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VAPORIZATION STUDIES OF STRONTIUM SULFATE

Lloyd Manabu Fuke
(M.S. thesis)

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VAPORIZATION STUDIES OF STRONTIUM SULFATE

Lloyd Manabu Fuke

Inorganic Materials Research Division, Lawrence Berkeley Laboratory
and Department of Materials Science and Engineering,
College of Engineering; University of California,
Berkeley, California 94720

ABSTRACT

The equilibrium dissociation pressure of strontium sulfate was measured, for the first time, by the torsion-effusion method in the temperature range 1370°K to 1540°K. The total pressure for the reaction $SrSO_4(s) = SrO(s) + SO_2(g) + \frac{1}{2} O_2(g)$ can be represented as

$$\log P = -(1.405 \pm 0.009) \times \frac{10^4}{T} + (7.167 \pm 0.065)$$

where the indicated errors are standard deviations from least squares analysis. The Second Law Method yielded for the enthalpy of vaporization (ΔH_v^o) 127.4 Kcal/gm-atom and for the entropy of vaporization (ΔS_v^o) 58.5 e.u. No dependency of vapor pressure upon the orifice area was observed.

I. INTRODUCTION

No measurements of the dissociation pressure of strontium sulfate have been reported. In a recent review of thermodynamic data for sulfates, Stern and Weise[1] report for strontium sulfate:

$$\Delta H_f^\circ = -345.3 \text{ Kcal/g-atom}$$

$$S^\circ \ (298.15^\circ K) \text{ estimated } 28.7 \text{ e.u.}$$

Only melting and phase transition points have been reported to the same degree of confidence. Heat capacity measurements have not been made. The present study yields the dissociation pressures and thermodynamic data for the dissociation reaction.

Apart from its intrinsic value, as new thermodynamic information for strontium sulfate, these results when coupled with planned torsion-Langmuir measurements may assist in the formulation of a more consistent theory of the kinetics of evaporation-condensation reactions. In the past, the kinetics of incongruent vaporization have usually been analyzed in terms of the simple Polanyi-Wigner[2] theory or in terms of absolute reaction rate theory.[3] Both theories assume that formation of an activated complex involving the gaseous dissociation product to be rate-limiting and tacitly ignore the possibilities that the slow step may involve formation of the solid reaction product or escape of the gaseous product through the porous solid product layer. The Hertz-Knudsen-Langmuir equation[4] is seldom, if ever, employed. Studies of calcite ($CaCO_3$), an incongruently vaporizing solid, have centered about eloquent,[5] but perhaps incorrect,[6] heat transfer models.

The kinetics of congruent vaporization reactions is universally studied under the formalism of the Hertz-Knudsen-Langmuir equation (hereafter abbreviated HKL). From the knowledge of the equilibrium vapor pressure, the HKL equation predicts the maximum possible rate at which a solid decomposes into a vacuum. A solid which vaporizes in a vacuum at this rate is said to possess unit vaporization coefficient, α_v.[7,8] Examples of compounds with $\alpha_v = 1$ are arsenolite (As_4O_6)[9] and the (0001) faces of lanthanum fluoride (LaF).[10]

For congruently vaporizing solids with $\alpha_v < 1$, comparisons of the equilibrium heat of vaporization (ΔH_v^o) and entropy of vaporization (ΔS_v^o) with the apparent heats and entropies (ΔH_v^* and ΔS_v^*) are instrumental in determining the rate-limiting step. Either a surface step or a desorption step may be rate-limiting.[4]

The HKL equation and comparisons of ΔH_v^o with ΔH_v^* and ΔS_v^o with ΔS_v^* may also provide the means by which the kinetics of incongruent vaporization reactions may be analyzed. The equilibrium dissociation pressure still yields the maximum possible rate of vaporization. Recently, D. Beruto and A. W. Searcy extended these concepts to calcite decomposition.[11]

This initial success provided the impetus for further torsion-effusion and torsion-Langmuir studies of inorganic salts. P. Mohazzabi investigated the kinetics of $BaSO_4$ decomposition.[12] This study of the equilibrium dissociation pressure of $SrSO_4$ represents the initial step in determining trends in metal sulfate decomposition.

Strontium sulfate should vaporize in the manner characteristic of metal sulfates,[1]

$$SrSO_4(s) = SrO(s) + SO_2(g) + \frac{1}{2} O_2(g)$$

The $SO_3 = SO_2 + \frac{1}{2} O_2$ equilibrium must also be considered. However, in the temperature range of interest, dissociation of SO_3 is thermodynamically favored (p. 4 of ref. 1) to the extent that the SO_3/SO_2 ratio is of the order 1/500. Thus, the concentration of SO_3 may be neglected in equilibrium studies.

II. EXPERIMENTAL

The torsion effusion apparatus is essentially the same as that employed by R. T. Coyle[13] and P. Mohazzabi.[12] Methods of calibration have been adequately described elsewhere.[13-15]

A. Sample Preparation

Strontium sulfate crystals from San Luis Potosí, Mexico, were analyzed by the American Spectrographic Laboratories, Inc. Impurities were reported in terms of oxides of elements:

Ca	0.15%
Ba	0.20%
Mg	<0.0005%

The crystals were ground to appropriately fine powder.

B. Knudsen Cells

In the temperature range of interest, reactions between the strontium sulfate and Knudsen effusion cell material are possible.[16] A convenient cell material is graphite; however, graphite reduces $SrSO_4$ to SrS. An alternate material is alumina. Although Al_2O_3 and $SrSO_4$ react to form $Sr(AlO_2)_2$, this solid state reaction could be ignored due to the formation of a protective layer of the product. At the temperature of a typical experiment (1500°K), solid state diffusion through the initial layer of $Sr(AlO_2)_2$ would occur at a negligible rate.

Minimization of cell assembly weight necessitated the use of graphite as the cell holder material. Because graphite and alumina react, the alumina cells were sheathed in protective molybdenum foil.

The Knudsen cells were modifications of a design by R. Galluzzo.[17] Three sets of orifices were prepared, 0.60 mm, 0.80 mm, and 1.00 mm. Tolerances were specified as ± 0.01 mm, with dimensions verified with a comparator microscope.

C. Furnace Calibration

A platinum/platinum-rhodium thermocouple was imbedded in a graphite cell holder. This assembly was displaced vertically in the coil furnace, with the temperature being recorded at 2 mm intervals. A two cm region was defined in which the temperature varied by less than 1.5°K. The thermocouple designed to monitor temperatures throughout the experiments was fed in from the bottom of the furnace and was stationed at a rather critical six mm below the suspended cell assembly. At distances less than six mm, the cell assembly sometimes contacted the tip of the thermocouple. At distances greater than eight mm, the indicated temperature varied at least 15°K below that of the constant profile region. Clarifying photographs and diagrams appeared in the thesis of R. T. Coyle.[13]

D. Tin Calibration

The cell assembly was suspended from a tungsten torsion fibre 0.0381 cm in diameter and 43 cm in length. The cells were charged with 99.999% pure tin pellets. The measured vapor pressure when compared with the accepted vapor pressure of tin[18] verifies the accuracy of the furnace temperature profile, the integrity of the torsion wire, and most important, determines the extent of correction for systematic errors (e.g. systematic temperature errors or peculiarities in cell geometry).

E. Strontium Sulfate Runs

Two independent runs with each set of orifices were conducted. The temperature range encompasses a phase transition point, 1425°K. The extremes in temperature range were governed by limitations of the apparatus. Strontium sulfate melts at 1878°K, but this temperature was beyond the capability of the furnace. Below 1370°K the dissociation pressure is too low to measure accurately.

III. RESULTS AND DISCUSSION

The results of six torsion effusion runs for strontium sulfate are depicted in Fig. 1. The pressures were calculated from the relationship

$$P = \frac{2\theta D}{\sum_i q_i A_i F_i} , \qquad (1)$$

where θ is the angle of cell rotation, D is the torsional constant of the suspension wire, q is the moment arm, A is the area of each orifice, and F is the Freeman-Searcy force correction factor[14,19] for each orifice. The Appendix lists, in tabular form, cell rotation angle as a function of temperature for the six strontium sulfate and three tin calibration experiments. Although three sets of orifices were employed in the sulfate study, no vapor pressure dependency upon orifice area was detected.

A least squares analysis[20] of the data yielded the following equilibrium thermodynamic values for strontium sulfate decomposition:

Table I. Least Squares Analysis

	Run No.	#Data pts.	ΔH_v^o(Kcal/gm-atom)	ΔS_v^o(e.u.)
0.60 mm dia. orifices	1	15	136.2	54.2
	2	16	132.8	65.4
0.80 mm dia. orifices	1	12	128.7	60.6
	2	14	131.3	61.9
100 mm dia. orifices	1	15	134.1	64.1
	2	12	132.9	63.3
Combined (all runs)	-	84	132.6	63.1

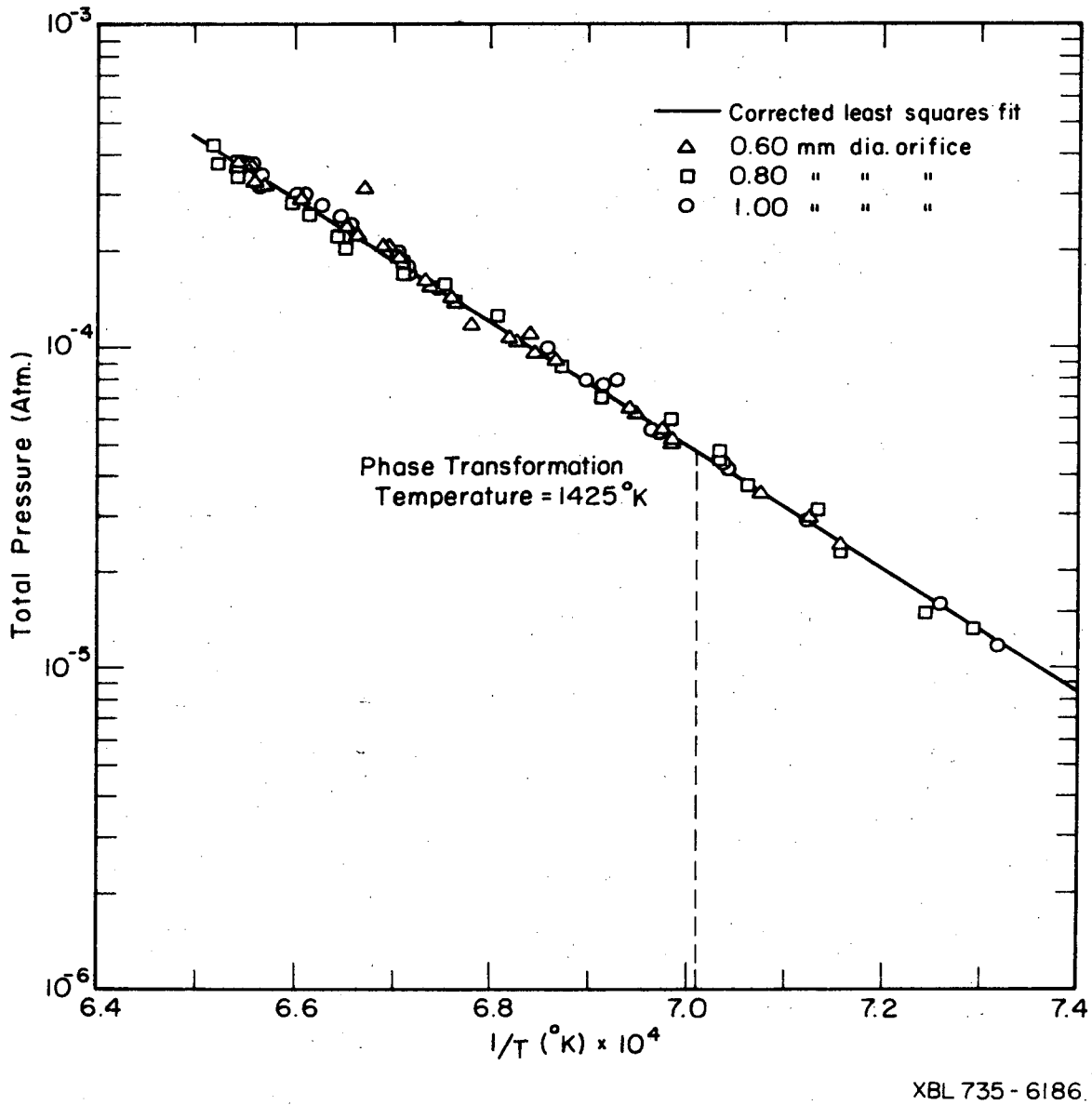

Figure 1. Equilibrium sublimation pressure of strontium sulfate

A correction to these calculations is necessary because the results of the tin calibration runs show a slight deviation from the accepted (Hultgren, et al.) compilations. The calculated enthalpy of vaporization of tin, 73.6 Kcal, is 4.1% higher than the equilibrium value of 70.7 Kcal; the experimentally obtained entropy of vaporization is 26.4 e.u, 7.7% higher than the accepted figure 24.5 e.u. These figures were taken at 1460°K, the midpoint of the temperature range employed.

To correct the heat of vaporization, manifested as the slope of the log P vs 1/T trace, ΔH_v^o is multiplied by the ratio of the experimentally-obtained value and the accepted value of the heats of tin vaporization. Because the entropy of vaporization is represented as the intercept of the log P vs 1/T trace, ΔS_v^o for the sulfate may be derived by subtracting the difference of the two tin intercepts (experimental and accepted values) from the sulfate intercept value. ΔH_v^o and ΔS_v^o are then recalculated with an expression of the form:

$$\ln P = -\frac{\Delta H_v^o}{RT} + \frac{\Delta S_v^o}{R}, \qquad (2)$$

where P is the total pressure.

For the particular dissociation reaction

$$SrSO_4(s) = SrO(s) + SO_2(g) + \frac{1}{2} O_2(g),$$

the following expression has been derived:[12]

$$\ln P = -\frac{2\Delta H_v^\circ}{3R}\left(\frac{1}{T}\right) + \frac{2}{3}\left(\frac{\Delta S_v^\circ}{R} - \ln C\right), \qquad (3)$$

where

$$C = \frac{2\left(M_{SO_2}/M_{O_2}\right)^{1/2}}{\left[2\left(M_{SO_2}/M_{O_2}\right)^{1/2}\right]^{3/2}} .$$

This ratio of molecular weights yields ln C = - 0.9740.

Thus, at the midpoint of the temperature range studied (1460°K),

$\Delta H_v^\circ = 127.4 \pm 0.9$ Kcal/gm-atom

$\Delta S_v^\circ = 58.5 \pm 0.4$ e.u.

Strontium sulfate was more volatile than barium sulfate. Between 1400°K and 1500°K, the equilibrium dissociation pressure of $SrSO_4$ was at least one order of magnitude greater than that of $BaSO_4$. For barium sulfate at 1490°K, the midpoint of the temperature scale of the Mohazzabi study,[12]

$\Delta H_v^\circ = 138.9 \pm 1.9$ Kcal/gm-atom

$\Delta S_v^\circ = 60.2 \pm 1.3$ e.u.

Third Law Method calculations for strontium sulfate were not attempted due to the lack of free energy function, entropy, and heat capacity data.

In principle, unless the heat of transition is negligible, there must be a change in slope at the phase transition temperature because the formation of a stable high-temperature solid phase is an endothermic process. A least squares analysis was conducted with 68 data points taken above the phase transition temperature (1425°K) in order to determine the approximate heat of transition. This analysis yielded

$$\Delta H_v^o = 127.5 \pm 1.3 \text{ Kcal/gm-atom}$$
$$\Delta S_v^o = 58.5 \pm 1.1 \text{ e.u.}$$

Since these results agree to within the limits of expected error with the values determined when the transition is neglected, it can be concluded that the heat of transition is small, possibly less than one kilocalorie per gram-atom of $SrSO_4$.

ACKNOWLEDGMENTS

As is true with any work conducted under the auspices of the Atomic Energy Commission, this paper represents the combined efforts of many talented, devoted individuals. I am grateful to Professor A. W. Searcy for extending the opportunity of sharing his insights and knowledge.

Three members of the IMRD support staff deserve special mention for their services. Emery Kozak was instrumental in ensuring reliability of the torsion-effusion apparatus. Will Lawrence fabricated the alumina cells quickly and efficiently despite committments to higher priority jobs. In addition to typing the original draft, Kelly Radmilovic volunteered valuable advice in collating this thesis.

I certainly cannot forget fellow student Pirooz Mohazzabi for his unselfish assistance with the interpretation of my data.

Above all, I thank my parents for their encouragement of my education. The sense of accomplishment and pride reflected by this thesis is as much theirs as it is mine.

APPENDIX

This appendix is a compilation of pertinent data and parameters necessary for the determination of vapor pressures. The equilibrium pressures were calculated with Eq. (1). Freeman-Searcy force factors were obtained from the D. A. Schulz thesis.[19] The heats and entropies of vaporization were calculated from least squares analyses.[20]

Freeman-Searcy force correction factors are:

(1) 0.60 mm diameter orifice

Cell #1 0.47203

Cell #2 0.47369

(2) 0.80 mm diameter orifice

Both cells 0.5436

(3) 1.00 mm diameter orifice

Cell #1 0.61839

Cell #2 0.62278

TIN CALIBRATION

0.80 mm diameter orifices

	T(°K)	Deflections (deg.)	P calculated (atm)
RUN NO. 1	1545	5.95	2.6553×10^{-5}
	1533	4.98	2.2224×10^{-5}
	1515	3.50	1.5619×10^{-5}
	1494	2.34	1.0442×10^{-5}
	1466	1.36	6.0691×10^{-6}
	1492	2.50	1.1157×10^{-5}
	1520	3.97	1.7717×10^{-5}
	1494	2.47	1.1023×10^{-5}
	1460	1.31	5.8460×10^{-6}
	1438	0.70	3.1238×10^{-6}
	1440	1.08	4.8196×10^{-6}
	1476	1.95	8.7021×10^{-6}
	1500	2.92	1.3031×10^{-5}
	1519	4.04	1.8029×10^{-5}
	1495	2.55	1.1380×10^{-5}
	1513	3.59	1.6021×10^{-5}
	1535	5.15	2.2982×10^{-5}
	1527	4.42	1.9725×10^{-5}
	1499	2.70	1.2049×10^{-5}
	1478	1.82	8.1219×10^{-6}
	1456	1.11	4.9535×10^{-6}
	1465	1.46	6.5154×10^{-6}
	1494	2.66	1.1871×10^{-5}
	1519	4.02	1.7940×10^{-5}
	1484	2.08	9.2822×10^{-6}

	T(°K)	Deflections (deg.)	P calculated (atm)
RUN NO. 2	1521	3.93	1.7538×10^{-5}
	1513	3.50	1.5619×10^{-5}
	1479	1.94	8.6575×10^{-6}
	1448	1.04	4.6411×10^{-6}
	1434	0.70	3.1238×10^{-6}
	1446	0.97	4.3287×10^{-6}
	1462	1.35	6.0245×10^{-6}
	1503	2.01	8.9698×10^{-6}
	1474	1.73	7.7203×10^{-6}
	1480	1.99	8.8806×10^{-6}
	1497	2.75	1.2272×10^{-5}
	1526	4.42	1.9725×10^{-5}
	1513	3.50	1.5619×10^{-5}
	1448	1.00	4.4626×10^{-6}

	T(°K)	Deflections (deg.)	P calculated (atm)
RUN NO. 3	1531	4.58	2.0439×10^{-5}
	1521	3.80	1.6958×10^{-5}
	1506	2.94	1.3120×10^{-5}
	1494	2.37	1.0576×10^{-5}
	1472	1.52	6.7832×10^{-6}
	1455	1.08	4.8196×10^{-6}
	1467	1.46	6.5154×10^{-6}
	1443	0.80	3.5701×10^{-6}
	1482	1.91	8.5236×10^{-6}
	1511	3.38	1.5084×10^{-5}
	1501	2.78	1.2406×10^{-5}
	1508	3.13	1.3968×10^{-5}
	1528	4.45	1.9859×10^{-5}
	1515	3.55	1.5842×10^{-5}
	1489	2.19	9.7731×10^{-6}

Least squares analysis yields for the 55 pts:

$\Delta H_v^o = 73.6 \pm 0.9$ Kcal

$\Delta S_v^o = 26.4 \pm 0.7$ e.u.

Hultgren selected values:

$\Delta H_v^o = 70.7$ Kcal

$\Delta S_v^o = 24.5$ e.u.

STRONTIUM SULFATE RUNS

0.60 mm dia. orifice

	T(°K)	Deflections (deg.)	P calculated (atm)
RUN NO. 1	1528	41.17	3.6528×10^{-4}
	1525	41.16	3.6528×10^{-4}
	1521	36.07	3.2000×10^{-4}
	1491	21.55	1.9130×10^{-4}
	1460	10.85	9.6194×10^{-5}
	1466	11.90	1.0573×10^{-4}
	1494	23.10	2.0495×10^{-4}
	1439	6.87	6.1096×10^{-5}
	1432	5.57	4.9397×10^{-5}
	1500	27.60	2.4482×10^{-4}
	1513	32.70	2.9031×10^{-4}
	1494	23.12	2.0517×10^{-4}
	1478	15.42	1.3692×10^{-4}
	1484	17.60	1.5621×10^{-4}
	1434	6.17	5.4813×10^{-5}

	T(°K)	Deflections (deg.)	P calculated (atm)
RUN NO. 2	1527	40.70	3.6115×10^{-4}
	1524	39.07	3.4663×10^{-4}
	1499	35.20	3.1240×10^{-4}
	1485	18.02	1.5988×10^{-4}
	1462	12.35	1.0962×10^{-4}
	1456	10.12	8.9908×10^{-5}
	1465	11.57	1.0269×10^{-4}
	1479	15.80	1.4017×10^{-4}
	1503	26.72	2.3701×10^{-4}
	1494	23.12	2.0516×10^{-4}
	1474	13.17	1.1699×10^{-4}
	1440	7.10	6.3044×10^{-5}
	1432	5.70	5.0479×10^{-5}
	1403	3.30	2.9247×10^{-5}
	1397	2.70	2.4048×10^{-5}
	1413	3.92	3.4880×10^{-5}

Least squares analysis of all 31 points yields:

$\Delta H_v^\circ = 133.9 \pm 1.3$ Kcal

$\Delta S_v^\circ = 61.6 \pm 0.3$ e.u.

0.80 mm diameter orifices

	T(°K)	Deflections (deg.)	P calculated (atm)
RUN NO. 1	1534	95.25	4.2506×10^{-4}
	1533	83.05	3.7062×10^{-4}
	1527	84.05	3.7508×10^{-4}
	1490	41.75	1.8631×10^{-4}
	1469	28.15	1.2562×10^{-4}
	1432	13.25	5.9130×10^{-5}
	1402	6.80	3.0346×10^{-5}
	1370	2.95	1.3165×10^{-5}
	1421	10.45	4.6634×10^{-5}
	1455	19.35	8.6351×10^{-5}
	1481	35.05	1.5641×10^{-4}
	1516	66.65	2.9743×10^{-4}

	T(°K)	Deflections (deg.)	P calculated (atm)
RUN NO. 2	1528	77.70	3.4674×10^{-4}
	1512	57.30	2.5571×10^{-4}
	1479	30.80	1.3745×10^{-4}
	1490	37.40	1.6690×10^{-4}
	1505	49.40	2.2045×10^{-4}
	1503	46.35	2.0684×10^{-4}
	1480	30.05	1.3410×10^{-4}
	1447	15.40	6.8724×10^{-5}
	1416	8.30	3.7040×10^{-5}
	1427	10.10	4.5072×10^{-5}
	1450	15.50	6.9170×10^{-5}
	1422	9.90	4.4180×10^{-5}
	1397	5.15	2.2982×10^{-5}
	1380	3.30	1.4727×10^{-5}

Least squares analysis of all 26 data points has:

$\Delta H_v^o = 130.8 \pm 1.6$ Kcal

$\Delta S_v^o = 61.6 \pm 0.5$ e.u.

1.00 mm diameter orifices

	T(°K)	Deflections (deg.)	P calculated (atm)
RUN NO. 1	1526	150.60	3.6727×10^{-4}
	1513	123.00	2.9989×10^{-4}
	1509	113.50	2.7668×10^{-4}
	1492	80.10	1.9524×10^{-4}
	1503	98.30	2.3960×10^{-4}
	1523	137.30	3.3470×10^{-4}
	1489	72.05	1.7569×10^{-4}
	1482	61.10	1.4892×10^{-4}
	1366	4.85	1.1826×10^{-5}
	1378	6.50	1.5842×10^{-5}
	1421	17.20	4.1948×10^{-5}
	1404	11.65	2.8382×10^{-5}
	1436	23.20	5.6541×10^{-5}
	1445	30.60	7.4526×10^{-5}
	1450	31.65	7.7114×10^{-5}

	T(°K)	Deflections (deg.)	P calculated (atm)
RUN NO. 2	1525	150.55	3.6700×10^{-4}
	1515	122.65	2.9897×10^{-4}
	1503	98.30	2.3961×10^{-4}
	1483	61.50	1.4992×10^{-4}
	1505	102.55	2.5001×10^{-4}
	1523	134.20	3.2714×10^{-4}
	1489	69.50	1.6942×10^{-4}
	1459	40.90	9.9657×10^{-5}
	1444	32.00	7.7993×10^{-5}
	1434	21.95	5.3512×10^{-5}
	1420	16.60	4.0513×10^{-5}
	1435	22.55	5.5028×10^{-5}

Least squares analysis for 27 data points in 1.00 mm orifices has:

$\Delta H_v^o = 133.9 \pm 1.2$ Kcal

$\Delta S_v^o = 64.0 \pm 0.9$ e.u.

Least squares analysis of all six runs (84 points) has:

$\Delta H_v^o = 132.6 \pm 0.9$ Kcal

$\Delta S_v^o = 63.1 \pm 0.4$ e.u.

When the corrections from deviations in the tin calibrations are incorporated, the thermodynamic quantities of interest for strontium sulfate are:

$\Delta H_v^o = 127.4 \pm 0.9$ Kcal

$\Delta S_v^o = 58.5 \pm 0.4$ e.u.

REFERENCES

1. K. H. Stern and E. L. Weise, High Temperature Properties and Decomposition of Inorganic Salts; Part One: Sulfates, NSRDS-NBS7, October 1966.
2. D. A. Young, Decomposition of Solids, Chapters 1 and 3, Pergamon Press, New York (1966).
3. R. D. Shannon, Trans. Far. Soc. 60, 1902 (1964).
4. A. W. Searcy, et al. (editors) Chemical and Mechanical Behavior of Inorganic Materials, Chapter six, Wiley-Interscience, New York (1968).
5. cf. A. W. D. Hills, Chem. Eng. Science 23, 297 (1968).
6. D. Beruto, unpublished work, University of California (1971).
7. cf. E. Rutner, et al. (editors) Condensation and Evaporation of Solids, Gordon and Breach, New York (1964).
8. cf J. P. Hirth and G. M. Pound, Condensation and Evaporation, Nucleation and Growth Processes, Pergamon Press, New York (1964).
9. I. Karutz and I. N. Stranski, Z. Anorg. Allg. Chemie. 292, 330 (1957).
10. R. W. Mar and A. W. Searcy, J. Phys. Chem. 71, 888 (1967).
11. D. Beruto and A. W. Searcy, unpublished work, University of California (1972).
12. P. Mohazzabi, M. S. Thesis, LBL-1416, January 1973.
13. R. T. Coyle, Ph.D. Thesis, LBL-136, January 1972.
14. J. Margrave (editor), The Characterization of High Temperature Vapors, Chapter 5, Wiley, New York (1967).
15. P. E. Hart, M.S. Thesis, UCRL-16568, December 1965.

16. C. A. Jacobson, et al. (editors), Encyclopedia of Chemical Reactions, Volumes One and Four, Rheinhold, New York (1946 and 1951).

17. R. Galluzzo, M.S. Thesis, UCRL-20528 April 1971.

18. R. Hultgren, et al. (editors), Supplement to Selected Values of Thermodynamic Properties of Metals and Alloys, unpublished compilation.

19. D. A. Schulz, Ph.D. Thesis (1962).

20. P. R. Bevington, Data Reduction and Error Analysis for the Physical Sciences, Chapters two and six, McGraw-Hill (1969).

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TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720