Correct Interpretation of Data for Better Understanding of Salt Pillar Behaviour in Mines

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ABSTRACT

Striking differences are present between testing procedures in laboratories and actual mining procedures. This has many times resulted in difficulties or errors when results of laboratory experiments are applied to mining conditions.

The most important factor attributing to the differences is that laboratory samples are usually being loaded whereas the salt rock surrounding a newly created mine opening is unloaded at least in one direction of stress. Reloading may occur when the overlaying strata begin to subside.

A number of erroneous conclusions based on laboratory tests and unapplicable theoretical assumptions have been published during the past few years. Although in situ measurements enabled correction the theories are nevertheless stressed in further publications with complete disregard of actual conditions and contradictory underground measurements. A number of cases of greater common interest will be explained in more detail.

In conclusion, it is felt that large numbers of in situ measurements are needed for the better understanding of rock salt behaviour under mining conditions.

INTRODUCTION

In 1940, a potash mine in Germany was destroyed by a rock burst. During the following years, at the Technical University of Berlin, Professor W. Schmidt did comprehensive research on salt rock behaviour under mining conditions. Most of his work in the laboratory, as well as in potash and rock salt mines, was devoted to the reasons for failures of salt pillars.

One of his most important findings was the answer to the question, "Why carnallite can behave in two very different ways; either deforming plastically, very easily without failure; or failing abruptly by brittle fracture without measurable plastic deformation?" To constant limited loads, carnallite responds by plastic creep. However, when the same carnallite is loaded or unloaded too fast, it will fail suddenly in an explosion-like manner. W. Schmidt (1943) was able to demonstrate these phenomena in his laboratory.

His conclusion was that plastic pillar deformation in a mine is by no means hazardous, even when it results in some slabbing off the surface of a pillar. This slabbing is due to plastic creep of the interior pillar which results in shortening in height, while the pillar surface tends to remain full height. Therefore, formation of slabs at the surface of a pillar should be regarded as an indication of safe condition with respect to a rockburst hazard in that the pillar is deforming plastically. This excludes the hazard of sudden failure (Schmidt, 1943).

These conclusions were not agreed to by other investigators who based their belief on conventional compressive testing in the laboratories. Formulas were developed to calculate allowable pillar loads, disregarding that there is quite a difference between the behaviour of an elastic material of known compressive strength as it is loaded, and the removal of an elastico-plastic material like salt rock out of a mass which is highly stressed by overburden weight.

It is, of course, much more convenient to conduct laboratory tests than to measure deformations underground. Moreover, underground measurements are quite time-consuming due to the time-dependency of most deformations. It usually takes years to get reliable results.

During the fifties considerable difficulties were experienced in German potash mines. Numerous papers dealing with these failures have been published, in particular in East Germany. During the past ten years, some East German writers have been, and still are, quite active at International Rock Mechanics Conferences, proposing and changing theories on rock mechanics aspects of potash mining.

In 1958, Hoefer emerged with a dissertation in which he claims to have found the exact solution for right pillar design in potash mines. His theory is based on Figure 1, in which measured pillar deformation rates are plotted versus pillar loads, which are calculated from extraction rates and depths.

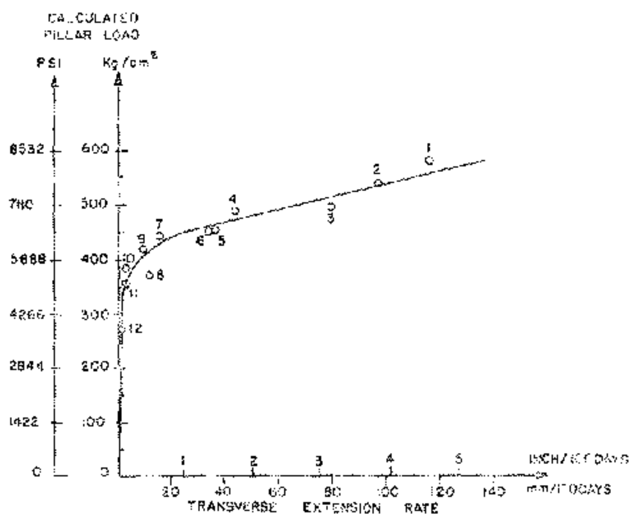

Figure 1. Rate of transverse extension in pillars as a function of the calculated pillar load. (Hoefer, 1958-1967)

This figure states that pillar deformation rates increase rapidly when a certain load is exceeded. Therefore, under high pressures conventional potash mining would become almost impossible because pillar deformation rates would become too high. However, some believed this figure was based on wrong assumptions. When it was presented for the first time in 1958, it was questioned by several published discussions (Wilkening, 1959; Baar, 1959). Nevertheless, it was again presented in New York, 1964, and Hoefer's reply to criticism was, "In his opinion the laws of nature would also hold true in salt mining."

I certainly agree with this statement. However, I still disagree with this figure. It has little in common with laws of nature. It is my concern, however, when Hoefer's curve is referred to in subsequent publications. The question whether this figure is right or wrong is by far not only an academic question. It strongly affects the economics of potash mining. I believe it is indispensable to analyze it in more detail.

Fortunately, all basic data on which this figure is based is published in Hoefer's dissertation (1958). So it is possible to reevaluate these data.

PILLAR DEFORMATION UNDER VARIOUS CONDITIONS

Before Hoefer's data is reevaluated, some fundamentals should be recalled:

(a) High deformation rates occur immediately after mining. Undisturbed deformations measured shortly after mining at IMCC (Canada), Esterhazy, are shown in Figure 2 (after Zahary, 1965). Total vertical and horizontal room closure is plotted versus time. Mining depth is 3140′, initial room width is 21′, initial room height is 7.5′. The rooms are cut by twin boring machines, resulting in an obround cross-section.

Measuring the horizontal closure (curve H) began 2 days after mining, measuring the vertical closure (Vm) started 4 days after mining.

Initial deformation rates are much higher in vertical than in horizontal direction. This is due to room size and room shape. Horizontal deformations are more restricted by less room height and by the circular pillar surface than are vertical deformations.

Curve Vm has been elongated to mining time zero. This gives an idea of how much deformation is not measured because measuring began 4 days after mining. The actual vertical deformation since mining is approximately by curve Va.

The total horizontal closure of a room represents the pillar extension between two rooms.

Similar pillar deformation curves have been found by European investigators. These deformations during the first days or weeks after mining are not caused by loading, but by stress relief in one direction from a highly stressed mass. This was pointed out in a contribution to the Second Symposium on Salt (1965).

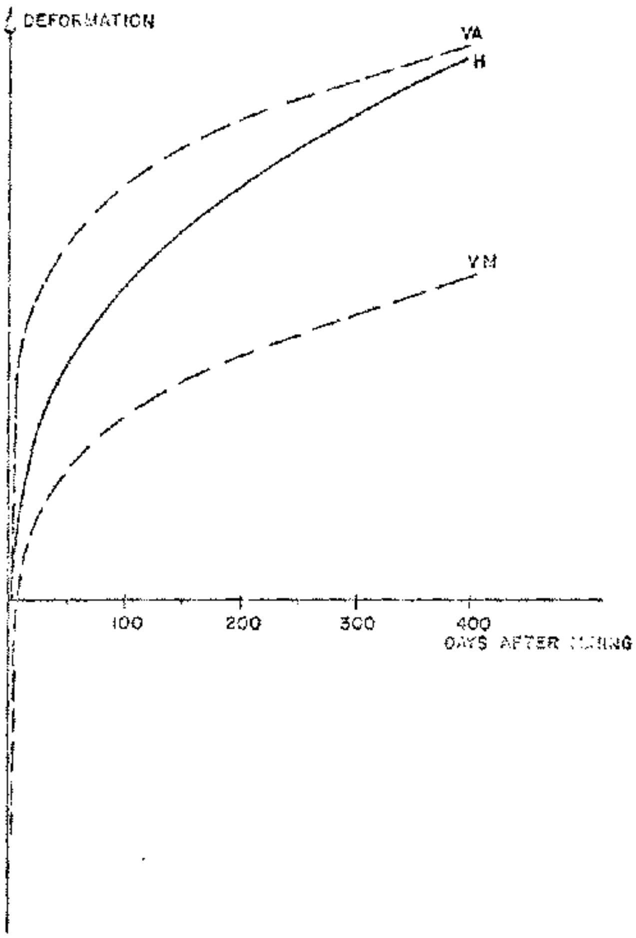

Figure 2. Typical room closure curves measured at IMCC (Canada) Ltd. (after Zahary, 1965).

H Horizontal Room Closure.

Vm Measured Vertical Closure.

Va Approximate Vertical Closure since Mining.

(b) *Temporary increase* in pillar deformation does not necessarily indicate increasing pillar loads. I would like to refer to Figure 3 which is taken from my paper presented to the Second Symposium of Salt (1965).

At points B in this figure, one side of the respective pillars was increased in height from 2.5 to 6 meters (8.1′ to 19.8′). This procedure does not influence the theoretical pillar load calculated from overburden weight and extraction rate.

However, increasing the pillar height means increasing the surface from which one direction of stresses is removed. This additional stress relief causes increasing creep rates.

(c) *Temporary increase* in creep rates can also be caused by blasting in the vicinity of a measuring site. Various degrees of influence of this type are shown in Figure 4 (from Kampf-Emden, 1956). The distance up to which an influence of mining activity on creep rates is measurable has been found to be up to 150′.

Again, I would like to emphasize in particular the typical course of a normal undisturbed creep curve (Fig. 2) developing after cutting an opening in a salt mass which is highly stressed by overburden load. Measuring the deformations plotted in Figure 2 began soon after mining. When openings are only a few days old, the deformation rates are considerably higher than they are after some weeks or after some months. The deformation rates then may slow down to nearly zero, but they are not dying away finally even in shallow depths and after many years.

What I would like to stress in particular is that in Figure 2 a considerable amount of deformation has not been measured because measuring began a few days after mining. Had measuring begun 50 or 100 days after mining, the respective parts in Figure 2 would be missing. Figure 2a.

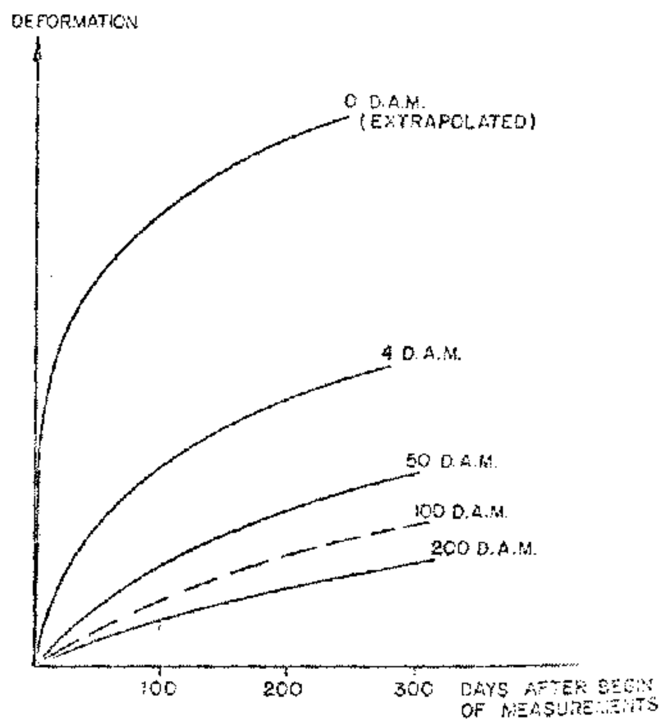

Figure 2a. Parts of curve Va, Figure 2, indicating what would have been measured had measurements begun 50 or more days after mining as indicated at the respective curves.

D.A.M. = DAYS AFTER MINING

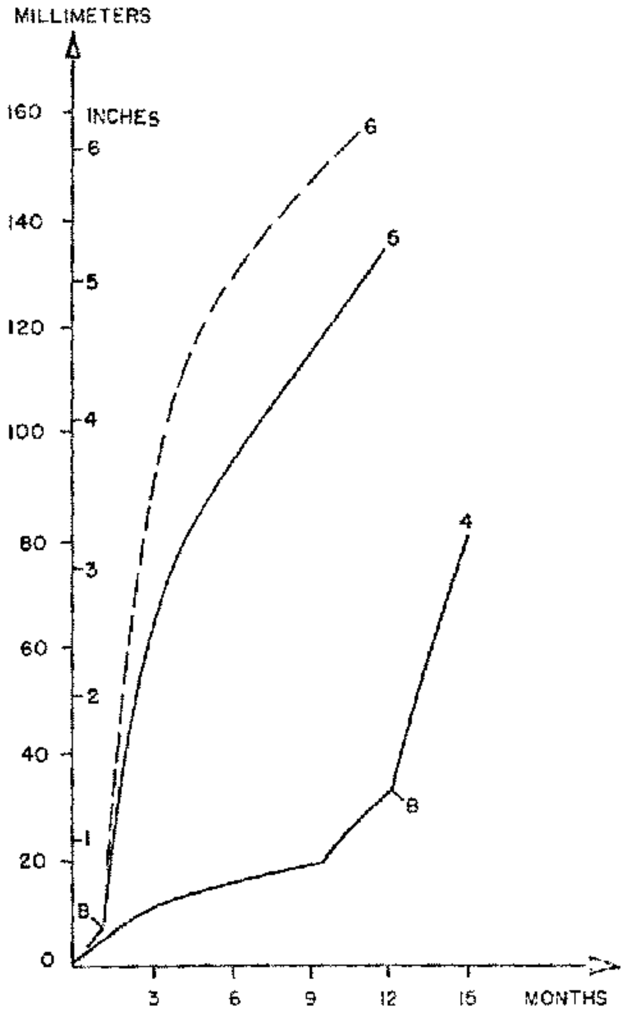

Figure 3. Pillar deformation curves affected by mining (Baar 1965). At points B, one pillar side was increased in height from 2.5 to 6 meters (8.1' to 19.8').

From this it is quite obvious that deformations calculated for a period of 100 days can greatly differ, just depending on the age of any particular opening or pillar. Whatever deformation rate per 100 days is wanted can be obtained by just picking a suitable time after mining for the first measurement, or by selecting a relatively short period during the early rapidly changing deformation period and projecting the same rate for 100 days.

INCORRECT EVALUATION OF MEASURED DEFORMATIONS

Now let us have a look at the measured pillar deformation curves which Hoefer used for plotting Figure 1. These curves are shown in Figure 5, each

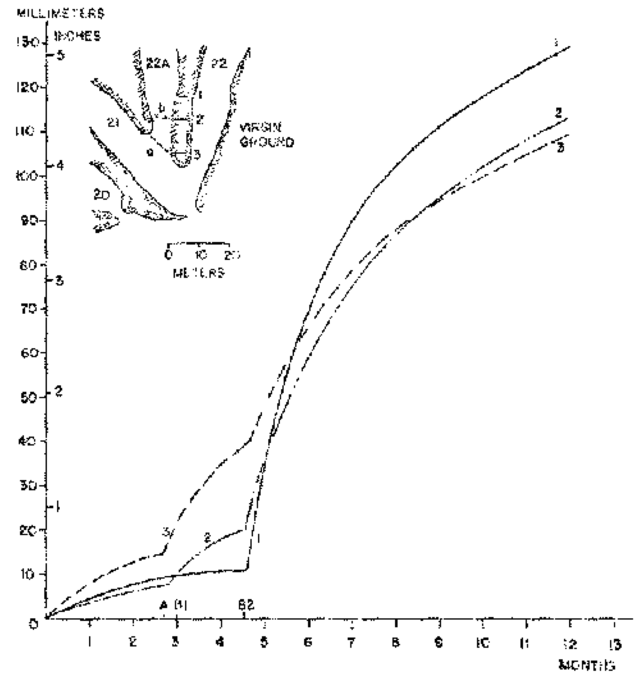

Figure 4. Interaction between pillar deformation and mining activities (Kampf-Emden, 1956).

1,2,3	Pillar deformation at the respective sites.
20,21,22	Rooms mined before measurements began.
22A	Room mined during measuring time.

Mining started at time A at line a, was discontinued at time B_1 at line b, and resumed at time B_2.

point in Figure 1 representing the deformation rate calculated from the respective curve in Figure 5 (same numbers).

Regarding what is known from Figures 2, 3 and 4, it is possible to analyze qualitatively the curves in Figure 5 and explain the probable reasons for any particular deviation from the normal course. This is done in Table I.

Table I.

Characteristics of Deformation Curves in Figure 5.

1. Regular relief deformation curve, measurements began shortly after mining.
2. Same, except measurements began more days after mining. Mining activity started approximately 50 days after measurements began.
3. Regular curve, measuring began approximately 50 more days after mining, compared to No. 1.

4. Measuring began some months after mining. Mining activity between 50 and 220 days caused temporary increase in deformation.

5. Same as 4, except mining activity started 150 days after beginning of measurements.

6. Same as 5, except mining activity was at a greater distance.

7-9. Regular deformation curves, measuring starting several months after mining.

10-12. Regular deformation curves, measuring starting more than 1 year after mining.

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Checking the details which are listed in Hoefer's dissertation strongly confirms the qualitative analysis given in Table I.

The quantitative differences between the 12 curves in Figure 5 can be explained easily when regard is paid to the following items which are known to affect the initial creep rates after mining an opening.

1. Depth below surface: The greater the depth, the greater the original stresses, the greater the initial creep rates.
2. Location with respect to outmined areas: Along the boundaries of an area in which the pillars are not fully loaded, the original stresses (Item 1) are increased by additional overburden load, resulting in higher initial creep rates.
3. Pillar height: The higher a pillar, the greater the free rock surface, the greater the initial creep rates.

All available pertinent data is compiled in Table II. From this compilation the reasons for differing deformation rates become quite obvious. There are 4 groups as shown in Table III.

Table II. Data of Curves in Figure 5.

Curve No.	Mine and Site No.	Depth (Meters/feet)	Pillar height (Meters/feet)	Age of Room When Measuring	Total Measuring Time (Days)	Mining Activity XXX Heavy XX Medium X Little	Pillar Deformation Rate as Calculated by Hoefer (1958) (Milimeters/inches) in 100 days
1	VO/4	1000/3280	3.8/12.5	Days	121	XXX	114/4.49
2	SOL/1	815/2673	4.0/13.1	Days	103	XXX	97.1/3.82
3	VO/3	1000/3280	5.5/18.0	Days	219	XXX	77.6/3.06
4	SOL/3	720/2362	5.0/16.4	Weeks	180	XX	42.5/1.67[1)]
5	BL/5	850/2788	6.5/21.3	Weeks	130	XX	33.8/1.33
6	SON/3	610/2001	9.0/29.5	Weeks	240	XX	33.0/1.30[2)]
7	BL/4	660/2165	6.0/19.7	Months	309	X	14.0/.55
8	SON/1	580/1902	8.0/26.2	Months	480	X	11.0/.43
9	SOL/2	720/2362	5.0/16.4	Months	485	X	9.7/.38
10	BL/1	590/1935	7.5/24.7	Months	1245	–	4.25/.17
11	RO/6	520/1706	4.0/13.1	Years	1039	–	3.17/.12
12	RO/1-3	370/1214	4.0/13.1	Years	463	–	1.81/.07

1) only to point A, Figure 5
2) only after point B, Figure 5

Table III.

Evaluation of Data in Table II.

Group I	Deformation rates over 3"/100 days
Curves 1-3	Measuring began shortly after mining. Heavy mining activity around the measuring sites.
	Measuring terminated before initial high deformation rates decreased.
Group II	Deformation rates between 1" and 3"/100 days.
Curves 4-6	Measurements began several weeks after mining. Deformations temporarily reactivated by mining activity.
	Group I parts of curves are missing.
Group III	Deformation rates between 2" and 1"/100 days.
Curves 7-9	Regular deformation curves, possibly indicating partly reloading of pillars by subsidence.
	Group I and II parts of curves are missing.
Group IV	Deformation rates less than 2"/100 days.
Curves 10-12	Probably indicating full pillar loads.
	Group I—III parts of curves are missing.

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Notice that some manipulation was necessary to obtain the listed Group II deformation rates: From Curve 4, the part after point A was cut off; and from Curve 6, the part before point B was cut off. This means that these deformation rates reflect mining activity rather than regular creep. At curve 5, no cutting was necessary since measurements were terminated before this curve returned to its regular course.

Hoefer gives no explanation for these manipulations, nor of the reasons for which these particular 12 curves were selected out of approximately 50 curves published in this dissertation. I believe he wanted to prove that salt rock deformation under constant load is governed by the same laws as is metal deformation.

Curve 1 in Figure 6 was considered to represent these laws. This curve shows the extension rates of tin wires under increasing loads, indicating "that the deformation rate increases slowly under low stress, but increases very fast under higher stress." (Hoefer 1958, p. 22)

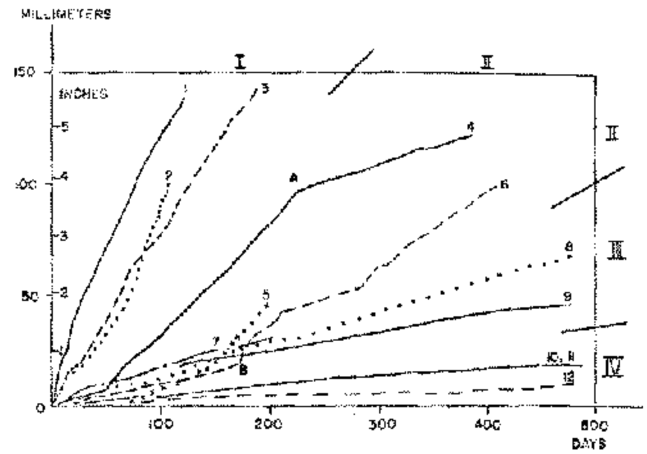

Figure 5. Pillar deformation curves selected to calculate deformation rates plotted in Figure 1 (Hoefer 1958).

1-12 Numbers of curves refer to same numbers in points in Figure 1.

A Part of curve after this point not included in calculation of deformation rate (Point 4, Fig. 1).

B Part of curve before this point not included in calculation of deformation rate (Point 6, Fig. 1).

I-IV Groups listed in Table II.

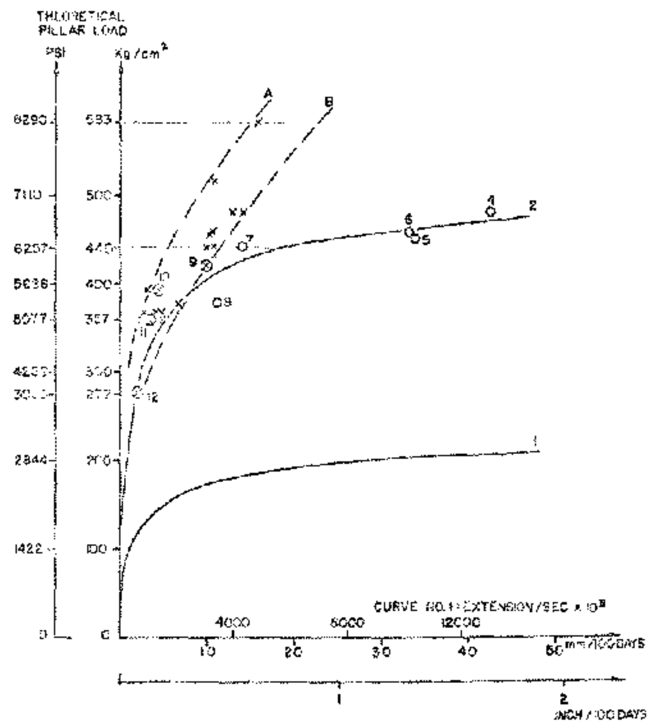

Figure 6. Corrected relationship between pillar deformation rates and pillar loads.

1 Hoefer's reference curve (tin wire).

2 Curve as constructed by Hoefer (Fig. 1).

X Correct values as listed in Table IV.

A,B Curves including a band in which all correct values are located.

In order to prove that pillar deformation in potash mines is governed by the same law, a similar relationship between pillar loads and deformation rates had to be found.

However, the pillar loads were not known. Hoefer calculated theoretical pillar loads from depths and extraction rates. This procedure is questionable. It is correct only in the case that full overburden subsidence has taken place. To achieve full subsidence and full pillar loads, an outmined area must be quite large, its diameter being greater than the depth under conditions as they normally prevail in potash mining areas. At the Rock Mechanics Conference in 1958 this particular assumption of full pillar loads was contradicted by several discussions. (Wilkening 1958; Baar 1959)

In his reply, Hoefer claimed that his figure is based on measured values. Their plot versus theoretical pillar loads results in Curve 2, Figure 6, which surprisingly equals qualitatively the reference curve (No. 1). This similarity between the two curves would prove that the measured pillars were fully loaded.

The similarity between the two curves is indeed surprising. Much more surprising, however, is what is found when checking all the approximately 50 measured curves from which 12 particular ones were selected.

All deformation rates as calculated by Hoefer are compiled in Table IV. Most of these listed rates cannot be considered as indicating deformation under full pillar loads. This is clearly revealed by the respective deformation curves which are shown in Hoefer's dissertation.

In Table IV, all values which obviously do not represent pillar loads, are put in brackets and marked:

I, When belonging to Group I of Table III (High deformation rates shortly after mining)

II, When belonging to Group II of Table III (Increased deformation rates due to mining activity)

X, When corrected because partly belonging to Group I or II.
Values before correction are put in brackets.

Underlined values only are considered to be suitable for construction of a curve which represents the relationship between pillar loads and deformation rates.

It is seen from Table IV that 17 measured values were available for theoretical pillar loads over 7000 psi. They run from 4.34 to 114 mm/100 days. The 3 values selected to construct the wished curve are by far the highest values, 114, 97.1 and 77.6. Only this arbitrary selection, disregarding 14 values which are much lower, made it possible to plot the points 1-3 of the desired curve. For theoretical pillar loads between 6400 and 7000 psi, things were more difficult. Seven values were available, running from 3.4 to 33.8 mm/100 days. There was no value available which would fit in between 33.8 and 77.6 mm/100 days. This difficulty was overcome by some tailoring, simply cutting off parts of measured curves where the deformation rates did not fit into the desired curve. This resulted in points 4 and 6.

There should be no question as to the scientific value of these arbitrary procedures to find the points 1-6 of the curve, the result is misleading. Any wished for curve could be found by selecting and tailoring suitable values.

CORRECT INTERPRETATION OF PILLAR DEFORMATION RATES

The misinterpretation does not do credit to the valuable information that had been collected over years by measurements in several mines. The data compiled in Table IV are believed to be quite sufficient for establishing the true relationship between pillar loads and pillar deformation rates.

For this purpose, all values which obviously do not represent deformations caused by loading must be eliminated. The reasons for elimination are given in Table IV. All high deformation rates exceeding the first value of 15.6 mm/100 days must be eliminated since they are caused by relief deformation shortly after mining or by mining activities in the vicinity of the respective measuring sites.

However, there are also a few very low deformation rates which have to be eliminated due to local conditions which would not allow full pillar loading.

All suitable deformation rates are underlined in Table IV. Only these values are plotted in Figure 6.

All these values are located in a band between curves A and B. In my opinion, this band is the most logical continuation of the course of curve 2 after approximately 5600 psi where Hoefer's curve turns over into a very flat course to join the criticized point 1-6.

The variations within the boundaries of curves A and B are easily explained by differences in pillar height, in petrography and mineralogy, and in loading conditions related to the extent of mined areas and to overburden behaviour.

Table IV. Measured Pillar Deformation Rates

#114# Values selected by Hoefer
32.4 Values selected by Hoefer and manipulated
15.6 Values suitable for Figure 6
(x19) Values corrected
(61.5) Values eliminated in Figure 6

Calculated Pillar Loads Kg/cm²/psi	Mine & No. of Measuring Site	Pillar Deformation Rate (mm/100 days)	REMARKS I High creep rates shortly after Mining. II Creep rates increased by Mining.
583 8290	VO 1	15.6 (x19)	I & II to 170 days.
	VO 2, 5-7	(61.5-22.5-26.8-29.2)	I & II
	VO 8-12	(31.9-45.8-39.7-46-39.7)	I & II
	VO 4	#114#	I & II
543 7721	SOL 1	#97.1#	I & II
513	B1 7, 8	(4.8-4.34)	Too low, not fully loaded
	B1 9	10.9	
510	SOL 5a	(16.8)	II
500 7110	VO 3	#77.6#	I & II
480 6826	SOL 3	14 (x*32.4*)	I & II eliminated
	SOL 4a	12.7 (x20.6)	I & II eliminated
457 6199	SON 3	10 (*21.9*)	II eliminated
	SON 4	10 (x24)	II eliminated
	SON 6a	(3.4)	Too low, not fully loaded
451 6413	B1 5	#33.8#	II
	B1 6a	(28.6)	II
440 6257	B1 4a	#13.9#	Site damaged
	B1 4b, c	10-10.6	
420 5974	SOL 2	#9.7#	
393 5589	B1 1, 2, 3	#4.3-2.9-4.2	
337	SON 5	6.7	
	SON 1,2	*12.1*-(14.1)	II
365	BL 1, 3, 4	4.9-4.3-2.9	
	BL 2	(9.9)	II
357 5076	RO 6a, 7b-c	#3.2#-4.9-2.5	
277 3939	RO 1-4	#1.7#-1.9-1.5-1.8	

Hoefer's conclusions from the curve he had constructed have resulted in some concern among scientists dealing with potash rock deformation in deep mines as in Saskatchewan. A correct evaluation of his basic data results in Curves A and B of Figure 6. These curves do not indicate a yield stress above which abnormal creep rates occur in potash rocks.

I would like to emphasize what several other researchers have found, for example, L. Obert (1967) and W. Dreyer (1967): If the width-to-height ratio of a pillar is greater than approximately 4, pillar failure is excluded. These very important findings allow considerable extraction rates even at depths of approximately 3500′ which sometimes is believed to be the limit for conventional potash mining.

In Saskatchewan mines, for example, pillar heights range from 7.5′ to 12′. These heights require minimum pillar widths of 28′ to 48′ respectively. Even in the case that a safety factor of 2 is applied, limiting the pillar width to 56′ and 96′ respectively, considerable extraction rates are allowable without pillar failure hazard.

I fully agree with L. Obert's (1967) statement:

"Because the tendency of evaporite minerals to creep rather than fracture if the lateral constraint is high enough, if the width-to-height pillar ratio in mine pillars is sufficiently large (4 or greater for salt and potash), the possibility of a chain reaction type of failure is excluded."

This statement supports what W. Schmidt reported some 20 years previous.

OCTAHEDRAL SHEAR STRENGTH OF SALT ROCKS

The favourable behaviour of salt rocks under normal mining conditions is in my opinion, due to the ability to easily perform stress redistributions as required by mining operations. Very low octahedral shear strengths of salt rocks play an important role allowing "plastic" envelopes or liner to develop around any new cavity immediately after a cavity is created.

Many investigators do not believe in low octahedral shear strengths of salt and potash. Possibly they are misled by conventional laboratory testing on samples which suffered strain hardening by deformation before or during testing.

It is well known that the limit of elastic behaviour of salt samples can be raised considerably by loading and unloading when uniaxial loads are applied.

Under triaxial stress conditions, however, as is the case behind the surface of an underground opening, the octahedral shear strength of salt rocks is only very little influenced by strain hardening.

This most important fact was concluded from pressure measurements in sealed bore holes. Some results were presented to the Second Symposium on Salt, 1965. This conclusion was recently confirmed by W. Dreyer's (1967) careful testing on samples under triaxial stress: The octahedral shear strength of rock salt under confinement was found to be only 50 psi at 285 psi load. It increased to 75 psi at 3700 psi load. Under the same loads but without confinement it increased from 135 psi to 1750 psi.

Many theoretical considerations and calculations are based on octahedral shear strengths around 1000 psi or even up to 2000 psi. (Which had been found by conventional testing). Such calculations must be misleading when the true octahedral shear strength of salt rocks is less than 100 psi.

CONCLUSIONS

Striking differences are present between testing procedures in laboratories and actual mining procedures. This has resulted in difficulties or errors when results of laboratory experiments are applied to mining conditions.

The most important factor attributing to the differences is that laboratory samples are usually being loaded, whereas the salt rock surrounding a newly created mine opening is unloaded at least in one direction of stress. Reloading may occur when the overlaying strata begin to subside.

In conclusion, it is felt that more underground measurements and correct interpretations are needed for better understanding of salt rock behaviour in mines. Time is a very important factor in salt rock deformation.

It is difficult in the laboratory to reproduce the stress conditions to which salt rock is subjected under mining conditions and to make sure that the properties of a salt sample are not changed before or during testing in a laboratory.

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