and the state want to find all the wells and properly plug and abandon them, at an estimated cost of $60,000 per well or almost $10 million for all the wells.

B. Electromagnetic detection method

Survey geophysicists considered a variety of techniques throughout the crisis that could be employed to find buried brine wells, but they focused mostly on properly locating the vent wells. Once we felt that all the wells needed had been drilled, we turned greater attention to finding brine wells.

We had had success using an electromagnetic (EM) instrument in other projects and arranged to take a rented one to Hutchinson for trials. The EM device measures the earth's electromagnetic field and distortions caused by conductive objects. The instrument makes measurements using a range of frequencies that allows us to create a three-dimensional image of the subsurface. High frequencies get attenuated quickly and do not penetrate very deep. Lower frequencies can penetrate more deeply. By comparing low to high frequency responses, the investigator can see if an object extends horizontally, such as a pipeline might, or vertically, as a well casing might.

In a 200- by 100-foot test plot, over 40,000 measurements were made with the EM device and stored in its computer. This allowed a highly detailed electromagnetic map to be made for each of a suite of different frequencies, or in effect, different depths. Anomalies identified on the maps were dug up by city workers with a backhoe to test the Survey's predictions. One previously unknown brine well has been confirmed to date.

As a result, the Survey purchased a new $15,000 instrument and city workers were trained on its use. Workers laid out survey areas and recorded the data. The computer files were sent electronically to the Survey offices in Lawrence where they were interpreted and recommendations made on where to dig.

The city is now hoping to acquire some temporary help (perhaps college students) to continue EM surveys of suspected brine well locations.

C. Microgravity detection method

The city's geologic consultants proposed making microgravity measurements to attempt to detect the tiny changes in the earth's gravity over the salt caverns associated with the brine wells. The Survey reviewed the proposal and cautioned that the gravity meters available were barely sensitive enough to detect the expected variations in the gravity field.

The city decided to fund this study to ensure that every reasonable approach was undertaken to identify the old brine wells. Results are not yet in on this project.

IX. SHOULD YAGGY BE RE-OPENED?

A. Loss of Yaggy storage will impact Kansas and the nation

The Yaggy storage field is one of 30 "hubs" in the national gas distribution system. It is a rapid response supplier because gas can be quickly removed from the salt cavern jugs during periods of peak demand. It is a key element of gas supply in central Kansas and has a national impact given the tight supply situation.

The Yaggy field is also a significant economic investment. Some estimates are that the value of the facility is in the range of $100 million. Is it realistic to consider permanently shutting down this operation?

Many residents of Hutchinson have demanded that Yaggy be closed and never re-opened. Many others express concern that if it does re-open, proper safeguards be in place to prevent a repeat of the crisis. Some question whether Yaggy can ever be operated to guarantee peace of mind to the city.

B. Regulations insufficient

The Kansas Legislature held three formal hearings on the Hutchinson crisis. One of the revelations of those hearings was that KDHE did not realize they had regulatory oversight of underground gas storage in former oil and gas fields. It appeared that the 13 operating fields in Kansas were not being monitored by anyone at the state level.

The city's geologic consultant described what he saw as deficiencies in the Kansas regulations and outlined what other states required for similar operations.

C. Legislature sets 2-year moratorium

KDHE has few duties related to the petroleum industry compared to the Kansas Corporation Commission, which regulates oil and gas exploration and production. This led to proposals in the legislature to turn over regulation of all underground gas storage to KCC from KDHE. In the end, the legislature passed a bill leaving regulation with KDHE but requiring a two-year moratorium on re-opening Yaggy while new regulations were drafted, reviewed, and adopted.

D. New estimate of gas loss is twice that initially reported

From the earliest days of the crisis, city officials challenged KGas's estimates of 73 MMcf (million cubic feet) of gas lost from Yaggy. The city's geologic consultant interpreted pressure records from the S-1 jug and concluded the amount was many times larger than reported. Hutchinson mayor Patrick McCreary told the Hutchinson News that 300 MMcf of gas was lost. KGas admitted that some amount in excess of the 73 MMcf of gas was lost but they had not been able to finalize those calculations.

In a letter to KDHE, the city, and the Survey from KGas on May 10, they reported a revised estimate of gas lost as 143 MMcf plus or minus 23 MMcf.

X. UNDERGROUND NATURAL GAS STORAGE

A. A growing industry

According to the Energy Information Agency (EIA) of the U.S. Department of Energy, in 2001, there were 27 gas storage operations using salt caverns. The Yaggy field is one of those. Some reconditioned salt mines are also being used for gas storage. There are 348 depleted oil or gas fields being used for natural gas storage in the nation and 40 storage sites where gas is injected into shallow aquifers like the type that carry ground water. There is work underway to use hard-rock mine workings for gas storage as well, but none are operational in the U.S.

In Kansas, the Yaggy field is the only underground natural gas storage field in a salt cavern. We also have four underground propane fields in salt caverns, but these contain liquids at relatively low pressures. There are thirteen gas storage operations in depleted oil and gas fields. In these latter fields, pressures are comparable to those when the fields were naturally producing oil and gas.

B. Similar leak in East Germany in 1988

Although the leaking of high-pressure natural gas from a salt cavern is unique, the role of geology in directing underground leaks is not. In April 1988, an underground storage facility for ethane in a salt cavern near Leipzig, developed a serious leak in a pipe. The ethane spread into an aquifer and found its way upwards through an aquitard along a fault zone. From there it flowed into another aquifer and spread out laterally, doming up the ground and breaking through to the surface as a mixture of water, ethane, and boulder clay. Craters formed out of which the boulder clay was ejected into surrounding fields. Fissures developed along the gas pathway. Nearby buildings cracked and concrete road slabs tilted. A scientific report published in 1996 concluded that the migration path of the ethane was controlled by the geologic structure.

C. Industry tries to understand what happened and why

The Solution Mining Research Institute (SMRI) in California has 90 corporate members worldwide that are watching developments in Hutchinson closely. Their director testified to the Kansas Legislature that nothing like this had ever happened before anywhere in the world. Some European projects might be on hold while they evaluate the consequences of the crisis. SMRI was emailing or faxing daily reports during much of the crisis to all its members.

A representative of a farmer's group in northern England contacted the Survey to find out more about what happened at Yaggy and Hutchinson. A similar facility is apparently under consideration for their area and they are concerned.

XI. WHAT'S LEFT?

A. Is the geologic model correct?

The fractured dolomite theory is plausible but not confirmed. Test results on the core through the producing zone in well DDV 67 are not available and the core has not yet been turned over to the Survey for additional study. None of us expected that a narrow band of dolomite could serve as a high-speed pathway for natural gas. None of us are yet convinced that this is the whole story.

B. How did the leak occur?

Video images of the S-1 wellbore clearly show a curved slice through the casing. How and when did it occur? And once the casing was breached, how long was it before the gas was able to move up along the casing to the shallower geologic layer that carried it towards Hutchinson? Was the cement behind the casing (between the casing and the borehole) intact, or did high-pressure gas eat a path through it over time? Is it possible the gas found a vertical pathway through the salt to the shallow layer?

C. How long until all the gas is vented?

City officials have asked from the beginning how much gas was lost at Yaggy and how much vented from vent wells and brine wells. With that information, they hoped to calculate how much gas remains under the city. KGas has declined to make such estimates. The Survey is reluctant to try to make similar guesses because there is too much uncertainty about the amount of gas flared.

Instead, we asked KGas to monitor flow rates and pressures at vent wells. This information, along with pressure build-up and draw-down tests, could allow us to treat the remaining gas under Hutchinson as if it were a reservoir being produced as gas fields are normally. By calculating how much the pressure drops with a given amount of production, it is theoretically possible to project how long it will take for the gas pressure to drop to the hydrostatic level. At that point, we would consider the gas to be effectively depleted, even though some residual gas will remain in pore spaces and fractures in the rock.

D. Under what conditions can Yaggy re-open?

Many unanswered questions remain about the geology of Yaggy. At least one observation well in the field failed to intercept gas at the producing horizon, indicating that the geologic pathway (the fractured dolomite zone?) may be just as narrow and restricted under the field as it is under the city. Was it a horrible coincidence that the leaking well just happened to hit the one conduit that would carry gas towards the city? Are there other conduits in different areas of the field that need to be identified and mapped?

The Survey would like to collect additional seismic reflection data on lines surrounding the field. These need to be correlated with detailed analyses of geologic and geophysical data from the Yaggy wells.

Some have suggested the installation of perforated or slotted monitoring pipes adjacent to all storage wells in Yaggy. Then, if there were ever a leak from a well, gas would show up at the surface in the pipe where it could be easily detected. Another suggestion is to drill a bank of wells across the pathway (and any other pathways found) to Hutchinson to act as interceptors and vent any gas that might escape from the field.

All of these ideas and others will be discussed as KDHE continues its two-year long review and revision of regulations controlling Yaggy.

E. Finding and plugging the brine wells

Use of the EM device to locate buried brine wells seems to be successful. However, the instrument response in some of the areas that need to be explored cannot be predicted. For that reason, the exploration process is considered still experimental. If we can test the technique in a variety of settings and create, in essence, a catalogue of responses, we can turn over the search effort to city workers and contractors. The Survey would then move into an advisory role.

F. What do we do next?

The Hutchinson gas crisis has been a continuing series of geologic surprises and unexpected complexities from the beginning. We have a general understanding of what happened and why, but the details and the confirmations are to varying degrees still unknown.

The Survey is developing a three-year work plan to answer many of the questions listed above. This is not merely an academic exercise. Important issues remain about the vulnerability of the city of Hutchinson and the possible re-opening of the Yaggy storage field. A complete post-mortem is needed to understand what regulatory reforms are needed. And lastly, we want to ensure that this catastrophe never occurs again, either here or at any of the other locations where high-pressure gas is stored.

ACKNOWLEDGEMENTS

The Kansas Geological Survey's response to the Hutchinson gas crisis was and continues to be a team effort with exceptional contributions from many of our scientists and technicians. Rick Miller and his seismic crew including Joe

Anderson and Dave Laflen, worked long hours in a cold January to collect superb quality data on the subsurface geology. Dr. Jianghai Xia and Dr. Susan Nissen processed these data and identified the geologic pathways for natural gas that were successfully drilled by Kansas Gas. Dr. Xia is now exploring for old brine wells under the city. Dr. Lynn Watney integrated the vast amounts data from drilling operations, geophysical well-logs, geological samples, and subsurface maps to unravel the complex geology under the city. Dave Young continues to work with the groundwater management district to monitor and evaluate water quality, and created our website on the crisis. Saibal Bhattacharya performed the calculations to determine how gas could travel many miles in a short time. He is currently analyzing pressure data to calculate how long gas may continue to vent. Rex Buchanan helped keep all the parties involved fully informed about new information and interpretations. Bill Bryson advised on the operational and regulatory history of Yaggy. Many others, including Alan Byrnes, Dr. Tim Carr, and Dr. Greg Ohlmacher, brought their expertise to bear on specific questions and problems during the past six months.

The contributions the Survey has made to the situation are due to the professionalism and dedication of this team. The other factor that needs to be recognized is the tremendous cooperation the Survey received from city, county, state, and federal collaborators, company representatives, and the citizens of Hutchinson.