QUESTIONS RAISED BY GAS CAVERNS THERMODYNAMICS

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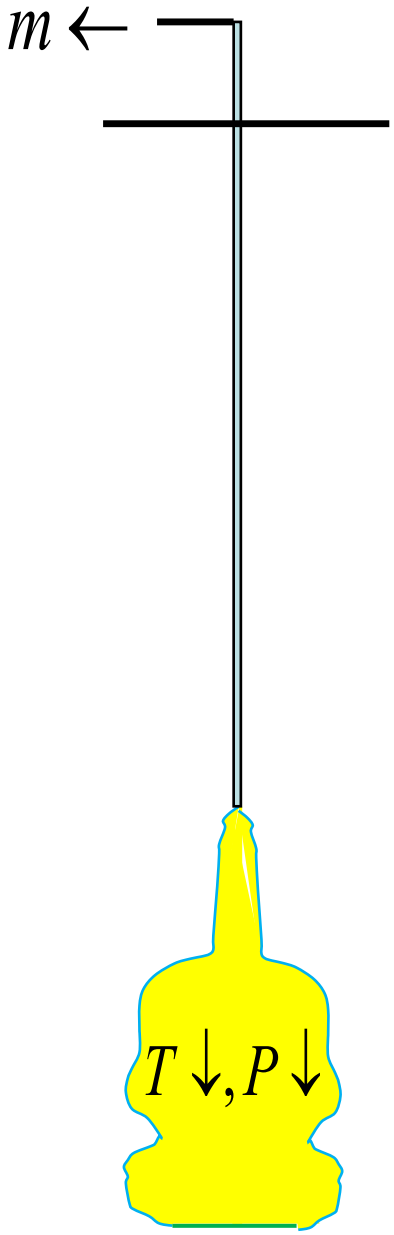
A TREND TO ‘’AGGRESSIVE’’ OPERATION OF GAS STORAGES IN SALT CAVERNS CAN BE OBSERVED



In the 70's-80's, gas storage caverns were developed mainly for seasonal storage. Gas was injected in summer and withdrawn in winter.

Needs of energy traders are changing toward more aggressive operating modes (1-2 MPa/day or 150-300 psi/day), with large swings, to take advantage of daily market prices

At the same time, interest in CAES (air storage) is increasing. In a CAES, pressure cycles are daily (0.5 MPa/hour or 70 psi/hr)

Both generate fast pressure and temperature changes

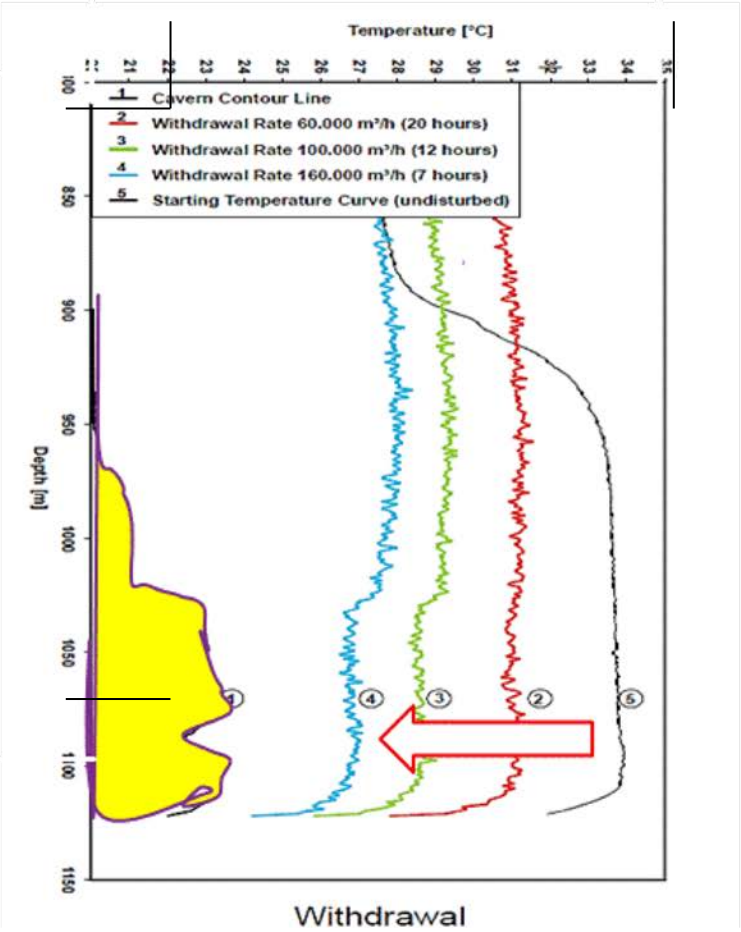
CAN THEY GENERATE THERMAL FRACTURES AT CAVERN WALL?

WORLD SALT SYMPOSIUM
June 19-21, 2018 Park City UT, USA

TEMPERATURE CHANGES IN A GAS CAVERN DURING GAS WITHDRAWAL

20°C 35°C

800 m



1 100 m

GAS TEMPERATURE CHANGES DURING GAS WITHDRAWAL
Klafki & al, 2003

WORLD SALT SYMPOSIUM
June 19-21, 2018 Park City UT, USA

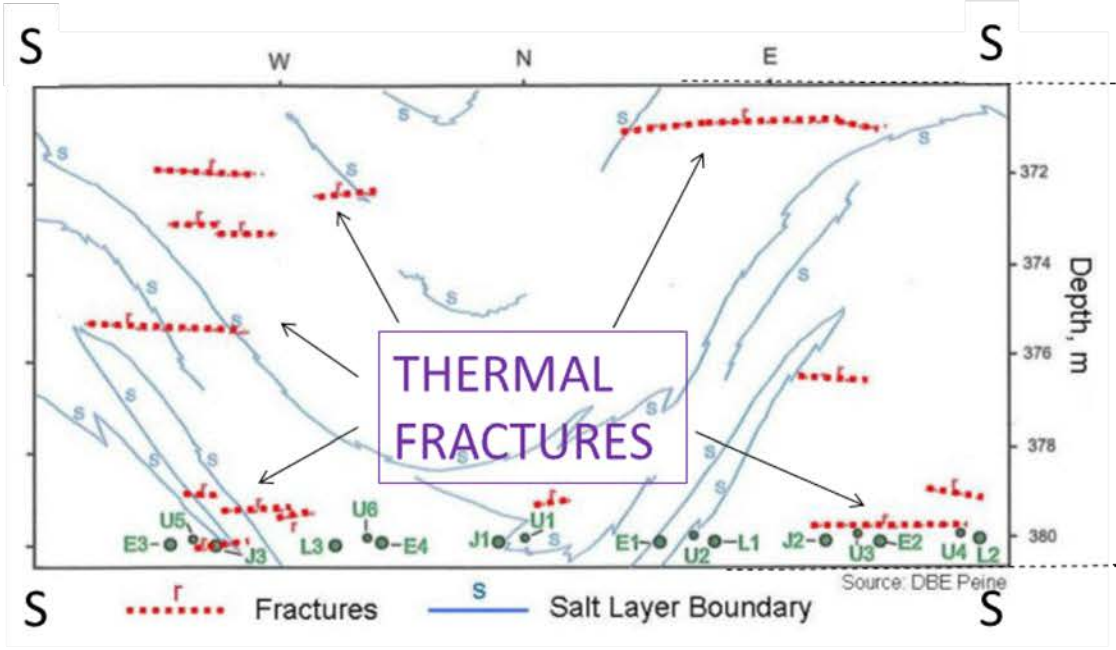
A VENTILATION SHAFT IN THE GORLEBEN SALT MINE

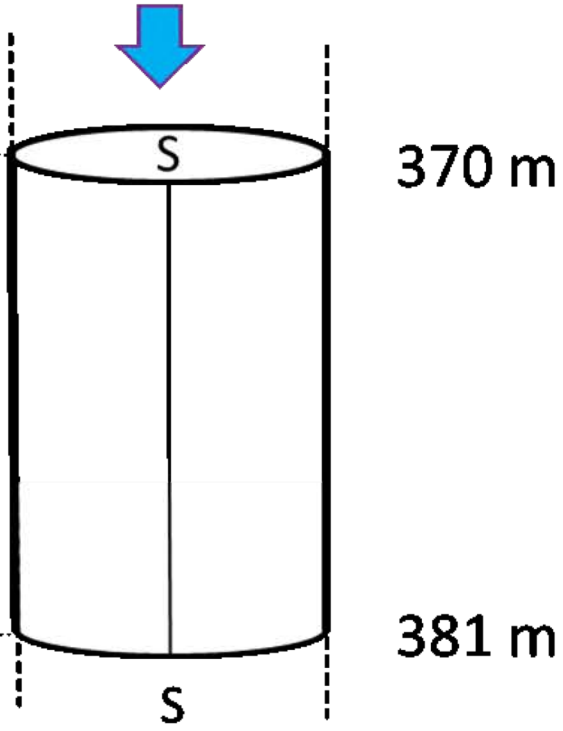
(EXAMPLES OF THERMAL FRACTURES)

WORLD SALT SYMPOSIUM

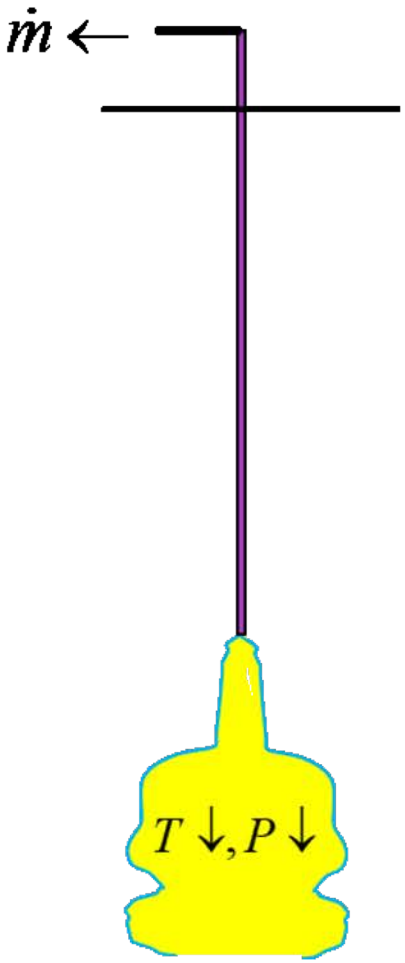
June 19-21, 2018 Park City UT, USA

A VENTILATION SHAFT IN THE GORLEBEN SALT MINE





"During the cold season, temperatures in the shaft decreased by 20°C … within a time period of 80 days… horizontal and vertical fractures were detected by routine inspections in the shaft. Theses fractures had an average spacing of about 2.8 m. The fracture aperture amounted up to several mm." (Wallner and Eickemeier, 2001, and Zapf et al., 2012)



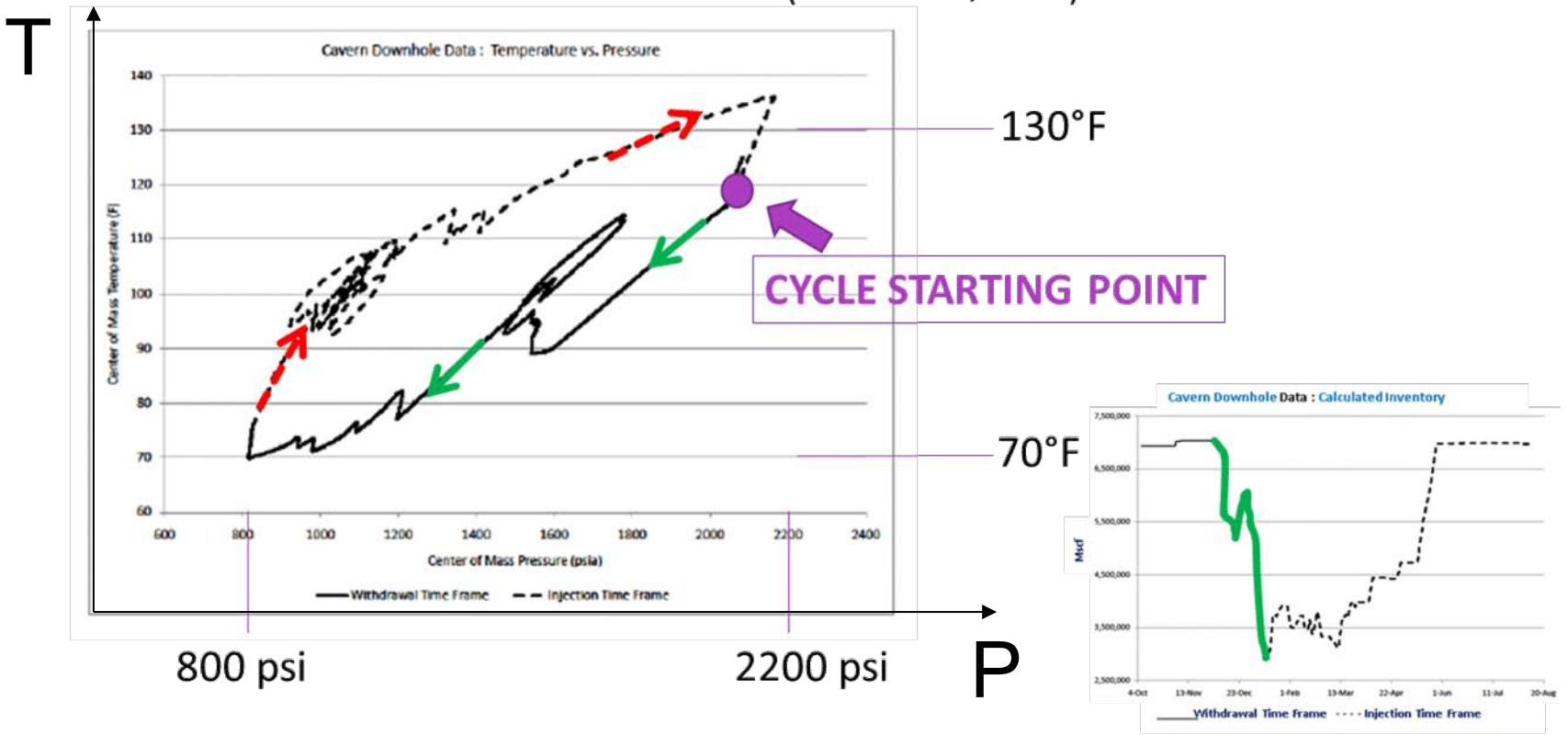
HOW LARGE ARE THE TEMPERATURE CHANGES DURING A FAST WITHDRAWAL?

Are they ADIABATIC?

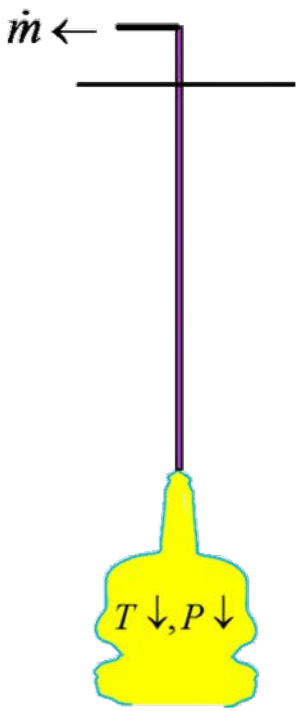
(No heat flow from the rock mass)

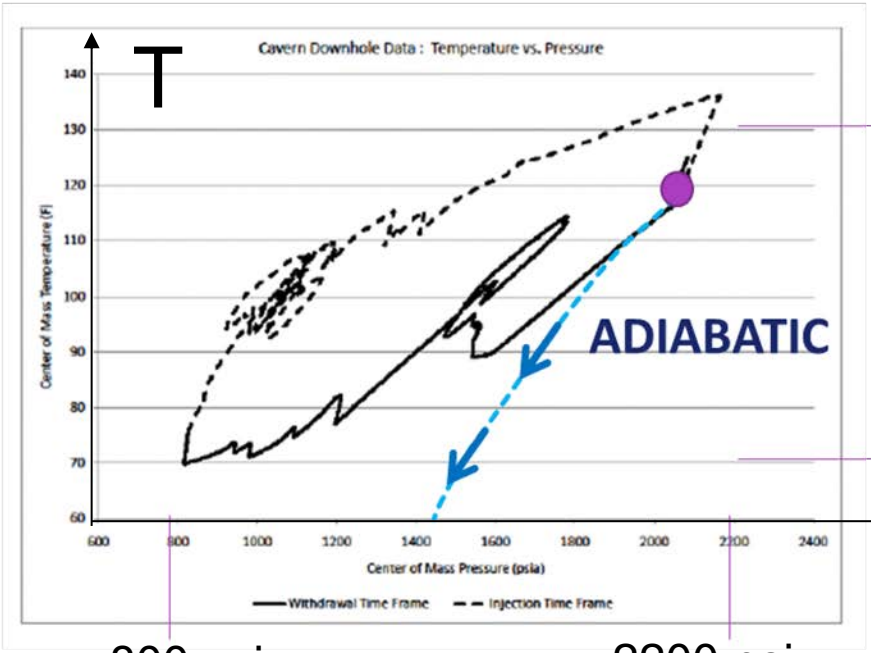
$$\left[\frac{\gamma}{\gamma-1}\frac{\dot{T}(t)}{T(t)}P(t)-\dot{P}(t)\right]V_c=0$$

PRESSURE-TEMPERATURE EVOLUTIONS DURING A CYCLE IN A GULF COAST CAVERN (BENEFIELD, 2010)



PRESSURE-TEMPERATURE EVOLUTIONS DURING A CYCLE IN A GULF-COAST CAVERN(BENEFIELD, 2010)





130°F
(54.4°C)

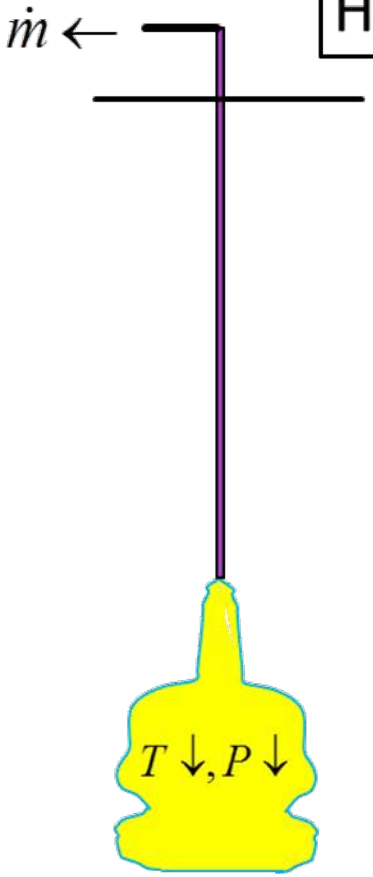
70°F
(21.1°C)

800 psi
(5.6 MPa)

2200 psi
(16.2 MPa)

TEMPERATURE EVOLUTIONS ARE FAR FROM BEING ADIABATIC: HEAT TRANFER FROM THE ROCK MASS MUST BE TAKEN INTO ACCOUNT

HOW LARGE ARE THE TEMPERATURE CHANGES?



HEAT FLUX FROM THE ROCK MASS MUST BE TAKEN INTO ACCOUNT

ADIABATIC

$$\left[\frac{\gamma}{\gamma-1}\frac{\dot{T}(t)}{T(t)}P(t)-\dot{P}(t)\right]=-\frac{\Sigma}{V}\frac{K_{salt}}{\sqrt{\pi k_{salt}}}\int_0^t\frac{\dot{T}(\tau)}{\sqrt{(t-\tau)}}\,d\tau$$

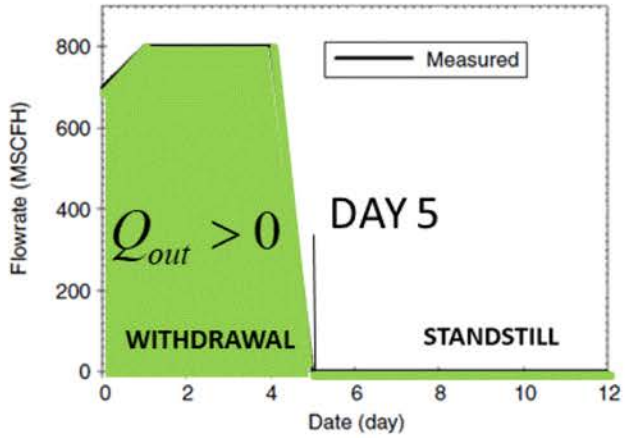
$$\left[\frac{\gamma}{\gamma-1}\frac{T(t)}{T(t)}P(t)-P(t)\right]=-\frac{\Sigma}{V}\frac{K_{salt}}{\sqrt{\pi k_{salt}}}\int_0^t\frac{T(\tau)}{\sqrt{(t-\tau)}}\,d\tau$$

$P(0)=P_0$ $\qquad T(0)=T_0$ $\qquad P(t)<0$

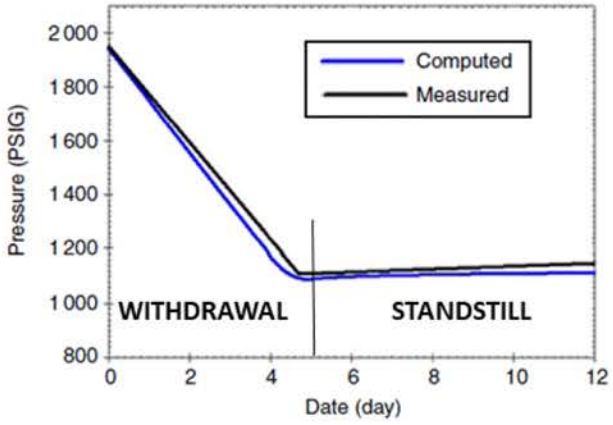
WHAT CAN BE LEARNED FROM THIS EQUATION?

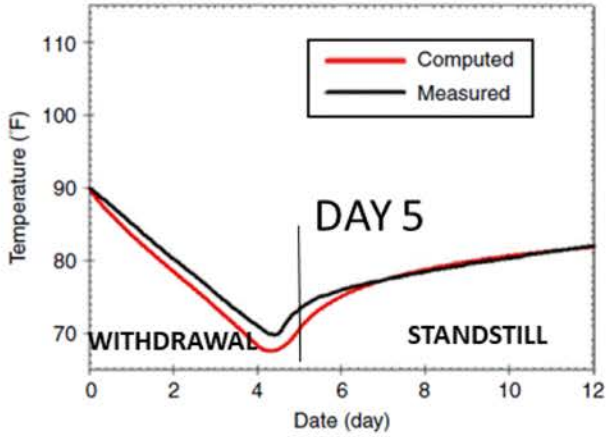
TEMPERATURE DROP RATE IS FASTER WHEN:

1. INITIAL PRESSURE P_0 IS SMALLER
2. CAVERN SURFACE/VOLUME RATIO Σ / V IS LARGER
3. PRESSURE DROP RATE $P(t)$ IS FASTER



$$\left[\frac{\gamma}{\gamma-1}\frac{\dot{T}(t)}{T(t)}P(t)-\dot{P}(t)\right]V_c=-\Sigma\frac{K_{salt}}{\sqrt{\pi k_{salt}}}\int_0^t\frac{\dot{T}(\tau)}{\sqrt{(t-\tau)}}\,d\tau$$

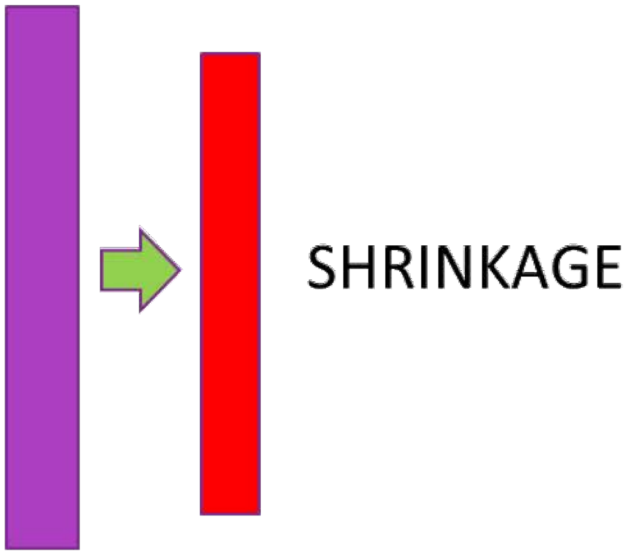




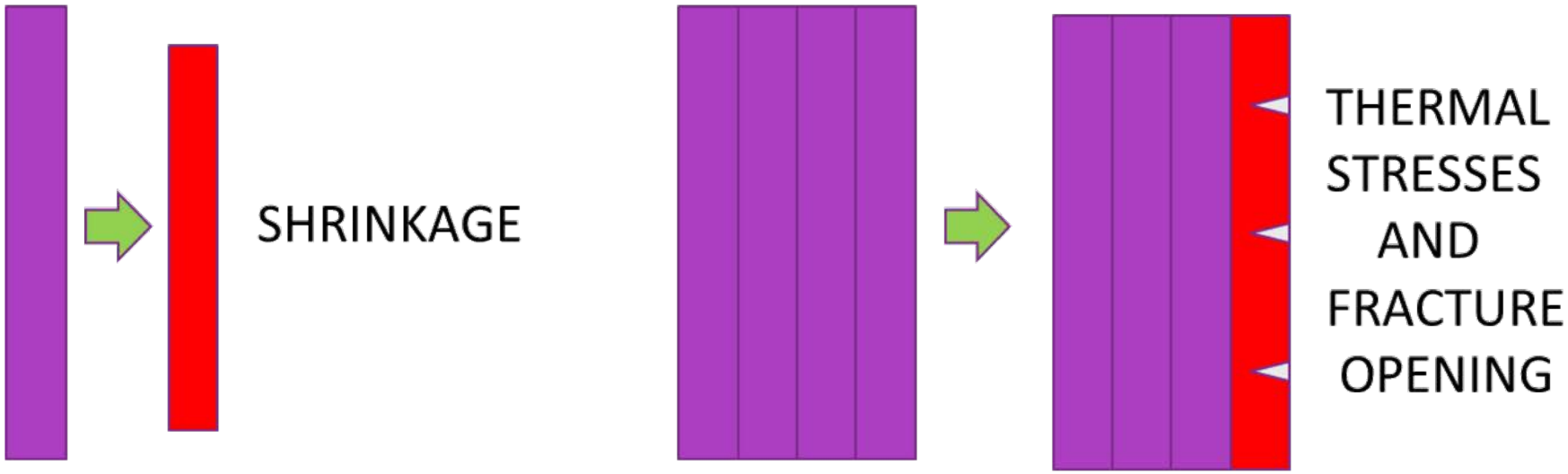
A GAS WITHDRAWAL TEST
Regina North #5 cavern
Melville, Canada
After Crossley, 1996

TENSILE STRESSES GENERATED AT CAVERN WALLS BY A GAS TEMPERATURE DROP

EFFECT OF A TEMPERATURE DROP

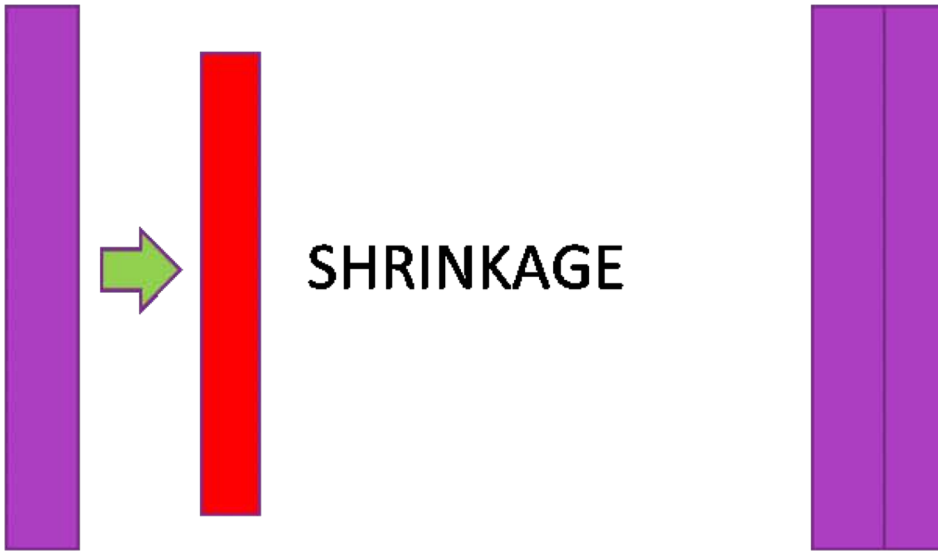


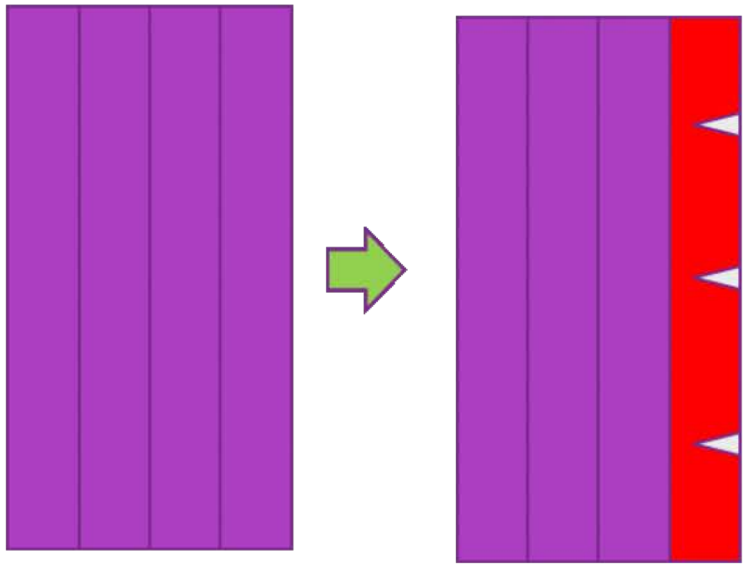
EFFECT OF A TEMPERATURE DROP



→ TENSILE STRESSES AT CAVERN WALL

EFFECT OF A TEMPERATURE DROP





$$\text{div grad } \underline{\underline{\sigma}} + \frac{1}{1+\nu}\,\text{grad grad (tr } \sigma) + k(1-2\nu)\,\text{grad grad } \theta + k(1+\nu)\frac{1-2\nu}{1-\nu}\Delta\theta\,\underline{\underline{1}} = \underline{\underline{0}}$$

ADDITIONAL THERMOELASTIC STRESSES

$$\Delta\sigma_{rr}(r) = \frac{E\alpha}{1-\nu}\int_a^r u\,\theta(u)\,du/r^2$$

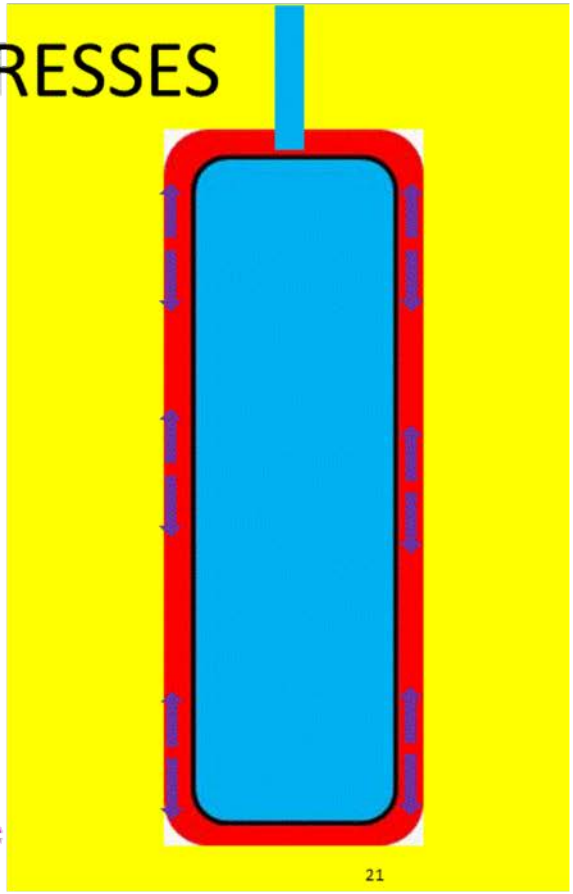
$$\Delta\sigma_{\varphi\varphi}(r) = -\frac{E\alpha}{1-\nu}\theta(r) + \frac{E\alpha}{1-\nu}\int_a^r u\,\theta(u)\,du/r^2$$

$$\Delta\sigma_{zz}(r) = -\frac{E\alpha}{1-\nu}\theta(r) + \frac{E\alpha}{1-\nu}\int_a^r u\,\theta(u)\,du/r^2$$

$\Delta\sigma_{\varphi\varphi}(a)$ and $\Delta\sigma_{zz}(a)$ are tensile stresses

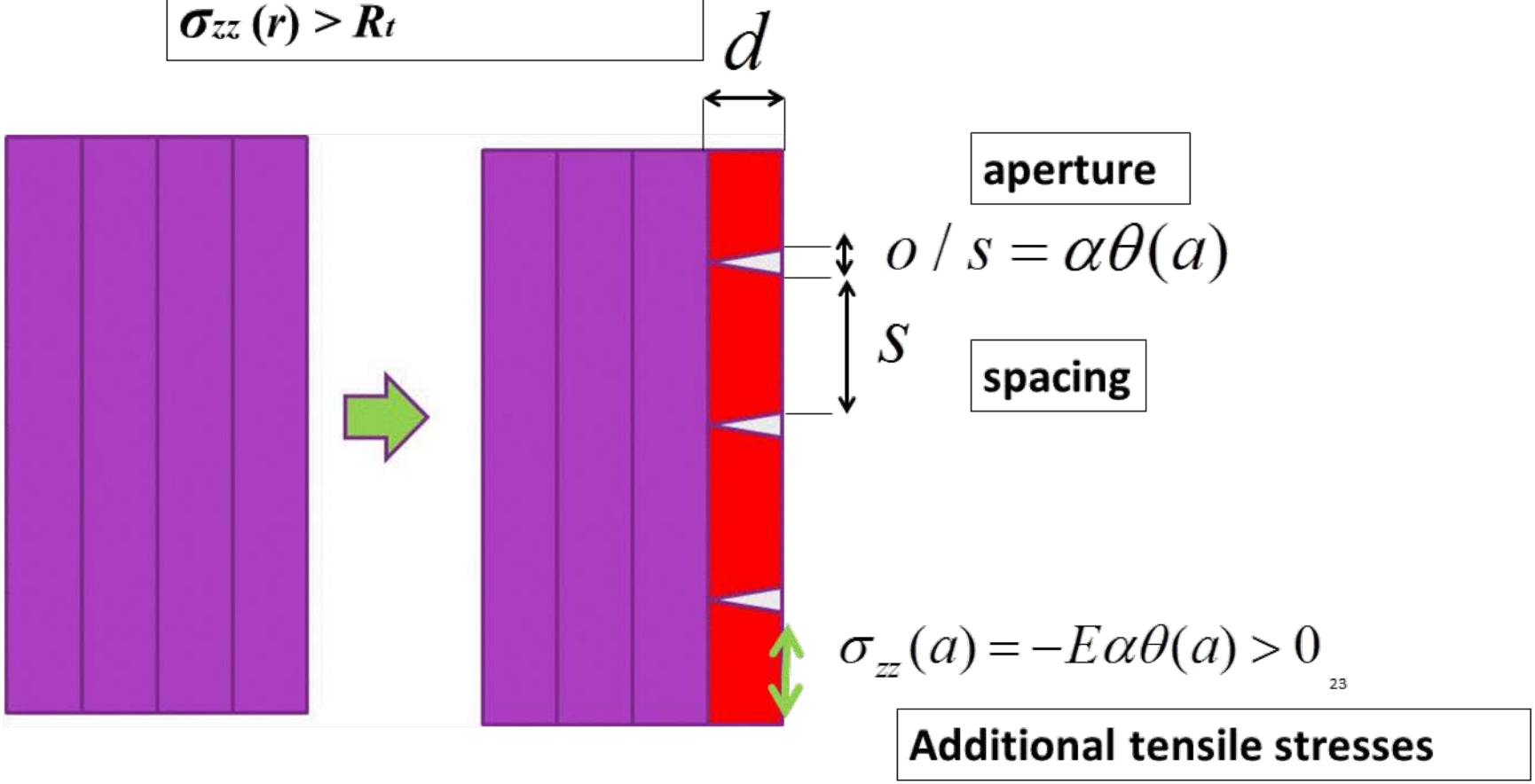
They can be quite large as $E\alpha/(1-\nu) \approx 1$ MPa/^{0}C

Stresses are quite small outside the thin heated zone

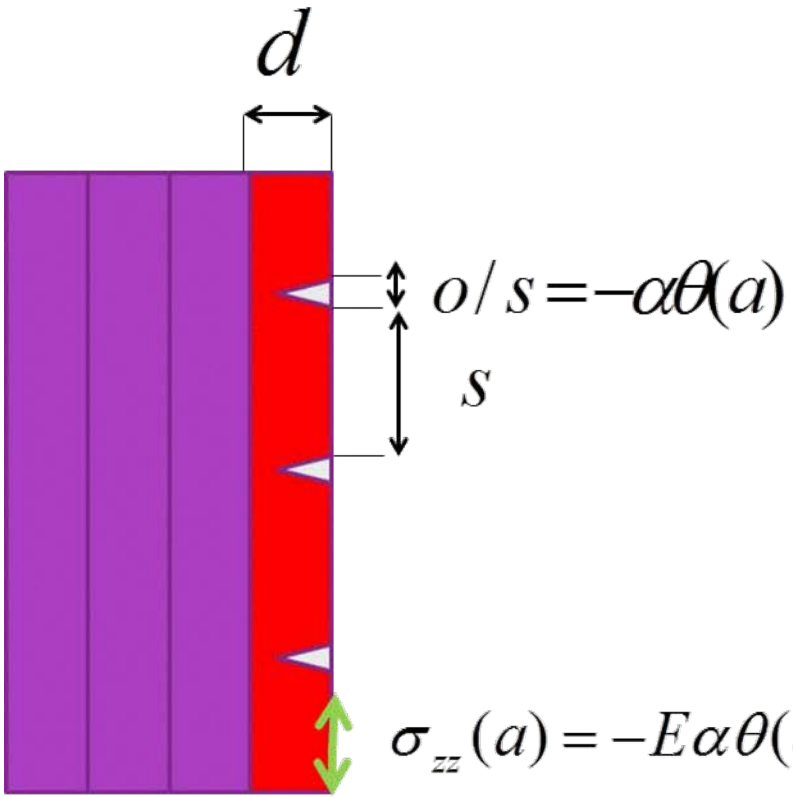


depth of the tensile zone

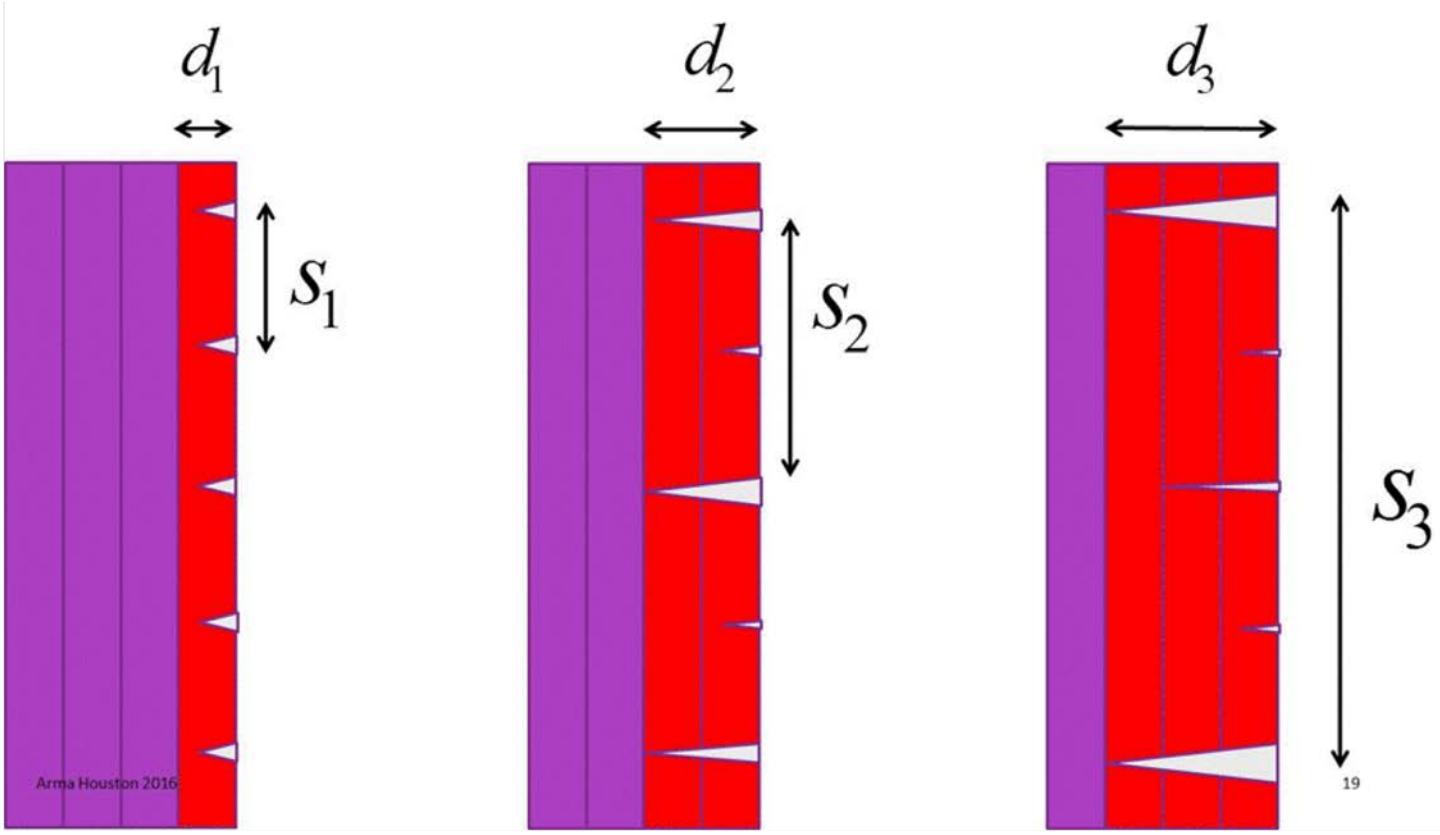
$\sigma_{zz}(r) > R_t$



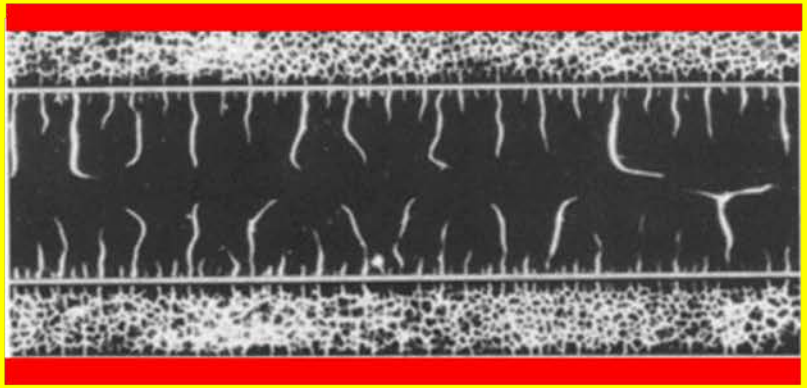
Additional tensile stresses



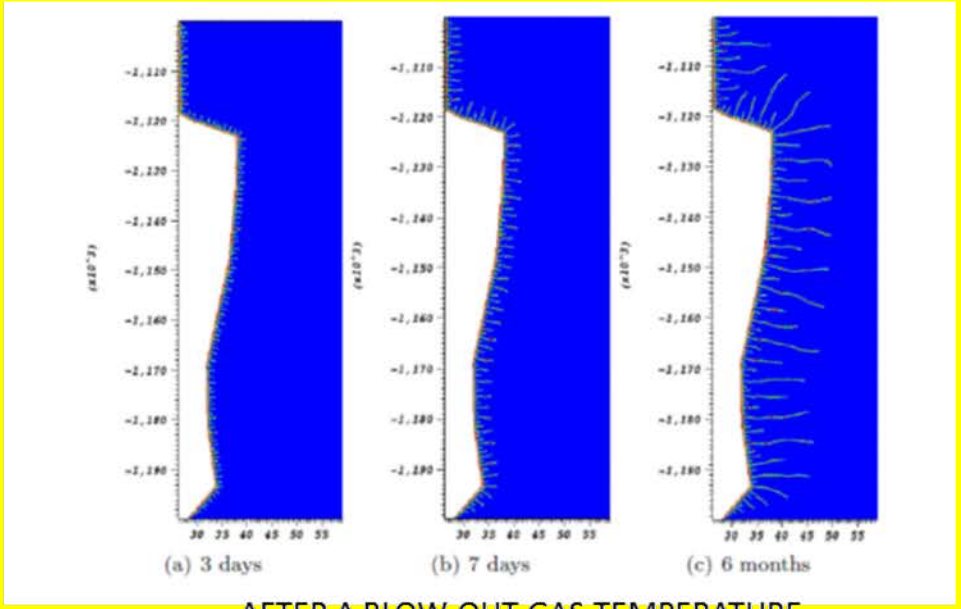
The *d*/*s* ratio?



1 DAY 4 DAYS 9 DAYS

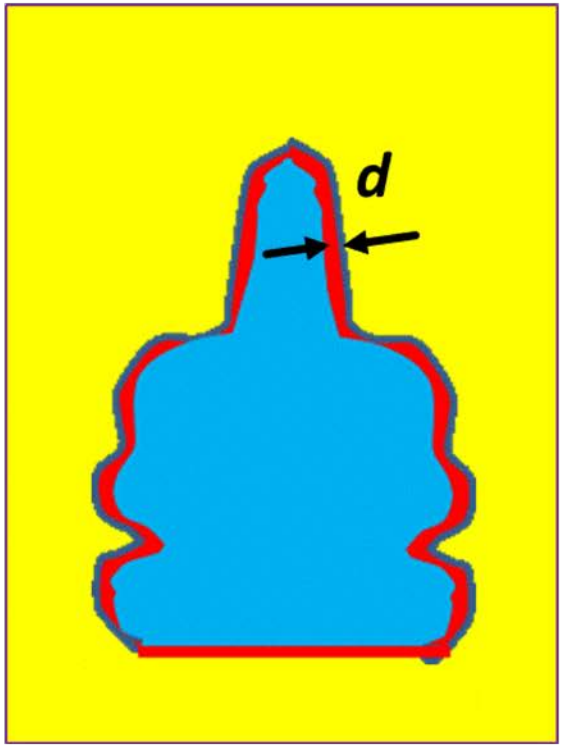


Bahr, H. A., Fischer, G., Weiss, H. J., 1986. *Thermal-shock crack patterns explained by single and multiple crack propagation.* Journal of Materials Science 21, 2716{2720, 10.1007/BF00551478.



AFTER A BLOW-OUT GAS TEMPERATURE WAS KEPT CONSTANT ΔT = -40°C

Sicsic P., Bérest P. (2014). *Thermal Cracking following a blowout in a gas storage cavern.* Int. J. Rock Mech. & Min. Sci. Vol. 71, October 2014, 320-329.



CONCLUSIONS

During a rapid depressurization

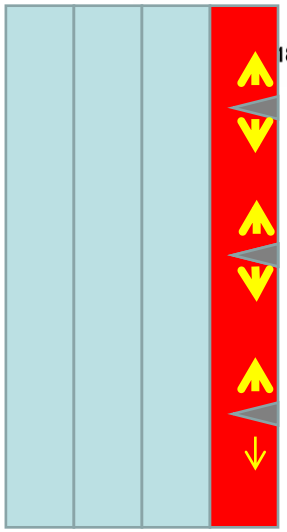
- A thin zone is cooled at cavern wall
- Thermal stresses are generated in this zone
- Tensile fractures appear
- They are perpendicular to the cavern wall
- Their depth is ≈ the thickness of the cooled zone

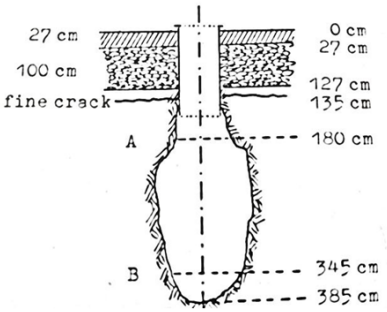
The risk of severe damage at cavern wall is small (in contrast with the case of a temperature increase)

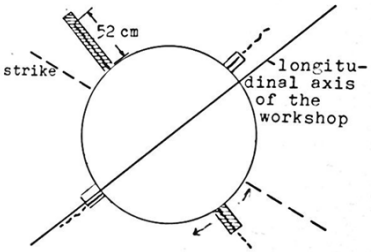
IN FACT, LARGE GAS TEMPERATURE INCREASE (SHEAR STRESSES) MAY RISE MORE CONCERNS THAN LARGE GAS TEMPERATURE DECREASE (TENSILE STRESSES)

COOLING

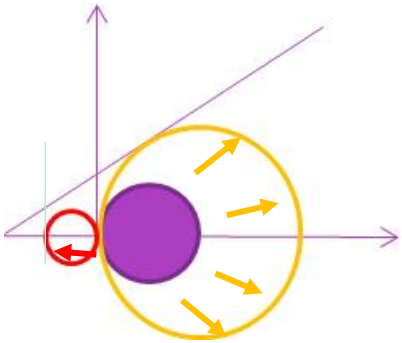
(tensile failure)





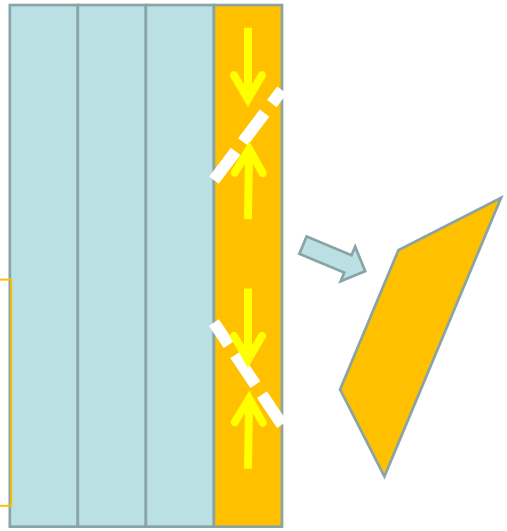


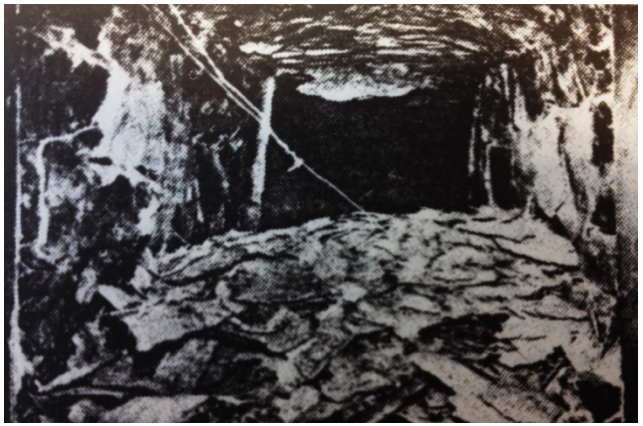
SALT CAVERN UNDERNEATH A DRIFT,
600 m deep, $\Delta T = -200°C$ (Dreyer, 1977)



HEATING

(shear failure)





EXHAUST GASES +315°C (Lee et al.,1980)

The risk of severe damage at cavern wall is small (in contrast with the case of a temperature increase)

QUESTIONS?