Compressed Air Energy Storage (CAES) Act
KCC Rule Development

KCC Open Meeting, Issue 3.– Final
June 16, 2010
Richard M. Valenti

Presentation Outline:

1. Kansas Wind Facilities (9 Active Wind Farms)
2. Regulatory Background (House Bill 2369).
3. Surface Plant Evolution (Three).
4. Underground Storage Types (2 – Cavity & Porosity Storage).
5. Solution Mine Salt Cavity (2 Active Facilities).
   A. CAES Regulatory Permits (Four + ?).
   B. Facility Concerns Overview.
   C. Design Parameters.
      1) Cavity Size
      2) Pressure / Depth (>1700').
      3) Salt Creep Convergence (?).
      4) Temperature (?).
      5) Rate (?).
      6) Kansas Salt Formations (Three).
   D. Technical Concerns.
   E. Kansas CAES Application (Yes, with proper design).
6. Excavated Salt Mine (No active facilities)
   A. Pressure / Depth Sensitivity (Shallow depth Limits).
   B. Kansas CAES Application (Yes?).

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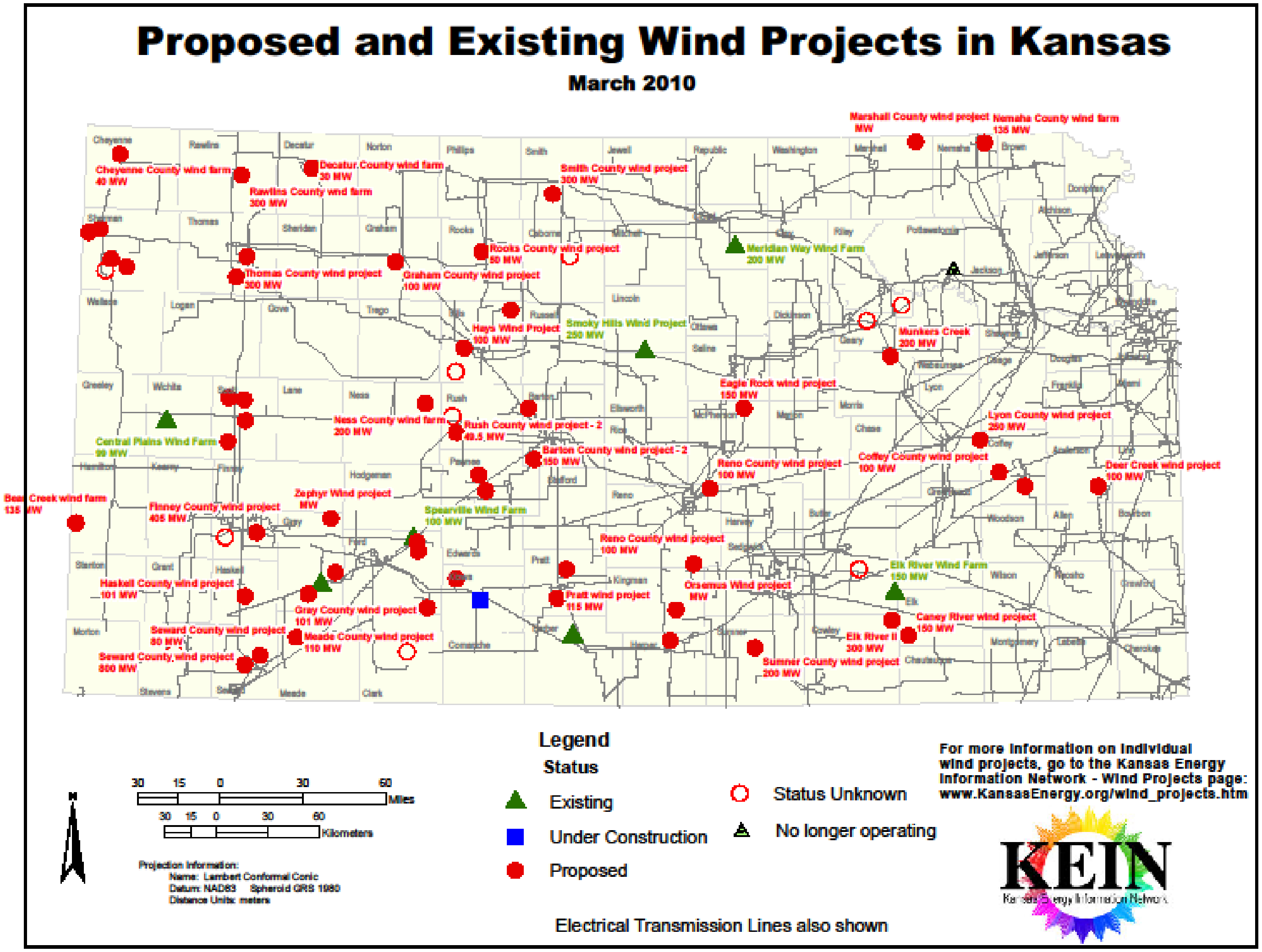
Kansas Wind Facilities

9-Active Facilities.



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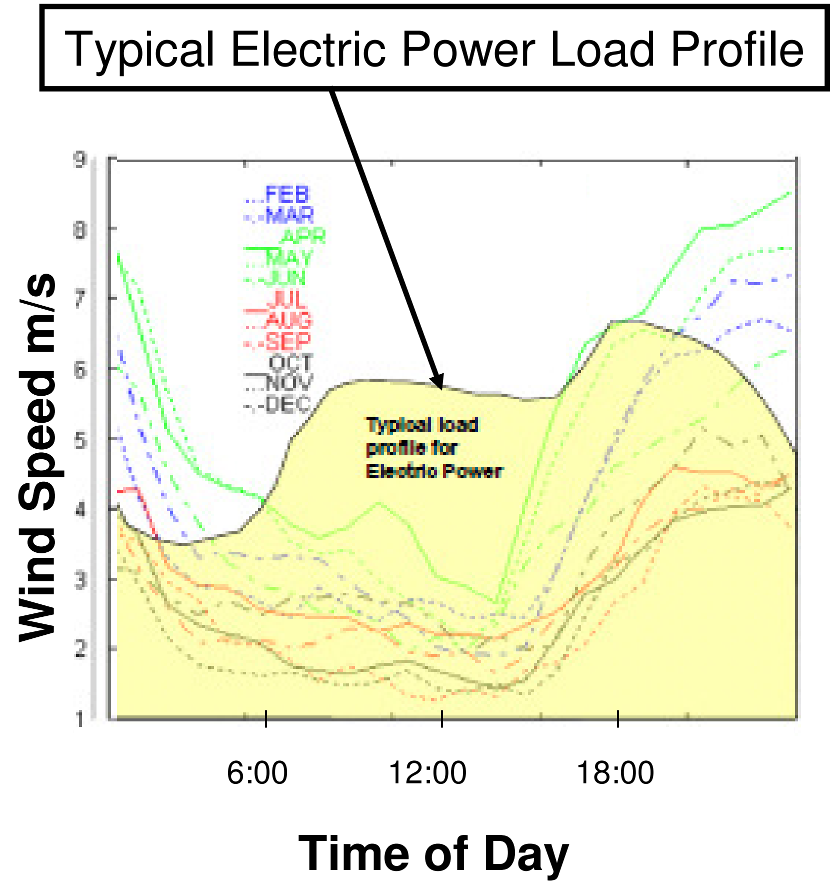
Kansas Wind Facilities

Spearville Wind Energy Facility - 100 MW

Nocturnal (Dracula) Wind Power Generation.



(New Mexico VLA Site)

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CAES Regulatory Background

Compressed Air Energy Storage Act.

K.S.A. Supp 66-1272 through 66-1279 and amendments (Senate substitute for House Bill 2369).

Statute became effective on July 1, 2009.

KCC has 18 months from the effective date to establish CAES rules and regulations.

K.A.R 82-3-1200 series CAES Regulations

CAES Regulatory Background.

K.S.A. Supp 66-1274.

KCC "shall establish rules and regulations establishing requirements, procedures and standards for the **safe and secure injection of compressed air into STORAGE WELLS**, which shall include **maintenance of UNDERGROUND storage** of compressed air."

<u>CAES Regulatory</u> <u>Background.</u>
K.S.A. 66-1274 shall specifically address:

1. Site selection,
2. Design and development,
3. Operation criteria,
4. Casing requirements,
5. Monitoring and measurement requirements,
6. Safety requirements,
7. Public notification,
8. Closure and abandonment requirements,
9. Financial assurance,
10. Long-term monitoring, and
11. KCC may adopt rules and regulations establishing fees for permitting, monitoring and inspecting operators of CAES wells and underground storage.

CAES Regulatory Background.
K.S.A. Supp 66-1275.

KDHE "shall establish rules and regulations establishing requirements, procedures and standards for the **monitoring of AIR EMISSIONS** coming from **compressed air energy storage wells and storage facilities** to ensure the wells and facilities comply with the Kansas air quality act."

NOTE: Includes underground or surface storage facilities.

CAES Regulatory Background.
K.S.A. 66-1276 MOU between KCC - KDHE

MOU Components:

1. Jurisdiction
2. Funding
3. Emergency Response.
4. Penalties
5. Notification of Penalty Orders.
6. Filings.
7. Overlapping Requirements

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CAES Regulatory Background.

K.S.A. 66-1277, The KCC upon finding: violations; penalties; hearing; judicial review.

K.S.A. 66-1278, KCC and agents; right of ingress and egress; restoration of premises.

K.S.A. 66-1279, KCC administered compressed air energy storage fund.

CAES Regulatory Background.

KCC Rules and Regulations (K.A.R. 82-3-1200) will be modeled after the following programs:

K.A.R. 28-45 KDHE (LPG); 9 Active Facilities; (520 Wells).

K.A.R. 28-45(a) KDHE (Natural Gas);1 Inactive Facility; (80 Wells).

K.A.R. 28-45(b) KDHE (Crude Oil); 0 Facilities.

K.A.R. 28-46-45. KDHE (Class III); 4 Active Facilities; (230 Wells).

K.A.R. 82-3-1000 KCC (Porosity Gas Storage) **18** / **7**Active Facilities; (862 / 105 Wells).
Total / **KCC**

K.A.R. 82-3-1100 KCC (CO_2 Storage) 0 Facilities.

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CAES Surface Plant Evolution.

Policy Support for Energy Storage
ARRA-Act 2009 shovel ready CAES units.

1. DOE Smart Grid funding, designated $50-$60 million for two utility scaled construction of CAES units.
   A. PG&E 300 MW plant.
   B. NYSEG 170 MW plant.

2. Proposed 20 % Investment Tax Credit.

3. "Clean Energy Bank" loan guarantees.
   CAES units qualify for these loan guarantees

CAES Surface Plant Evolution.

1. 1st Generation CAES – 1 active **290 MW** facility.
   - Huntorf CAES, Hannover, Germany – Active Dec'78

2. 2nd Generation CAES – 1 active **110 MW** facility.
   - Power South (AEC) CAES, McIntosh Al. – Active Jun'91

   Compressed Air Production Side. More efficient surface facility use of recuperator (heat exchanger) and expanders (turbine) to generate electricity.

3. 3rd Generation Adiabatic CAES – no active facilities.

   Compressed Air Injection Side. Heat from the compression cycle is stored (not lost) and used to preheat the air during the electric generation cycle. Natural gas is not burned to reheat gas during power generation cycle.

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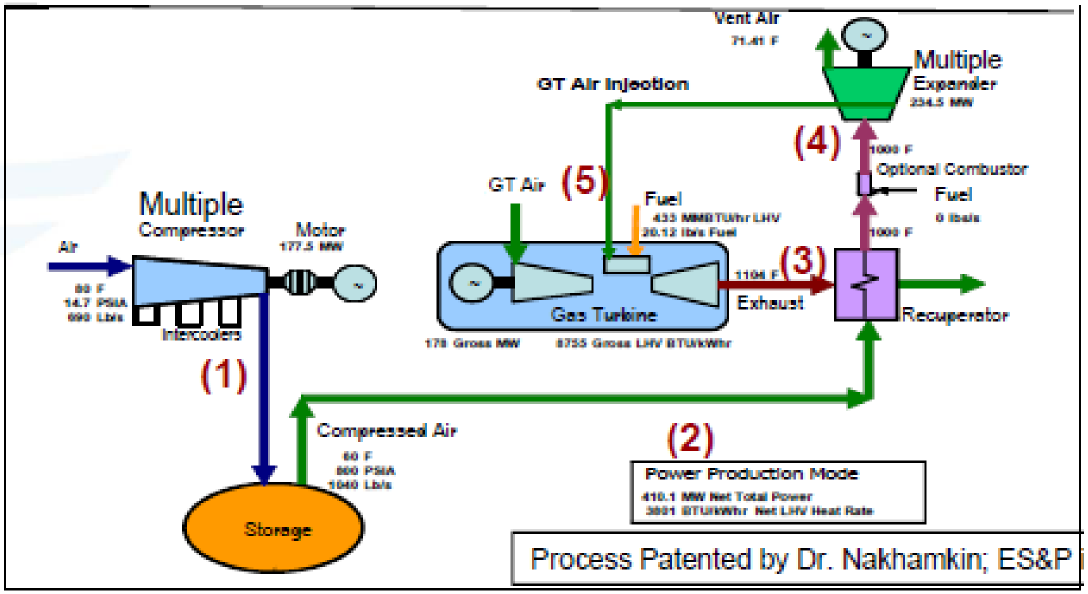
CAES Surface Plant Evolution.

CAES Plant 2nd Generation Overview:



1. Air is compressed into an underground storage facility. Compressor Inter coolers and after coolers reduce air temp before injection into underground storage. Monitor Injection Air Temp, Pressure & Rate?

2. The pressurized air in underground storage is released; Underground storage limitations: Size, Pressure, Temp & Rate?

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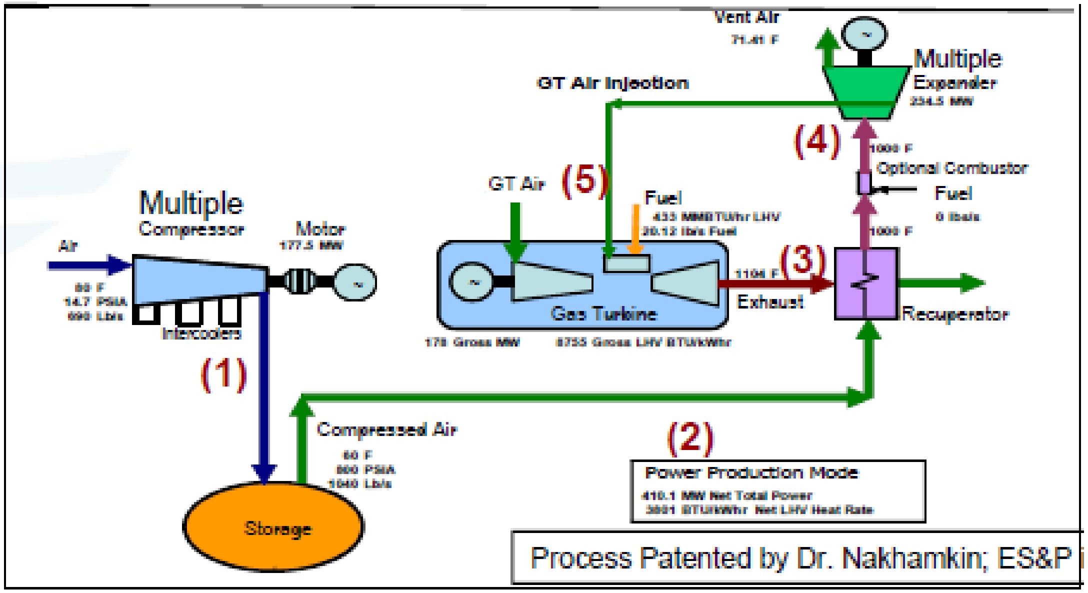
CAES Surface Plant Evolution.

CAES Plant 2nd Generation Overview :

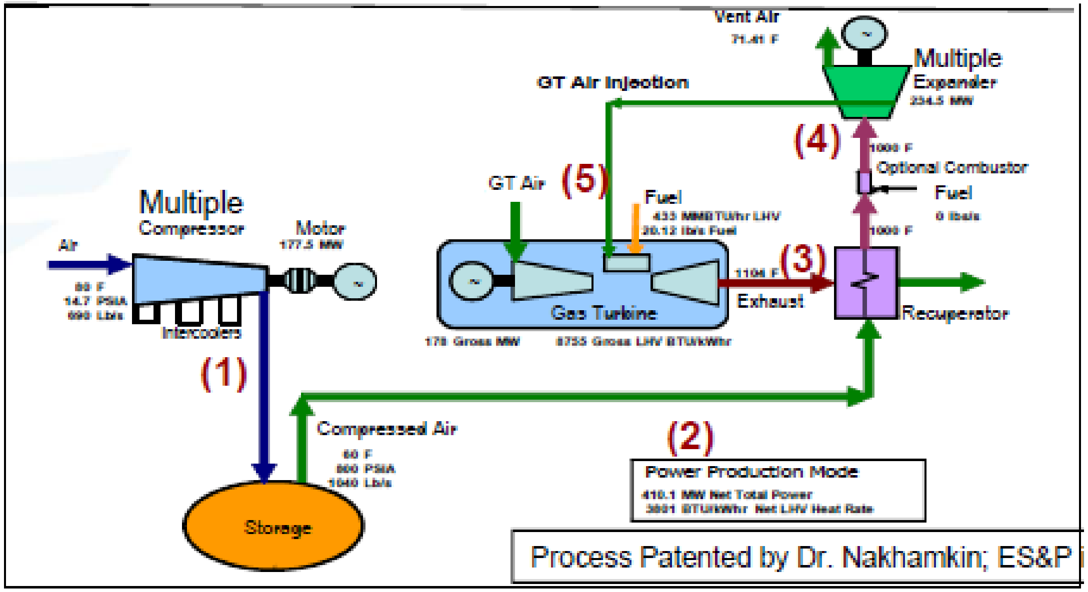


3. Small natural gas-fired combustion turbine is activated, generating power and also producing exhaust heat which is combined with the cool, expanding air in a recuperator (heat exchanger).

4. The heated, expanding air flows through an expander (a turbine), creating electricity.

CAES Surface Plant Evolution.

CAES Plant 2nd Generation Overview :



5. The air flowing through the expander is routed to the natural gas fired turbine which increases the megawatt output.

CAES Surface Plant Evolution.

Match Surface Turbo-machinery with Underground Storage Vessel (Existing Equipment):

Equipment Manufacturer	Plant Size (MW)	Minimum Inlet Pressure (psi)	Minimum Flow Rate (lbs/MW hr)	Total Min. Flow Rate (lb/hr)	Min Flow MMCFPD
Allison	15	200	9500	142,500	45
ABB	50	700-800	9500	475,000	149
Dresser Rand	134	830	9500	1,273,000	400
Alstom	300	900	9500	2,850,000	896
Westinghouse (501D5)	350	750	9500	3,325,000	1,046
Westinghouse (501F)	450	750	9500	4,275,000	1,345

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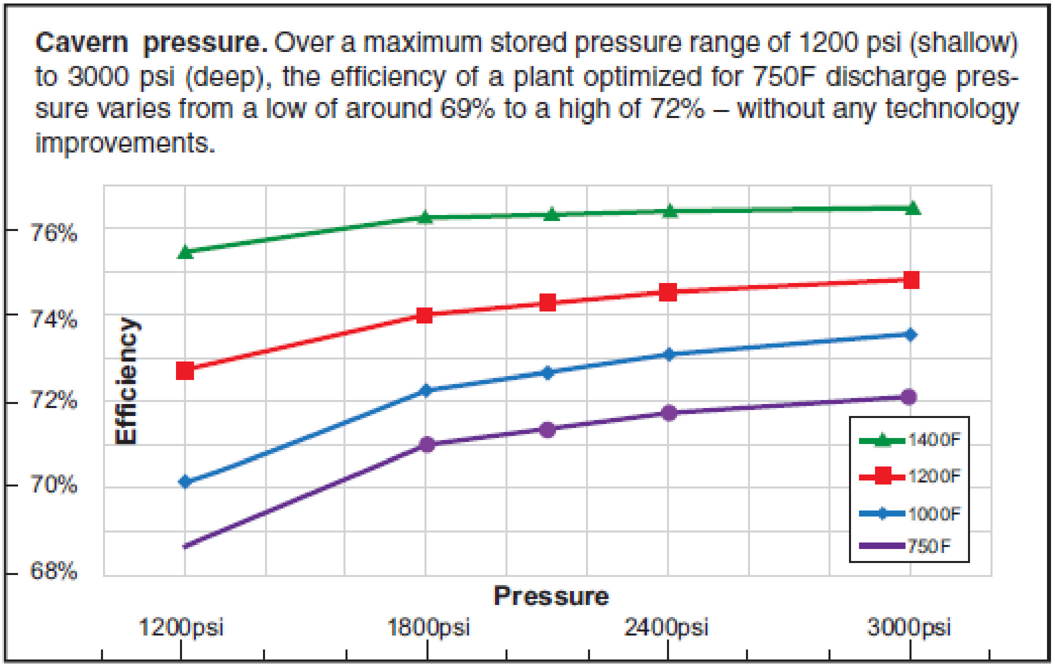
CAES Surface Plant Evolution.

Surface Plant Efficiency Increases by 3.5% IF Underground Storage Pressure Is Increased to 3,000 psi.



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CAES Underground Storage Types:

1. Cavity Storage.

A. Solution Mined Salt Cavity.

- Huntorf CAES, Hannover, Germany – Active
- Power South (AEC) CAES, McIntosh Al. – Active

B. Excavated (Salt or Limestone) Mine Cavity.

- First Energy CAES, Norton, OH – Proposed
- Pacific Northwest Laboratory, Pittsfield, IL.- Feasibility Study

2. Porosity Storage.

A. Aquifer Geologic Structure.

- Iowa Stored Energy Park CAES, Traer, IA – EPA Experimental Permit application.

B. Depleted Natural Gas / Oil Reservoir

- None

CAES Underground Storage Types:

KCC Proposed Rules & Regulations

1. **Cavity Storage.**
   A. Solution Mined Salt Cavity.
      (830 existing storage & solution mining well inventory.)
      K.A.R. 82-3-1200
   B. Excavated (Salt-Limestone-Gypsum) Mine Cavity.
      (3 active salt mines)
      K.A.R. 82-3-1200a
2. **Porosity Storage.**
   A. Aquifer Geologic Structure.
      K.A.R. 82-3-1200b
   B. Depleted Natural Gas / Oil Reservoir
      K.A.R. 82-3-1200c

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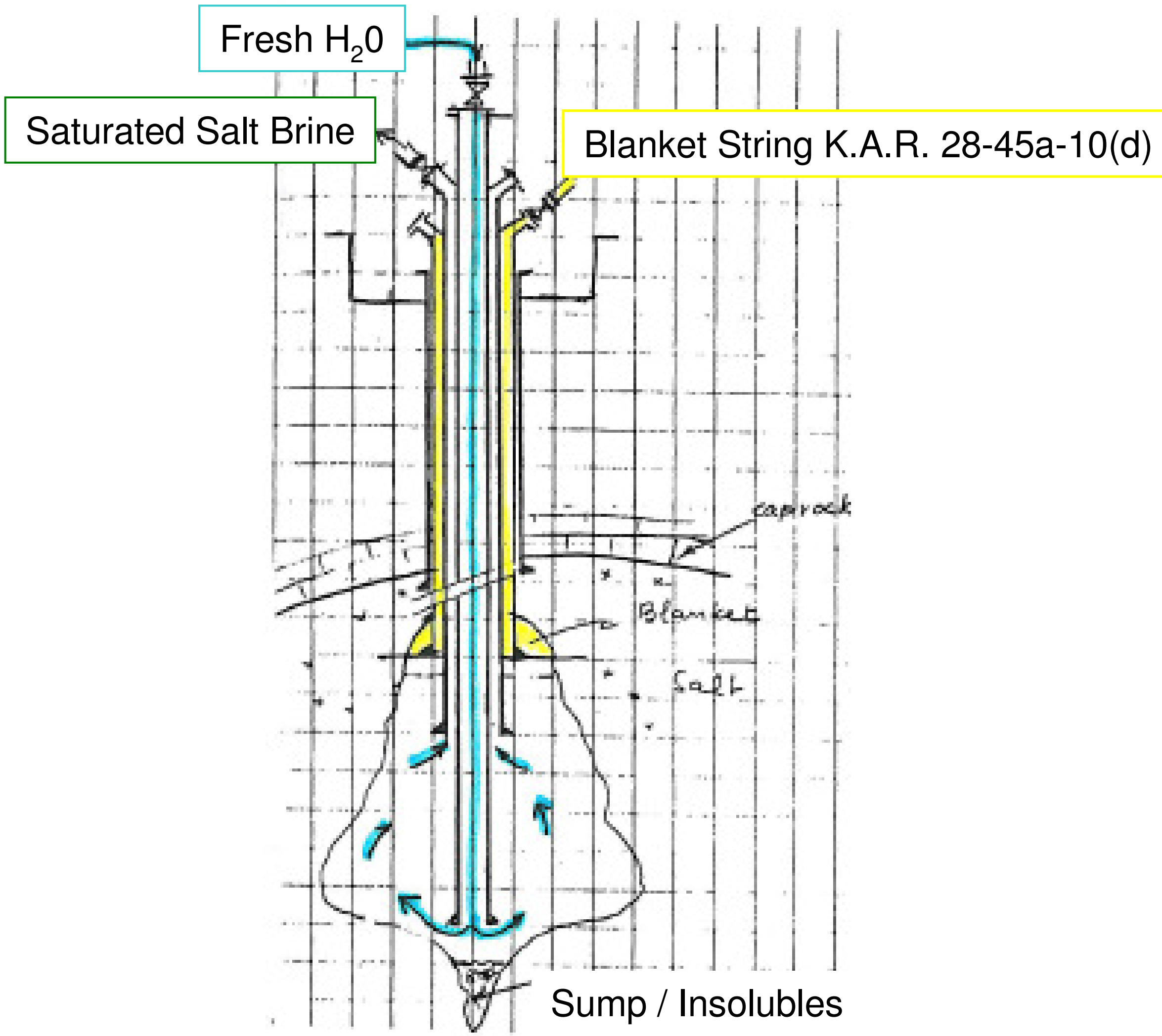
Cavity Storage – Understand Failures

Preventing Problems From Womb to Tomb

(From Drilling to Plug & Abandonment)

Surface crater near the Hutchinson, Kansas
Cargill Salt Co. plant (Nov '74).

Solution Mined Salt Cavity



Direct Leaching Process

Solution Mined Salt Cavity

K.S.A. Supp 66-1274.

KCC “shall establish rules and regulations establishing requirements, procedures and standards for the **safe and secure injection of compressed air into STORAGE WELLS**, which shall include **maintenance of UNDERGROUND storage** of compressed air.”

Note: Does not include the creation of a solution mined salt cavity

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Solution Mined Salt Cavity

CAES Regulatory Permits

1. KDHE CAES Air.
2. DWR Fresh Water Supply (6,900 to 1,900 Acre-Ft).
3. KDHE CAES (Authorization to create salt cavity?)
4. KCC CAES (Include creation of salt cavity?).
5. A. KDHE Class I (Disposal of saturated brine).
5. B. KCC Class II EOR (Disposal of saturated brine).

Solution Mined Salt Cavity

Injection Side Facility Concerns:

1. Surface subsidence due to loss of mechanical integrity (Dissolution of salt).
2. Compressor air intake near the exhaust of the natural gas fired turbine. (Resulting in a toxic underground storage facility.)
3. Production casing corrosion due to oxygen rich compressed air.
4. Compressor after coolers not functioning properly and wet compressed air is injected into underground salt cavity. (Cavern Instability due to dissolution of salt from wet compressed air injection.)
5. Salt roof cavity instability due to improper stabilization of the layered shales in the upper portion of the salt deposit.
6. Thermodynamic heat exchange between underground storage facility and surroundings.

Solution Mined Salt Cavity

Production Side Facility Concerns:

1. Production casing corrosion due to salt water saturated compressed air production.
2. Steel piping systems should be protected with linings or a non-ferrous system installed. Rust caused the Huntorf, CAES facility to shut down after two months of operation.
3. Blanket (oil) materials used to preserve the salt roof during the creation of the salt cavity, will be released at surface during the power generation cycle.
4. Sulfate-reducing bacteria thrive in oxygen rich environments resulting in H_2S production where there was no initial H_2S present. (Flaring H_2S creates sulfur dioxide.)
5. Salt Cavern stability due to compressed air production:
   A. High underground storage withdrawal rates. Turbulent air flow could have potential of producing salt which is detrimental to rotating surface turbo machinery and cavern stability.
   B. Low operating pressures.

Solution Mine Salt Cavern

Design Parameters matching Underground Storage Facility and Surface Turbo-Machinery.

1. Underground Storage Dimensions - Volume:

A. McIntosh Facility:	750' x 240'	19.8 MMCF - 110 MW (26 Hr)
B. Huntorf Facility:	500' x 200'	5.5 MMCF - 290 MW (3 Hr)
C. Kansas LPG Facility:	100' x 160'	1.1 MMCF (200 MBBL)

2. Underground Storage Depth:

A. McIntosh Facility:	1,506'
B. Huntorf Facility:	2,150'
C. Kansas LPG Facility:	<1,000'
D. Kansas Class III Facility:	<1,000'

3. Casing Size (Last cemented Casing in top of salt)

A. McIntosh Facility:	20"
B. Huntorf Facility:	24-½"
C. Kansas LPG Facility:	13-5/8" (Recently 20")
D. Kansas Class III Facility:	7" to 8-5/8"

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Solution Mine Salt Cavern

Design Parameters matching Underground Storage Facility and Surface Turbo-Machinery.

4. Surface Facility Operating Pressure Range.

A. McIntosh Facility: 680 to 1,280 Psi
B. Huntorf Facility: 625 to 1,450 Psi

5. Underground Temperature Injection / Withdrawal.

A. McIntosh Facility: ? 120^{o}F / ? ^{o}F
B. Huntorf Facility: ? ^{o}F / (50^{o} to 105^{o} F)

6. Underground Injection / Withdrawal Rate.

A. McIntosh Facility: ? / 230 MMCFPD
B. Huntorf Facility: ? / 1,071 MMCFPD
C. Saskatchewan Natural Gas: 8 / 20 MMCFPD
D. New Porosity Gas Storage: 250 / 500 MMCFPD

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Solution Mine Salt Cavern

Salt Cavern Volume & Roof Thickness Sensitivity

Conclusion: In order to reduce the total number of CAES wells at a Future Kansas facility: 1. Salt Thickness > 200' 2. Salt Cavern Roof < 150'

McIntosh CAES	Huntorf CAES	
238 Ft. Cavern Diameter	60 meters	197 Ft. Cavern Diameter
119 Ft. Cavern Radius	30 meters	98 Ft. Cavern Radius
753 Ft. Cavern Height	150 meters	492 Ft. Cavern Height
33 MMCF Cylindrical Cavern Volume		15 MMCF Cylindrical Cavern Volume
20 MMCF Actual Cavern Volume		6 MMCF Actual Cavern Volume
59% of Cylindrical Cavern Volume		37% of Cylindrical Cavern Volume

48% Average of McIntoch & Huntorf Cylindrical Cavern Volume

Future Kansas CAES
200 Ft. Hutchinson Salt Thickness
150 Ft. Salt Roof Thickness
300 Ft. Cavern Diameter
150 Ft. Cavern Radius
50 Ft. Cavern Height
1.7 MMCF Estimated Cavern Volume
11.7 Wells Total - Mcintosh
3.2 Wells Total - Huntorf

Future Kansas CAES
200 Ft. Hutchinson Salt Thickness
100 Ft. Salt Roof Thickness
300 Ft. Cavern Diameter
150 Ft. Cavern Radius
100 Ft. Cavern Height
3.4 MMCF Estimated Cavern Volume
5.8 Wells Total - Mcintosh
1.6 Wells Total - Huntorf

Future Kansas CAES
400 Ft. Hutchinson Salt Thickness
150 Ft. Salt Roof Thickness
300 Ft. Cavern Diameter
150 Ft. Cavern Radius
250 Ft. Cavern Height
8.5 Ft^3 Estimated Cavern Volume
2.3 Wells Total - Mcintosh
0.6 Wells Total - Huntorf

Future Kansas CAES
400 Ft. Hutchinson Salt Thickness
100 Ft. Salt Roof Thickness
300 Ft. Cavern Diameter
150 Ft. Cavern Radius
300 Ft. Cavern Height
10.2 Ft^3 Estimated Cavern Volume
1.9 Wells Total - Mcintosh
0.5 Wells Total - Huntorf

Solution Mine Salt Cavern

Maximum Operating Pressure Range:

1. Max. pressure is a function of the depth of the cavity roof.
   - A. McIntosh Facility: 0.90 Psi/Ft
   - B. Huntorf Facility: 0.70 Psi/Ft
   - C. Natural Gas Storage Facilities: 0.7 to 0.9 Psi/Ft
   - D. Kansas Natural Gas K.A.R. 28-45a-10(e)(1): **0.75 Psi/Ft**
   - E. Kansas Crude Oil K.A.R. 28-45b-10(f): **0.80 Psi/Ft**
2. Max. Pressure / Depth Sensitivity
   - A. McIntosh max press surface turbo-machinery: 1,280 Psi
   - B. Huntorf max press surface turbo-machinery: 1,450 Psi
   - C. Future Kansas Facilities:
     1) Salt Cavern Depth To Surface: > **1,700'** = 1,280 Psi / 0.75 Psi/Ft
     2) Salt Cavern Depth To Surface: > **1,900'** = 1,450 Psi / 0.75 Psi/Ft

Solution Mine Salt Cavern

Minimum Operating Pressure Range:

Kansas Natural Gas Storage K.A.R. 28-45a-10(f): "Shall maintain a minimum operating pressure that is protective of cavern integrity."

The minimum operating pressure is a function of:

1. Surface turbo-machinery minimum inlet pressure.
   - A. McIntosh Facility: 680 Psi (0.36 Psi/Ft)
   - B. Huntorf Facility: 625 Psi (0.29 Psi/Ft)
2. Rock mechanics (Salt Creep Convergence).

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Solution Mine Salt Cavern

Minimum Operating Pressure Range:
Salt Creep Convergence.

The rheology of salt under temp and press conditions in cavities give rise to plastic deformation which, in time, results in the loss of cavity volume.

1. Eminence Salt Dome. Selma, Alabama - Natural gas storage facility experienced a salt cavity closure of 40 – 60% within 5 years of storage Operations.
2. Huntorf Germany CAES – No salt creep convergence problems based on historical sonar surveys. The Cavern stability is designed for several months at atmospheric pressure.
3. McIntosh Alabama CAES Facilities – No salt creep convergence problems based on historical sonar surveys.

Solution Mine Salt Cavern

Minimum Operating Pressure Range:

Salt Creep Convergence Models.

Salt cavern closure based on min surface turbo-machinery operating press.

For Cylindrical Cavities

$$\left(\frac{\Delta V}{V}\right) = -200\ A\ \mathrm{Exp}\left(-\frac{Q}{RT}\right)\left(\frac{\sqrt{3}}{2}\right)^{n+1}\left[\frac{2(p_o - p_i)}{n\sigma_c}\right]^n t$$

For Spherical Cavities

$$\left(\frac{\Delta V}{V}\right) = -150\ A\ \mathrm{Exp}\left(-\frac{Q}{RT}\right)\left[\frac{3(p_o - p_i)}{2n\sigma_c}\right]^n t$$

where:

A, Q and n are rheological parameters related to the constitutive temperature dependent creep model.

T is the absolute temperature of the salt in ° K

p_o is the prevailing *in-situ* triaxial pressure in psia (approximately equal to 1 psig per foot of depth)

p_i = the pressure inside the cavity, psia

t = the time for which the closure is calculated, sec.

R is a material parameter of the salt, cal./(mole × °K)

σ_c is a constant used to normalize the stress in the Steady State Power Law by Norton, psi

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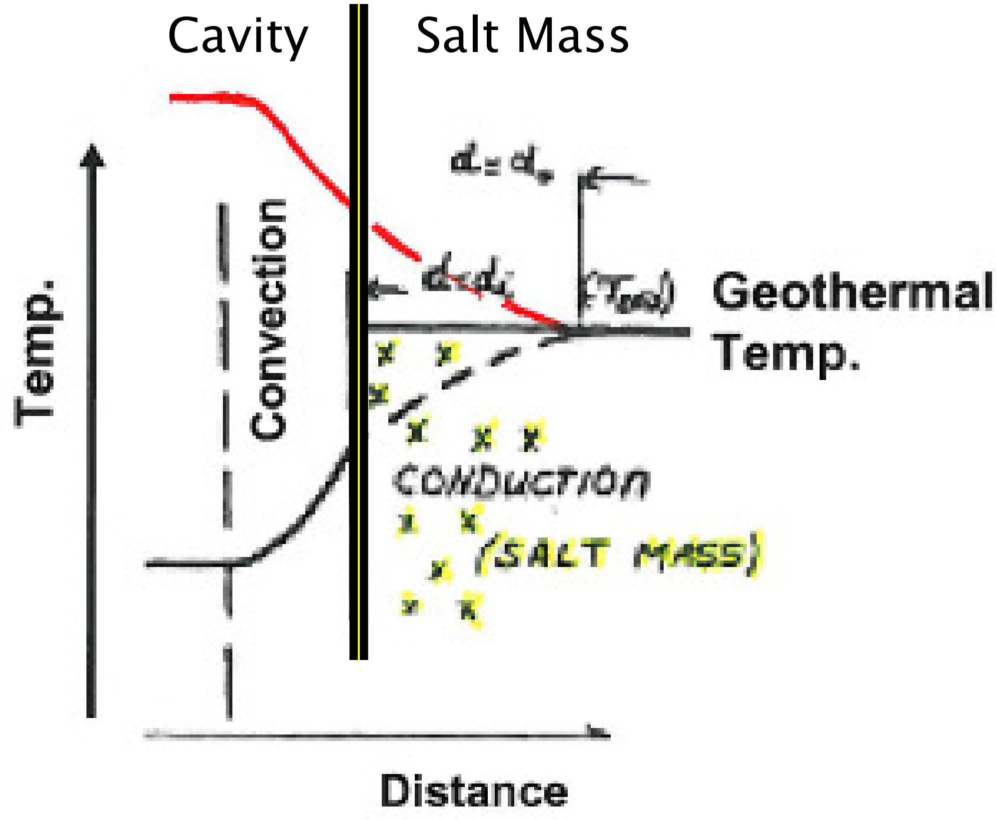
Solution Mine Salt Cavern

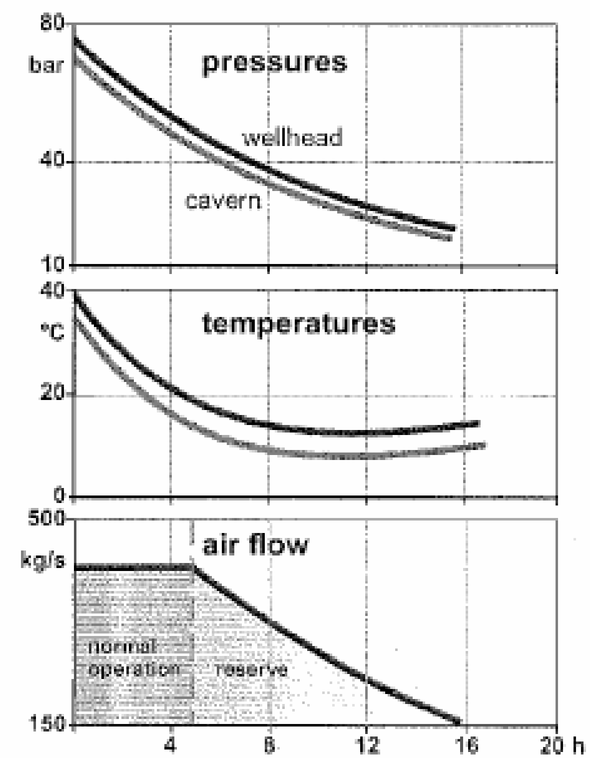
Minimum Operating Pressure Range:
Salt Creep Convergence Solutions.

1. Determine if min operating pressure of surface turbo machinery will cause significant closure of salt cavity?
2. Report when salt cavern pressure is below min operating pressure or when cavity pressure is at atmospheric pressure?
3. Report time duration when cavity is below min operating pressure?
4. Plan for a more frequent cavity integrity test if pressure falls below min operating pressure?

<u>Solution Mine Salt Cavern</u>

Temperature Interaction with Underground Storage Facility.
Injection / Withdrawal Operations. (Highly Complicated Process)





Huntorf Cavern Withdrawal

Solution Mine Salt Cavern

Temperature Interaction with Underground Storage Facility.

Salt cavern stability if compressor inter coolers inject hotter air than surrounding geothermal temp. in salt formation?

1. Increased Salt Creep Rate? (Negative)
2. Increased Storage Volume? (Positive)
3. Monitor Injection temp?

Solution Mine Salt Cavern

Rate Interaction with Underground Storage Facility. Monitor compressed air withdrawal rate?

1. Production casing should be in center of cavity to prevent salt cavern collapse due to:
    1. Wet (fresh) compressed air injection.
    2. High turbulent withdrawal rate. (230 to 1,071 MMCFPD)
2. Huntorf Facility: Packer Less completion with 260’ (53 % from cavern top) of free hanging casing in cavern. Limits salt production during high rate withdrawals.
3. Kansas LPG storage withdrawal operations have optimum saturated brine injection rates to prevent excessive tubing vibration.

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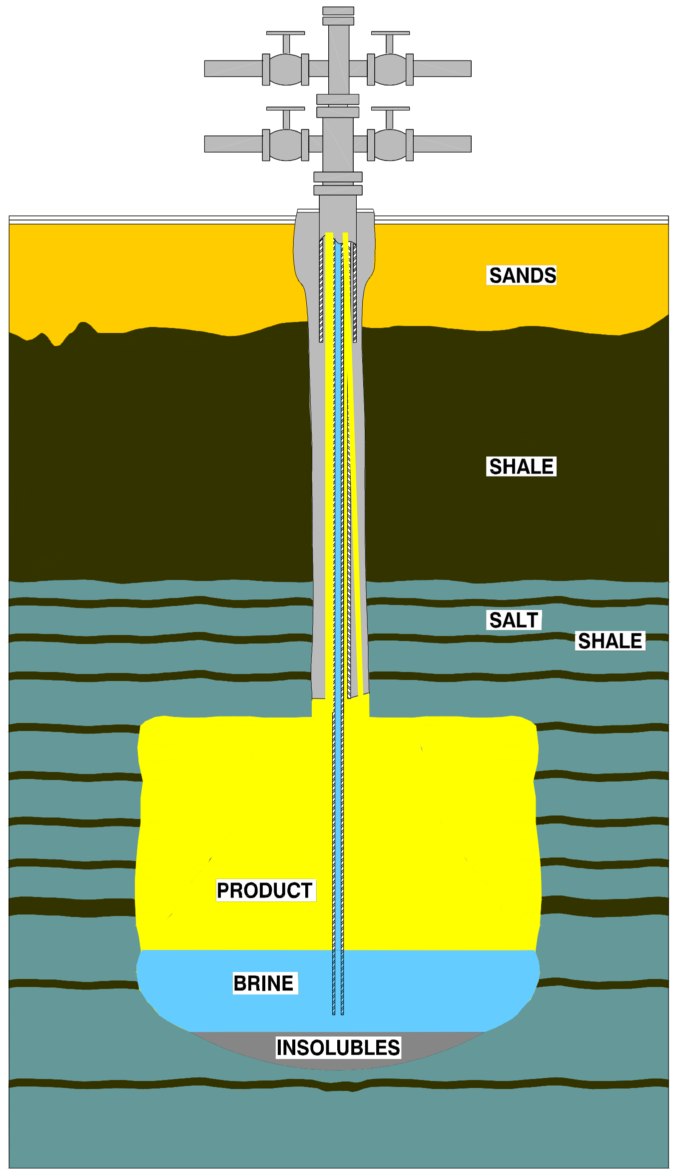
Solution Mine Salt Cavity / LPG Storage Operations



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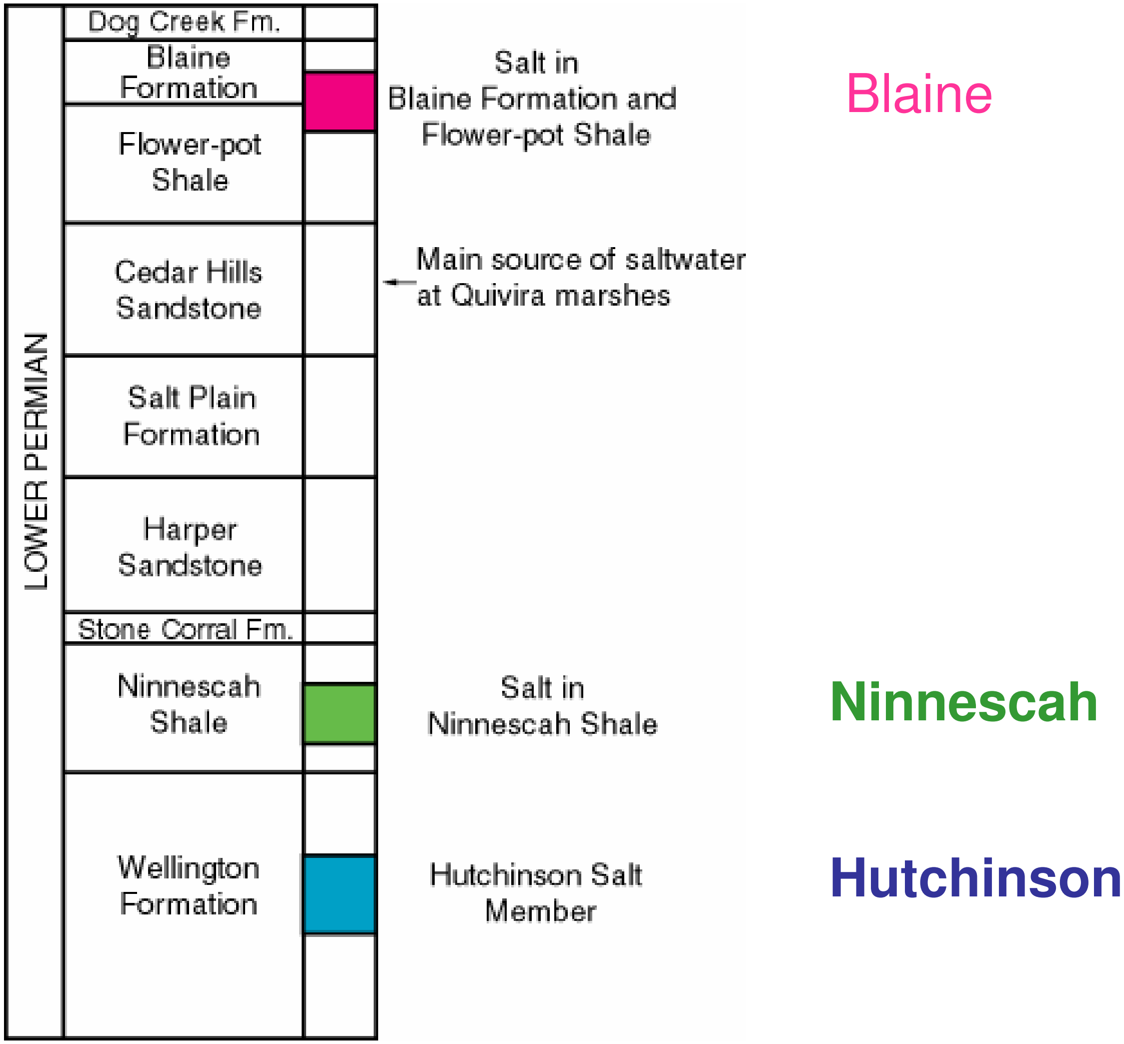
Underground Salt Formations In Kansas



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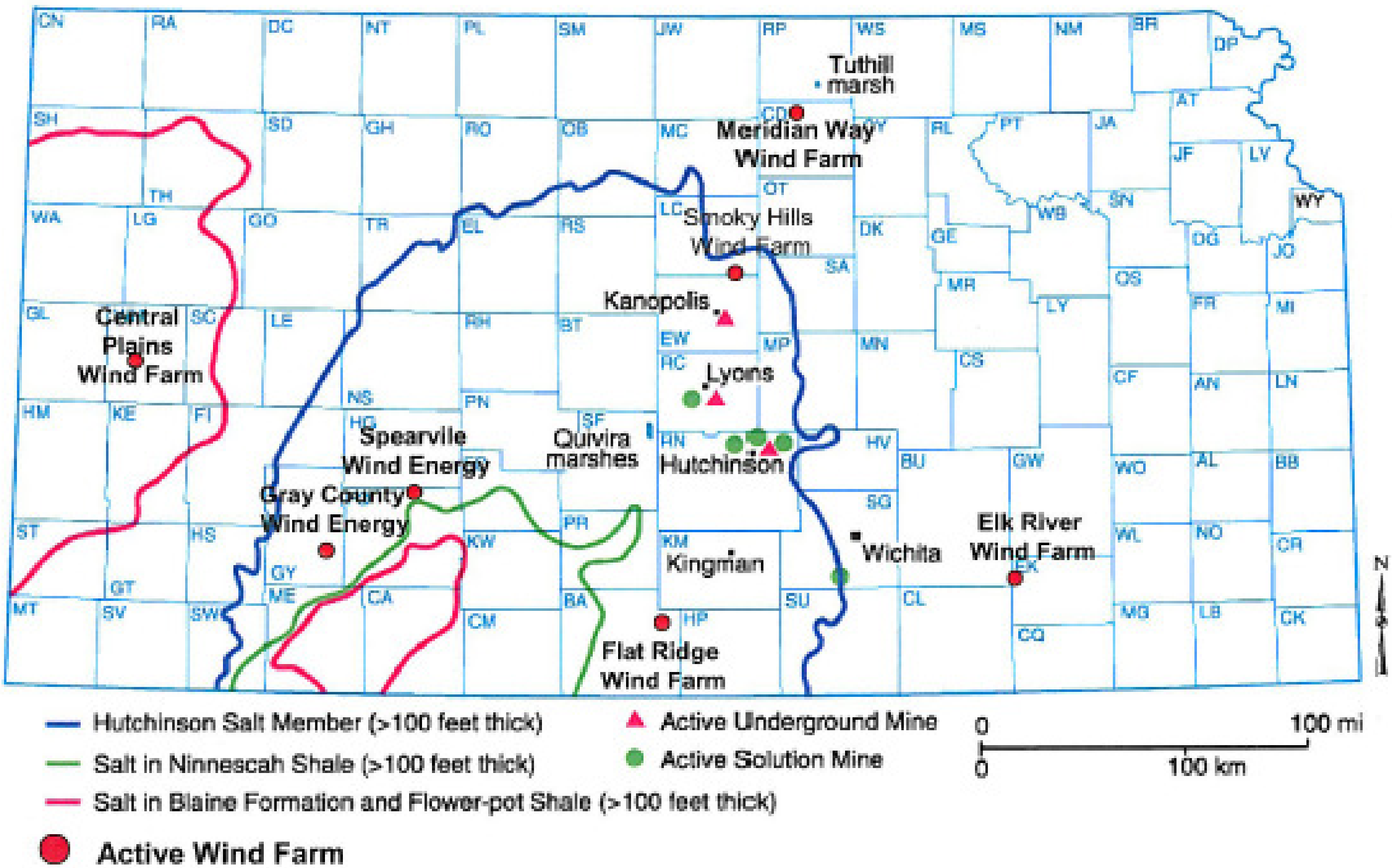
Aerial Extent of Underground Salt Formations **> 100'**



Salt Formations: 1. Blaine Formation and the Flower-pot Shale.
2. Ninnescah Shale,
3. Hutchinson Salt Member

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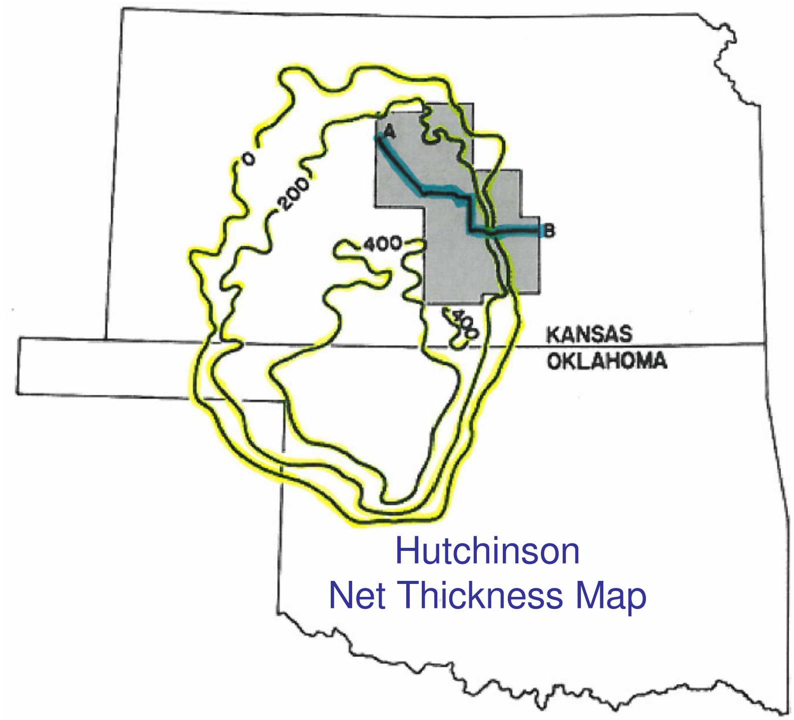
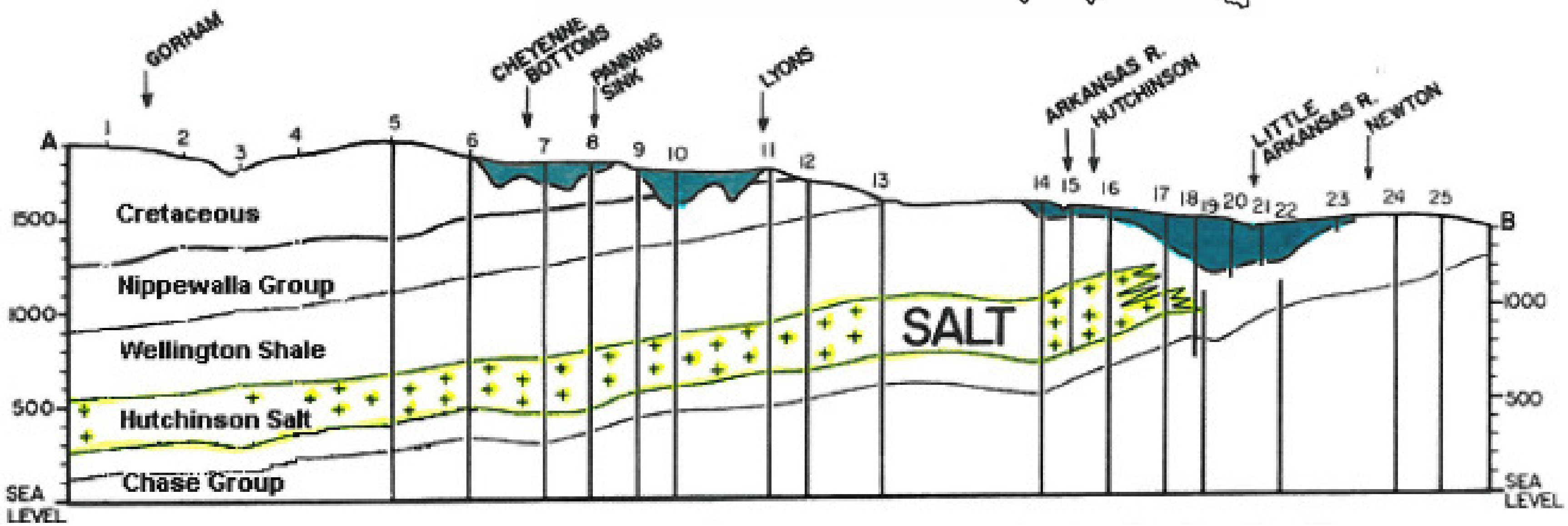
Hutchinson Salt





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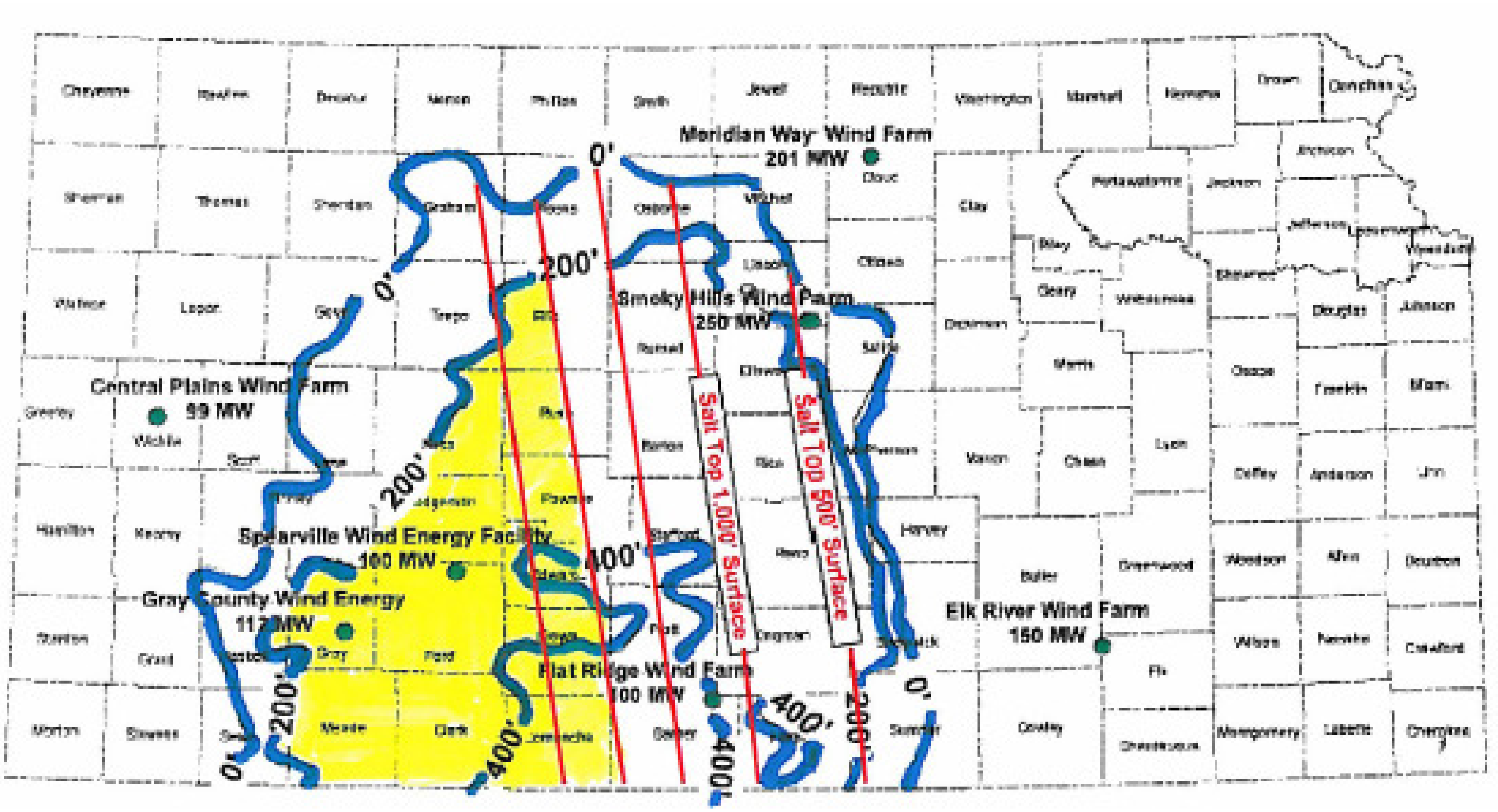
Hutchinson Salt Suitable for Solution Mine CAES.



- Wind Farms Operating In Kansas, April 2009
- Hutchinson Salt Thickness Map (Ft.)
- Depth From Surface to Hutchinson Salt (Ft.)
- Salt Thickness > 200', & Depth > 1,800'

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<u>Solution Mine Salt Cavern</u>

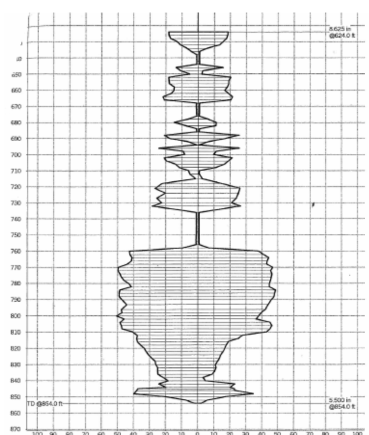
Multi-Cavity Storage: **Caution**

Multi-cavity storage instillations in a single well should be considered with additional monitoring & surveying requirements.

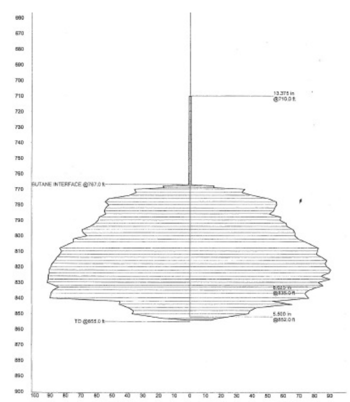
1. The Blaine, Flower Pot and Ninnescah Salts are **shallow** < 1000'. Shallow salt formations are compatible with only 15 MW surface turbo-machinery (min. inlet pressure = 200 psi).

2. Wet compressed air injection and high withdrawal rates may contribute to cavern instability.

Kansas Sonar Surveys



Multi-Cavity



Single Cavity

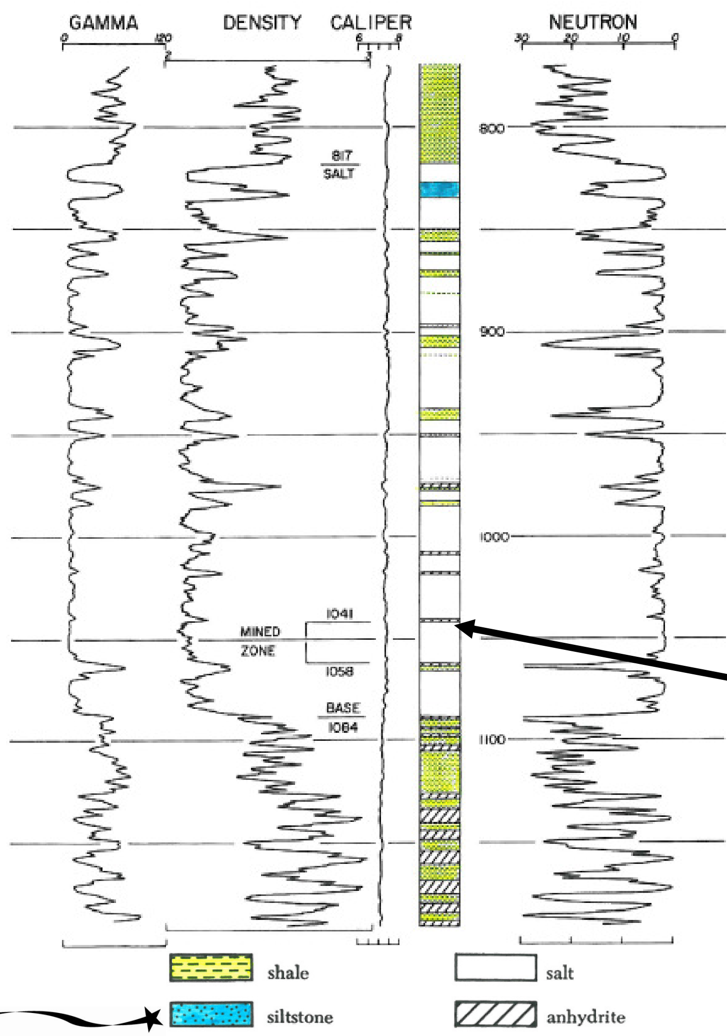
Solution Mine Salt Cavern

Sonar Monitoring **Caution.**

1. Sonar surveys are conducted in low pressure natural gas environments (< 1,500 psi) when salt cavity is filled with brine, prior to filling with gas.
2. No additional sonar surveys are required during the operational life of cavity, since the well is designed and monitored such that water does not enter the cavern.
3. The salt roof thickness is more critical to cavern stability in Kansas and therefore it is monitored every five years by a gamma – density log. In addition, surface elevation surveys are conducted every two years to identify surface subsidence.
4. The Huntorf CAES facility was lowered to atmospheric pressure and a heated laser tool surveyed the cavern. The heated laser tool eliminated the condensation of moisture on the lens and cavern contours were successfully obtained.

Excavated Mine Cavity

Open Hole Well Log



Underground mines in Kansas range in depth from 600 to 1,000 feet.

Excavated Mine Cavity

Salt Mine **Volume Sensitivity**

1. Mine Height: 17'
2. Mine Area: 26.7 Acres – McIntosh
3. Mine Area: 7.4 Acres – Huntorf

Salt Mine **Pressure Sensitivity**

1. Mine Depth Range (Ft): 600' to 1,000'
2. Operating Press Range 0.80 Psi/Ft: 480 to 800 Psi (Bottom Hole Press)

Conclusion: Kansas Salt Mines are shallow and compatible with only 15 MW surface turbo-machinery (min. inlet pressure = 200 psi).

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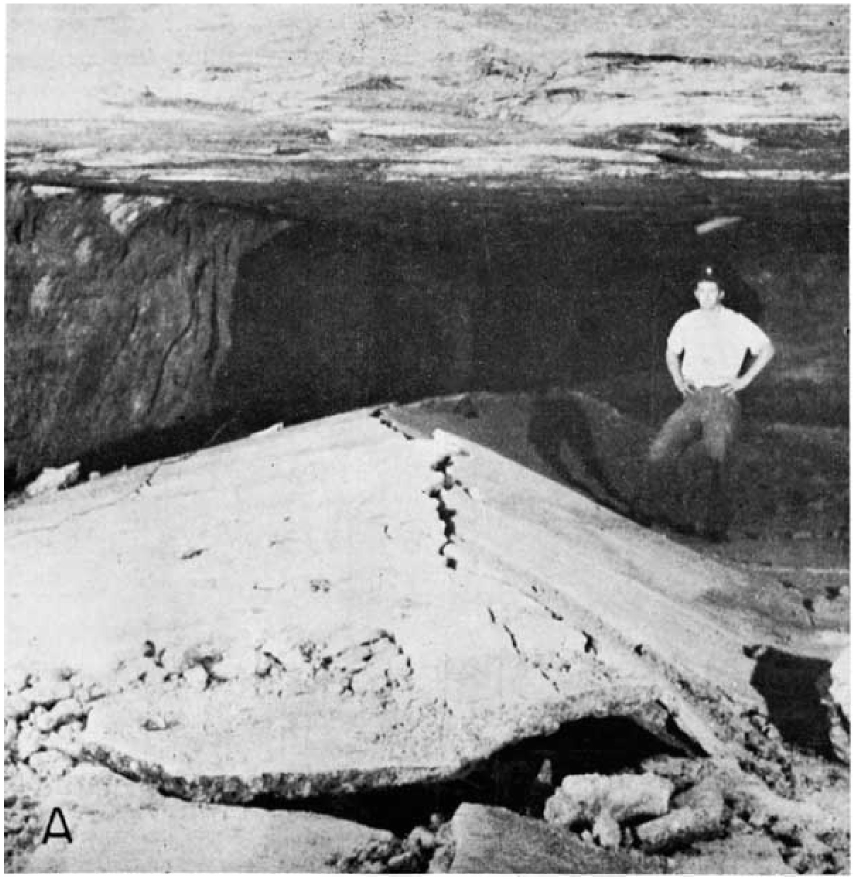
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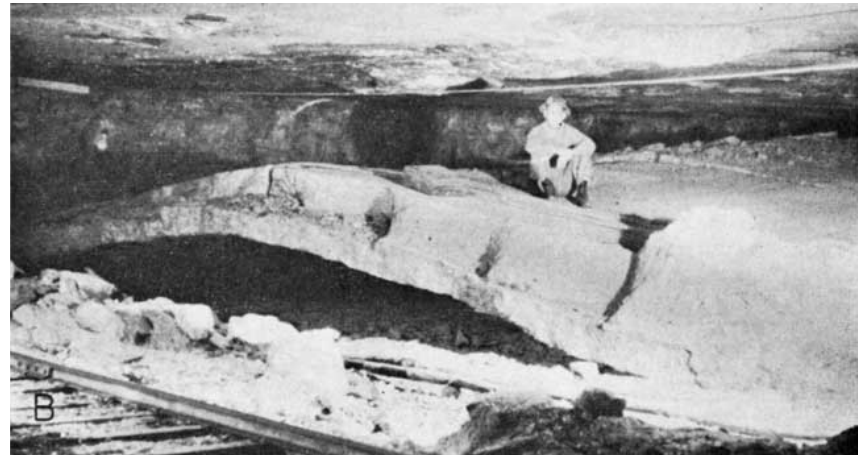
B

The End

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Solution Mined Salt Cavity / LPG Storage Operations