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SOLUBILITY OF GASES IN GLASS. III. EXPERIMENTAL STUDIES OF He, Ne, AND H_2 IN FUSED SILICA

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ABSTRACT

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A previously derived model of gas solubility in glass was compared with experiment for a variety of systems. Three main categories of solubility were considered: (a) physical solubility of monatomic gases, (b) physical solubility of polyatomic gases, and (c) chemical solubility of polyatomic gases. Case (a) was observed for helium and neon in fused silica. Variations of the thermal history of the fused silica did not appear to have a measurable effect on physical solubility as evidenced in the helium data. Case (b) was observed for hydrogen in fused silica. Physical solubility was measured by a modified Seiverts' technique and was characterized by a linear dependence on pressure. Binding energies for the physically dissolved species were of the order expected for van der Waals bonding. Vibrational frequencies were on the order of 10^{13} sec^{-1} with the heavier species having the lower frequencies. Case (c) was observed for hydrogen in fused silica using previous literature data. The fused silica of this study did not display chemical solution of hydrogen perhaps due to the presence of water-produced hydroxyls. Comparison of the model with the literature data showed a $p^{1/2}$ pressure dependence for the solubility (indicative of dissociation) and a binding energy of about 63 kcal/mole (indicative of chemical bonding).

INTRODUCTION

Experimental measurements of gas-in-glass solubility were made in order to test available statistical mechanical models of gas solubility in glass.[1,2] New measurements were desirable as most of the literature data was available over a limited temperature range or from indirect measurements (usually from permeation and diffusion experiments).[3,4]

The glass used was fused silica, the simplest of the silicate glasses and a commonly used material. The gases used were those known to be most soluble in fused silica, viz. helium, neon, and hydrogen. The primary experimental technique was a modification of Seiverts' method[5] used for measuring gas solubility in liquid metal alloys. Also, the chemical absorption of hydrogen was measured from the infrared absorption spectra. Hydrogen is of special interest as it shows both physical and chemical solubility.

EXPERIMENTAL METHOD

The solubility of helium, neon, and hydrogen in fused silica was measured. Care was taken to specifically characterize the thermal history of the fused silica. The measurement of gas solubility was made by two techniques: a modified Seiverts' technique and infrared absorption.

Thermal History

Brückner[6] reported a decrease in the density of fused silica with increased water content where the "water" existed in the glass as hydroxyl units. However, Douglas and Isard[7] reported an increase of similar magnitude in the density of fused silica with increased fictive temperature. Therefore, in order to have a well characterized fused

silica, it was necessary to have a knowledge of the simultaneous effects of both "water" content and fictive temperature on the glass density (which is indicative of the glass structure).

The sample material studied was a standard commercial fused silica[8] in the form of thin (about 0.005 in. thick) disks. An emission spectrographic analysis of the types of glass specimens used in this study is summarized in Table I. Specimens were treated with fictive temperatures of 1000, 1100, and 1200°C and in water vapor pressures from 0 to 1 atm. The treatments were ended with air quenches in order to "freeze in" the equilibrium glass structures. Details of the thermal history experiments are given elsewhere.[9]

Special care was taken in handling any fused silica in order to prevent devitrification. A standard preliminary cleaning procedure involved four steps: (a) 1 minute in xylene, (b) 15 seconds in a 5% HF solution, (c) 1 minute in distilled water, and (d) 1 minute in acetone. By handling the silica only with clean tweezers following this cleaning, no devitrification problems occurred.

Seiverts' Method of Measuring Solubility

A modification of Seiverts' method[5] was the primary technique used to measure gas solubility. A cell containing the sample material (fused silica) was evacuated, filled with the gas of interest to about 1 atm, and then sealed. The pressure of the system dropped slowly as the gas dissolved into the specimen. The total pressure drop indicated the amount of gas dissolved in the known amount of specimen at the final pressure and temperature.

Each sample cell was 1-3/4 inch deep and 3/4 inch diameter and located symmetrically in a nickel block. One cell was filled with fused silica rods of either 1 or 6 mm O.D., and the other was empty. The empty cell served as a control to monitor any pressure fluctuations which were not associated with solubility. The pressure in each cell was monitored by pressure transducers.[10] Nickel capillary tubing connected each transducer with its respective cell. The cells were heated in a Kanthal wound furnace. The cells and furnace were in a closed chamber which was evacuated and back-filled with argon.

A typical run involved evacuating the cells and heating the system to the experimental temperature. Care was taken to evacuate the experimental cell sufficiently to completely desaturate the fused silica of any dissolved gas. The cells were then back-filled with about one atmosphere of the gas of interest; the individual cell-transducer systems were sealed off; and the pressure of each was monitored. Depending on the system and temperature of operation, a final equilibrium pressure would be established in the experimental cell in from 30 minutes to 24 hours.

The high solubility of hydrogen in nickel required replacing the nickel cells with fused silica cells. Fused silica was then used both as the container and the specimen. This was undesirable but required because fused silica has about as low hydrogen solubility as any conveniently available container material. The amount of gas lost to the container in each experiment was indicated by the control cell, and the correction was made.

Ir Measurement of Solubility

A supplementary method for measuring gas solubility was available for the specific case of chemically dissolved hydrogen in fused silica. It has been noted[11,12] that chemically dissolved hydrogen is present as hydroxyl groups, which give an absorption peak at 2.7 μ in the ir spectra. This situation is essentially the same as noted for water solubility[13] and the experimental technique is very similar.

Disks of the kind used in the thermal history experiments were placed in a Brew furnace and heated to the desired temperature in one atmosphere of flowing hydrogen. The disks were cooled as quickly as possible (at about 300°C/min.) in order to quench in the chemically dissolved hydrogen.

The disks were placed in a Beckman IR-4 infrared spectrometer, and the ir spectrum was monitored from 2 to 5 μ to measure the hydroxyl peak.

RESULTS AND DISCUSSION

Solubility model equations have been derived in previous papers.[1,2] These equations express the solubility (n_s) of gas atoms or molecules at a given pressure as a function of temperature, fundamental constants, and material parameters.

The temperature range of interest extends from room temperature to near the glass transition temperature (around 1000°C for fused silica). The mass, m, of a given dissolved atom or molecule is known. The number of sites per unit volume, N_s, can be calculated with great accuracy for a crystal, since N_s is simply the number of most probable (usually largest) openings in the structure which would serve as solubility sites. The disordered structure of glass makes such estimates more difficult.

Furthermore, for chemical solubility, the "reactivity" of possible sites is a factor. For glasses with structures similar to known crystalline forms, a satisfactory estimate should be possible.

Values of θ_r, θ_{vi}, and ε_{el} for most common molecules in the gaseous state are readily available. The two parameters for the dissolved species are the vibrational frequency, ν, and the binding energy, E(0). Both can be estimated from calculations of the attractive and repulsive potentials acting on the dissolved species in the assumed solubility sites. But even for well-defined sites in a crystalline structure, only approximate values can be obtained because of uncertainty about the exact potentials involved. Consequently, ν and E(0) were chosen (see below) to best fit the experimental solubility data by varying them around values found by others for helium and neon solubility in crystalline oxides.

Following a summary of the characterization of the glass, the experimental solubility results will be correlated with the solubility equations.

Characterization of Fused Silica

Figure 1 shows the dependency of the density of fused silica on both water (or -OH) content and fictive temperature.[9] These data indicated the state of the solubility specimens following a given thermal treatment. The convenient glass transition range for fused silica is 1000 to 1200°C. Below 1000°C, structural relaxation occurs very slowly making equilibrium densities difficult to obtain. Above 1200°C, relaxation is rapid making quenches difficult. Also, devitrification becomes a problem above 1200°C. Most solubility specimens were given a fictive

temperature of 1100°C and were nearly water-free. Figure 1(a) indicates the best fit isotherms for the density-hydroxyl content variation. Figure 1(b) shows the density-fictive temperature constant composition curves corresponding to the isotherms of Fig. 1(a).

Physical Solubility - Helium in Fused Silica

The results of a typical experimental run with the Seiverts' type equipment is shown in Fig. 2 indicating the specimen cell pressure as a function of time. The pressure drop shown in Fig. 2 indicates about 90% of the gas solubility in the glass. However, some gas (about 10% of the total amount dissolved) enters the glass during the brief period of time when the cells are being filled with gas before the cells are sealed (at time = 0 in Fig. 2). The solubility data in this paper includes both contributions, i.e., the total solubility.

The collected solubility data for the helium-fused silica system are given in Table II. Three sets of data are noted. The (1100°C, "dry") set refers to a silica with a fictive temperature of 1100°C and nearly free of chemically dissolved water. The (1200°C, "dry") set refers to a water-free silica with a 1200°C fictive temperature. The (1100°C, "wet") data refers to a silica with 1100°C fictive temperature which was held for 7 days under 1 atm water vapor pressure at 1100°C giving a content of about 0.09 weight percent -OH. Within the scatter of the data, all three sets appear to follow essentially one curve as shown in Fig. 3.

It should also be noted that 1 mm silica rods were used as specimens for runs below 250°C, and 6 mm rods were used above 250°C because of the increasing diffusivity of helium in fused silica with temperature. Around 250°C, both sizes were used, and the resulting data were generally

in good agreement.

One feature of the physical solubility equation (Eq. (6) of ref. 1) is the linear dependence of solubility, n_s, on pressure, p. An experimental test of this feature for helium in fused silica at 209°C is shown in Fig. 4.

Figure 3 compares the experimental data for helium in fused silica with a plot of the physical solubility equation. The mass, $m = 6.64 \times 10^{-24}$ g, is that for helium. The number of sites, $N_s = 2.22 \times 10^{22}$ sites per cm^3 of glass, is that calculated for fused silica which has a slightly distorted cristobalite structure.[14] The values of ν ($= 6.9 \times 10^{12}$ sec^{-1}) and E(0) (= -1.5 kcal/mole) were chosen to give the best visual fit between the theoretical curve of Fig. 3 and the linear least squares fit of the data. The theoretical plot has a slight curvature. Both ν and E(0) are in good agreement with the range of values found for helium solubility in crystalline oxides including cristobalite.[15,16] For instance, Barrer and Vaughan[16] calculated ν to be in the range of 1.9 - 7.8×10^{12} sec^{-1} and E(0) from -2.0 to -3.16 kcal/mole for helium in cristobalite with the variation depending upon the method of calculation. This agreement of experiment and theory using reasonable parameters is considered quite satisfactory. The linear dependence of the solubility, n_s, on pressure, p, in Fig. 4 further displays this agreement.

It appears that the solubility of helium in fused silica is relatively insensitive to the thermal history of the glass. Some properties such as viscosity and the velocity of sound have been shown to be sensitive to small quantities of OH.[13] However, a property such as physical gas solubility would be expected to be primarily sensitive to

the site density, N_s, which (along with the bulk density) is varied by much less than 1% by any thermal treatment given to the samples of these experiments. Other parameters such as ν and E(0) which would depend upon the site geometry would reflect similarly small percentage changes. This insensitivity of solubility to thermal history is in agreement with the findings of Masaryk[17] that helium permeation through fused silica was only slightly affected by thermal history.

Physical Solubility - Neon in Fused Silica

The solubility data for the neon-fused silica system are given in Table III. Only (1100°C, "dry") data are given.

Figure 5 compares the experimental data for neon in fused silica with a plot of the physical solubility equation. The mass for neon is $m = 3.55 \times 10^{-23}$ g. The site density, N_s, is unchanged from the previous section. The values of ν (= 4.38×10^{12} sec^{-1}) and E(0) (= -2.8 kcal/mole) were chosen to give the closest agreement between the theoretical curve and the linear bestfit line of the data. The E(0) is in the same range found for helium and agrees favorably with the calculations of Barrer and Vaughan[16] for neon in crystalline silica. The lower ν is expected because the vibrational frequency of a harmonic oscillator is inversely proportional to the square root of its mass. This observation is discussed further in the next section. As with helium, good agreement is shown in Fig. 5 between the Ne-SiO_2 data and the model.

Physical Solubility - Hydrogen in Fused Silica

Data for the physical solubility of hydrogen in fused silica is given in Table IV. Only (1100°C, "dry") data were obtained.

An important test of the hydrogen data is the dependence of solubility on pressure. A linear dependence on pressure indicates molecular solubility, and a dependence on pressure to the one-half indicates dissociative solubility. Figure 6 shows a plot of solubility versus pressure at 447°C indicating linear dependence on pressure which is consistent with molecular solubility.

Figure 7 compares the experimental data for the physical solubility of hydrogen in fused silica with a plot of Eq. (8) of ref. 2 and is, as noted before, equivalent to Eq. (6) of ref. 1 for the monatomic case. The mass, m, of H_2 is 3.35×10^{-24} g. The site density, N_s, is unchanged from the previous sections. As for the monatomic cases, the values of ν (= 1.22×10^{13} sec^{-1}) and E(0) (= -3.04 kcal/mole) were chosen to give the closest agreement between the theoretical curve and the linear best-fit of the data. These values of ν and E(0) are in general agreement with those found for the monatomic gases. In the previous section, it was noted that the heavier dissolved species would be expected to have the lower values of ν. Table V summarizes the mass and vibrational frequency relationships for the three physically dissolved gases of this study. The results of Table V are in good qualitative agreement with the expectation noted above although ν is not exactly inversely proportional to the square root of the mass, m. The deviation could result from different force constants for the three oscillators, non-ideality of the oscillation, imprecision of the data, or, more likely, a combination of all these factors. However, the overall agreement between the model and experimental results for physical hydrogen solubility is considered quite satisfactory.

Chemical Solubility - Hydrogen in Fused Silica

Lee, et al.[11,18-20] have reported the chemical solubility of hydrogen in fused silica above 500°C. This solubility was in addition to the physical solubility. However, Lee's data had a good deal of scatter and the results varied greatly between different types of fused silica. This lack of reproducibility might be the result of impurity dependence of the chemical hydrogen solubility. Bell, et al.[12] have reported what appears to be the only unambiguous data for chemical hydrogen solubility in fused silica. Using essentially water-free silica,[21] the concentration of chemically dissolved hydrogen (as OH units) was determined after various treatments in hydrogen gas using ir spectroscopy as described in the Experimental Method Section. Unfortunately, experiments were carried out at only two temperatures. At 800°C under 1 atm of hydrogen gas, a solubility of 0.0018 weight percent OH was obtained. At 1050°C, the hydroxyl content was 0.00165 weight percent. Although only two temperatures were studied, extensive observations of the pressure dependencies of solubility were made at each temperature. The results, shown in Fig. 8, closely follow a $p^{1/2}$ dependency for the solubility indicating dissociative or chemical solubility of the hydrogen.

Attempts were made to reproduce the result of Bell, but all were unsuccessful. No chemical hydrogen solubility was observed in the Amersil fused silica used in this study. The first attempt was to reproduce the experimental technique of Bell. However, this objective was hindered by two factors. First, the low concentration of chemical hydrogen as reported by Bell would not be sufficient to produce measureable

ir absorption for the thin (aout 0.005 in. thick) disks. The solubility of water as OH in the silica was about two orders of magnitude higher than the hydrogen-produced OH concentration making the thinner disks acceptable for water solubility measurements but not for chemically dissolved hydrogen. The second problem arose when thicker disks were used in order to obtain a measurable ir absorption. The as-received Amersil had a significant "water" content (about 0.01 weight percent -OH) which would require prohibitively long times to desaturate because the diffusivity of chemically dissolved water is much lower than that for chemically dissolved hydrogen. Consequently, the high "water" absorption peak at 2.7 μ masked any "hydrogen" absorption peak at the same wavelength in the ir range. Therefore, chemical hydrogen solubility in Amersil could not be measured by ir techniques even though the possibility of solubility still existed.

The second attempt to observe this solubility was with the modified Seiverts' apparatus used in measuring the physical solubility of hydrogen below 500°C. The chemical solubility reported by Bell is on the order of 6×10^{17} equivalent molecules of H_2 per cm^3 at 1 atm H_2 pressure at 800°C. Extrapolation of the physical data to this temperature gives a solubility of about 2×10^{17} molecules H_2 per cm^3 atm which means the chemical solubility should be the primary contribution in this temperature range and should be easily measurable with the Seiverts' apparatus. The diffusivities of chemical hydrogen as given by Bell indicated saturation times on the order of one or two hours in this temperature range. However, several experimental runs in the temperature range of 700 to 800°C failed to show any significant solubility above the level expected

for physical solubility and solubility increased as p^1 indicating non-dissociation. Even considering the additional experimental uncertainty which was introduced by the increasing hydrogen permeation through the walls of the silica cells in this temperature range, it can be concluded that any chemical solubility of hydrogen in the Amersil material could not be more than a few percent of the values found by Bell in I. R. Vitreosil.

The anomalous results of Lee and the contrasting results of Bell and this study indicate that the chemical solubility of hydrogen in fused silica is highly sensitive to the history of the glass specimens. The most likely hinderence to the chemical solution of hydrogen would seem to be the water dissolved as OH in the glass. Even the relatively dry Amersil used in this study probably contained an OH concentration due to water as great or even greater than the potential OH concentration which could have resulted from hydrogen solution. Consequently, the Bell data obtained in a material unusually free of water-produced hydroxyls can be considered the most meaningful indication of chemically dissolved hydrogen in fused silica, and it provides the best opportunity for testing the chemical solubility equation.

All of the variables in Eq. (15) of ref. 2, except one, are fixed for the given system. The mass, m, of a hydrogen molecule is 3.35×10^{-24} g. The values of θ_r (= 87.5°K), θ_{vi} (= 6350°K), and ε_{el} (= $-D_e$ = -7.63×10^{-12} ergs/molecule) were all obtained from the JANAF Table[22] data for molecular hydrogen. The site density, N_s, was again 2.22×10^{22} sites per cm^3. The value of θ_v (= 5330°K) corresponds to the observed ir absorption peak for hydrogen-produced hydroxyls in fused silica at a

wavelength of 2.7 μ. This leaves only E(0), the binding energy of the dissociated hydrogen atom to the silica structure, unspecified. A value of -63 kcal/mole for E(0) gave general agreement with the solubility values found by Bell over the temperature range of 800 to 1050°C. (See Fig. 9.) This value is indicative of a relatively strong chemical bond and contrasts with the values of a few kilocalories found for physical solubility which were indicative of relatively weak van der Waals bonding. At this point, it is difficult to determine the significance of the conflicting slopes of the data and the plot. Bell's data shows a slight decrease of solubility with temperature while the plot rises slightly with temperature. Additional solubility data could provide definite determination of the experimental temperature dependence of solubility. The disagreement could be the result of the idealized assumptions used in deriving the equation. In particular, 1050°C is well into the transition range of fused silica so that the assumption of a rigid structure implicit in the model is less valid. However, Fig. 9 is qualitatively satisfactory since it gives general agreement in the magnitude of solubility over the temperature range using an E(0) value indicative of chemical bonding of the dissociated hydrogen atom to the silica structure.

SUMMARY

The solubility of gases in silica glass below its transition range, i.e., where it is a rigid solid, has been examined. The statistical thermodynamics of the system provided a basic model of the solubility. The solubility equations gave the solubility (in atoms or molecules per cubic centimeter of glass) as a function of gas pressure, temperature,

fundamental constants, and material parameters. Three main categories of solubility were considered: (a) physical solubility of monatomic gases, (b) physical solubility of polyatomic gases, and (c) chemical solubility of polyatomic gases. The results for (a) and (b) were essentially equivalent. The results for (c) depend upon the specific system involved.

The model was compared with experimental results for a variety of systems. The physical solubility of the monatomic gases for helium and neon in fused silica were measured by a modified Seiverts' technique. Variations in the thermal history of the fused silica did not have a measurable effect on physical solubility as evidenced in the helium data. The physical solubility of polyatomic gases was observed for hydrogen in fused silica, again using the Seiverts' technique. Physical solubility was characterized by a linear dependence on pressure. Binding energies for the physically dissolved species were of the order expected for van der Waals bonding. Vibrational frequencies of the dissolved species ranged from 4.38×10^{12} to 1.22×10^{13} sec^{-1} with the heavier species having the lower frequencies, as expected. Experiments of this study using both Seiverts' method and ir spectroscopy could not observe chemical solubility of hydrogen in the Amersil specimens. However, literature data on I. R. Vitreosil displayed the $p^{1/2}$ dependence indicative of chemical solubility. Comparison of the data with the model gave a binding energy of about 63 kilocalories per mole indicative of a relatively strong chemical bond between the dissolved hydrogen atom and the silica structure. It appears that chemical solubility of hydrogen in fused silica is highly sensitive to specimen history,

especially the water-produced hydroxyl concentration.

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Table I. Emission Spectrographic Analysis of Fused Silica Specimens*

Reported as oxides of the elements indicated.

	0.005 inch thick disk (thermal history specimen)	1 mm dia. rod (solubility specimen)	6 mm dia. rod (solubility specimen)
Si	Principal constituent in each sample		
Al	0.002%	0.003%	0.015%
Ca	<0.001	0.005	<0.001
Ti	--	0.001	--
Mg	<0.001	<0.001	<0.001

* Amersil CFQ Rod, Standard Quality (T-08); Amersil, Inc., San Francisco, California.

Table II. Solubility Data for Helium in Fused Silica

T(°K)	Solubility (atoms/cc·atm)			T(°K)	Solubility (atoms/cc·atm)		
325	4.59×10^{17}		(C,a)	476	2.99×10^{17}		(C,a)
326	4.65	"	(A,a)	482	2.98	"	(A,a)
327	4.78	"	(C,a)	486	2.68	"	(B,a)
352	4.39	"	(A,a)	523	2.53	"	(C,a)
375	3.97	"	(A,a)	523	2.69	"	(C,a)
376	4.25	"	(C,a)	528	2.79	"	(A,a)
379	4.08	"	(C,a)	529	3.03	"	(A,b)
381	4.22	"	(B,a)	529	2.80	"	(A,b)
401	3.57	"	(A,a)	624	2.56	"	(A,b)
424	3.56	"	(C,a)	624	2.46	"	(A,b)
428	3.80	"	(A,a)	716	2.20	"	(A,b)
431	3.34	"	(C,a)	721	2.20	"	(A,b)
450	3.25	"	(A,a)	811	2.01	"	(A,b)
476	2.85	"	(C,a)	813	1.94	"	(A,b)

A - T_F = 1100°C, "dry"

B - T_F = 1100°C, "wet"

C - T_F = 1200°C, "dry"

a - 1 mm dia. rods

b - 6 mm dia. rods

Table III. Solubility Data for Neon in Fused Silica

T(°K)	Solubility (atoms/cc.atm)	
670	2.09×10^{17}	(a)
716	1.91 "	(a)
762	2.03 "	(a)
764	1.82 "	(a)
808	1.69 "	(a)
815	1.54 "	(a)
856	1.52 "	(a)
859	1.53 "	(a)
902	1.36 "	(a)
904	1.48 "	(a)
955	1.35 "	(a)
955	1.41 "	(a)
1040	1.21 "	(b)
1050	1.42 "	(b)

a - 1 mm dia. rods (T_F = 1100°C, "dry")

b - 6 mm dia. rods (T_F = 1100°C, "dry")

Table IV. Physical Solubility Data for Hydrogen in Fused Silica

T(°K)	Solubility (molecules/cc.atm)*
582	4.35×10^{17}
583	4.84 "
631	3.67 "
631	3.68 "
675	3.50 "
680	3.33 "
720	3.21 "
721	3.28 "
765	2.80 "
766	2.90 "

*All specimens - 1 mm dia. with T_F = 1100°C, "dry"

Table V. Summary of Mass and Vibrational Frequency Relationships for Physically Dissolved Gases

Gas species	Mass	Vibrational frequency (ν)	$(m/m_{H_2})^{1/2}$	(ν_{H_2}/ν)
H_2	3.35×10^{-24} g	1.22×10^{13} sec^{-1}	1.0	1.0
He	6.64×10^{-24}	6.90×10^{12}	1.41	1.77
Ne	3.35×10^{-23}	4.38×10^{12}	3.16	2.79

FIGURE CAPTIONS

Fig. 1. Summary of thermal history experiments for fused silica (after ref. 9).

Fig. 2. Experimental cell pressure versus time for a typical Seiverts' type solubility experiment.

Fig. 3. Helium-fused silica data with plot of the physical solubility model equation.

Fig. 4. Solubility versus pressure for helium in fused silica at 209°C.

Fig. 5. Neon-fused silica data with plot of the physical solubility model equation.

Fig. 6. Solubility versus pressure for physically dissolved hydrogen in fused silica at 447°C.

Fig. 7. Hydrogen-fused silica data with plot of the physical solubility model equation.

Fig. 8. Solubility versus $(\text{pressure})^{1/2}$ for chemically dissolved hydrogen in fused silica at 800 and 1050°C (after ref. 12).

Fig. 9. Hydrogen-fused silica data with plot of the chemical solubility model equation.

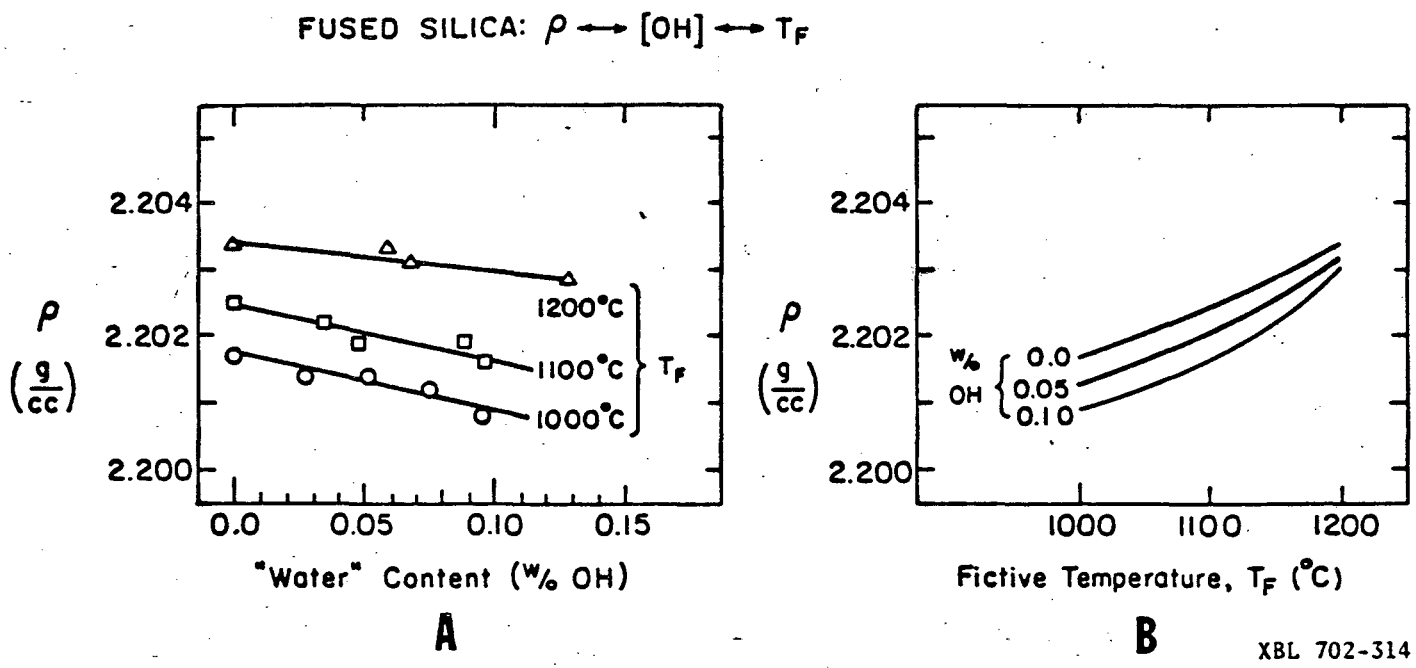
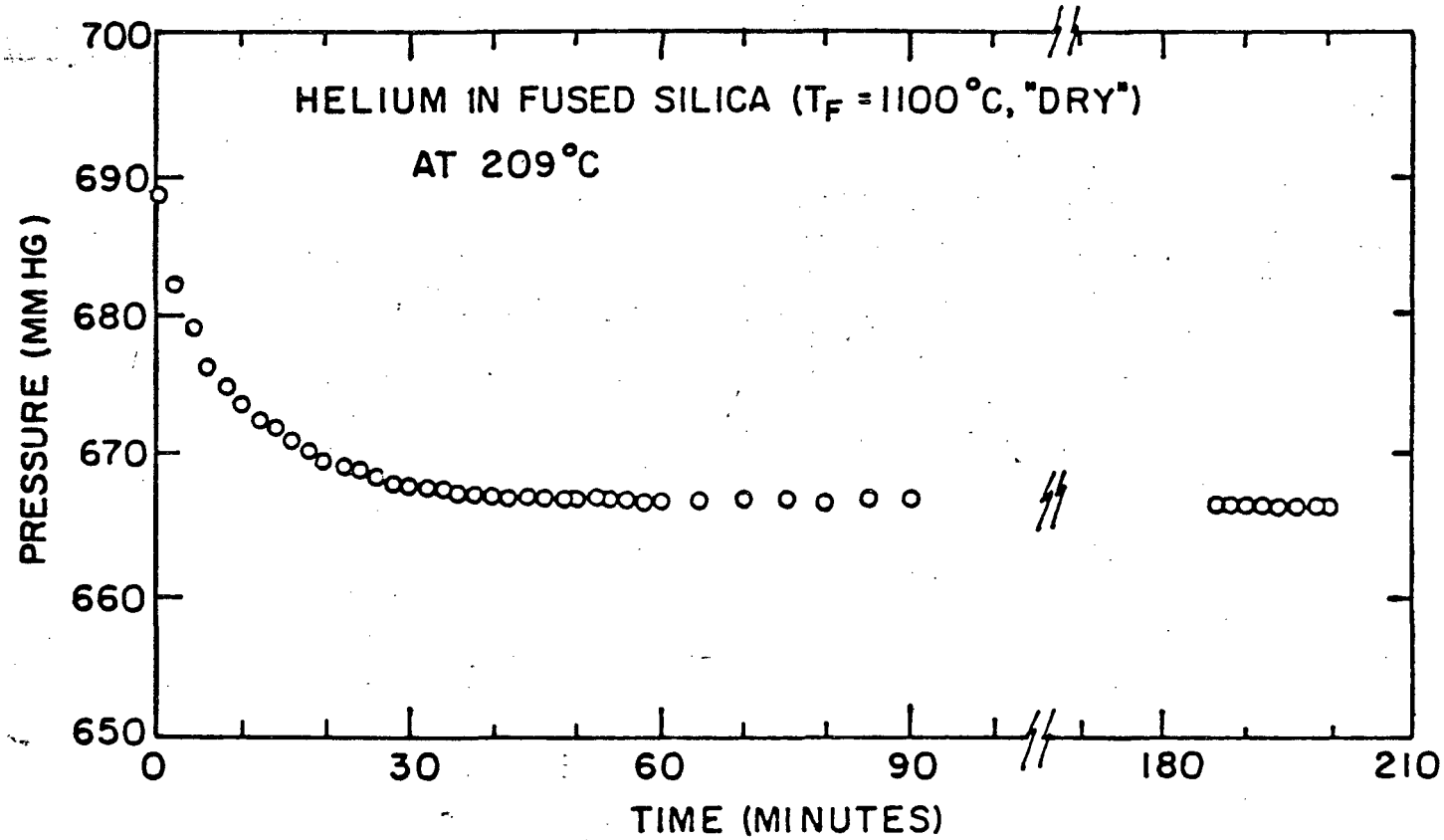
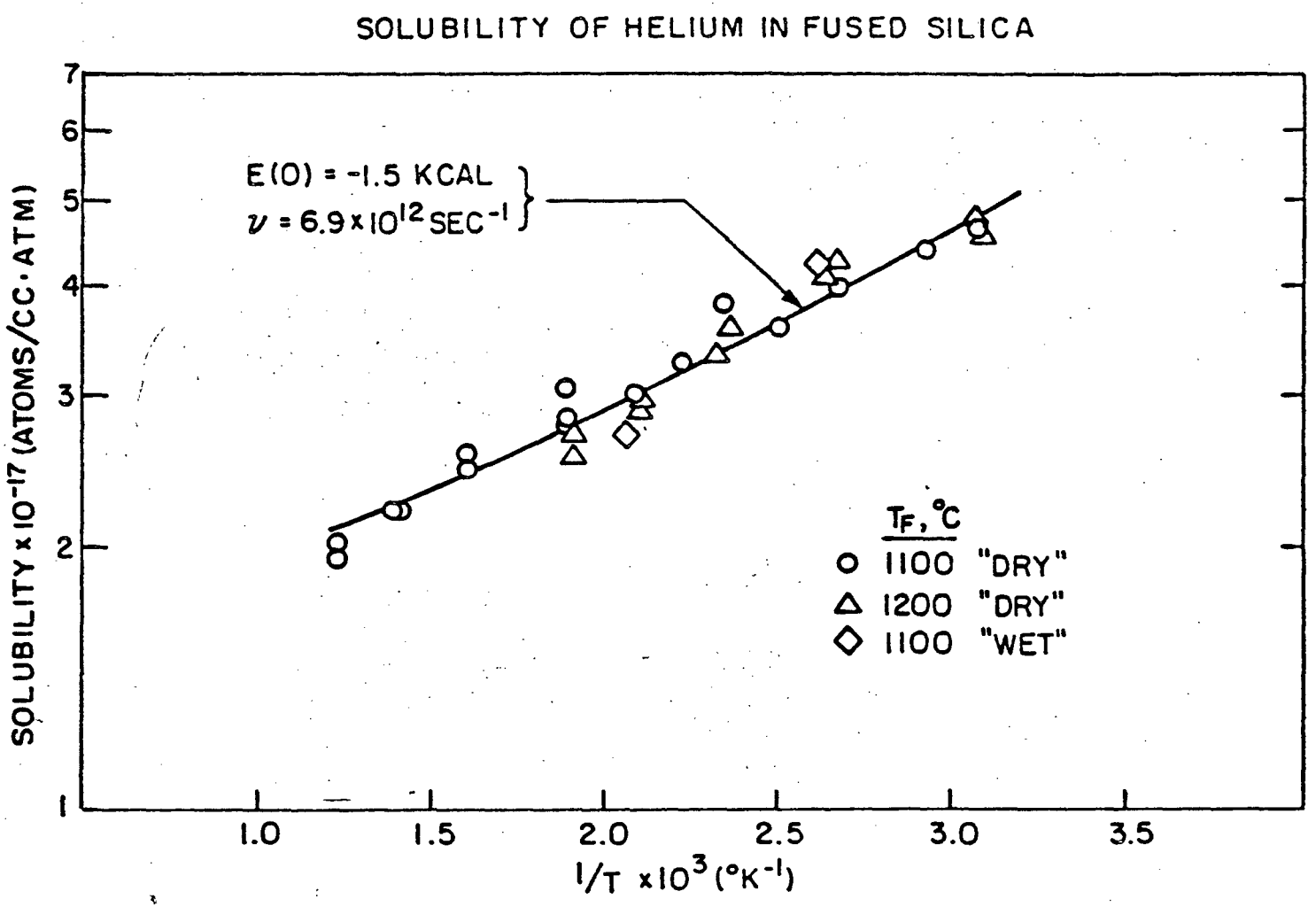

FUSED SILICA: ρ ⟷ [OH] ⟷ T_F
ρ (g/cc)
2.204
2.202
2.200
0.0
0.05
0.10
0.15
1200°C
1100°C
1000°C
T_F
"Water" Content (w/o OH)
A
1000
1100
1200
w/o OH
0.0
0.05
0.10
Fictive Temperature, T_F (°C)
B
XBL 702-314

Fig. 1



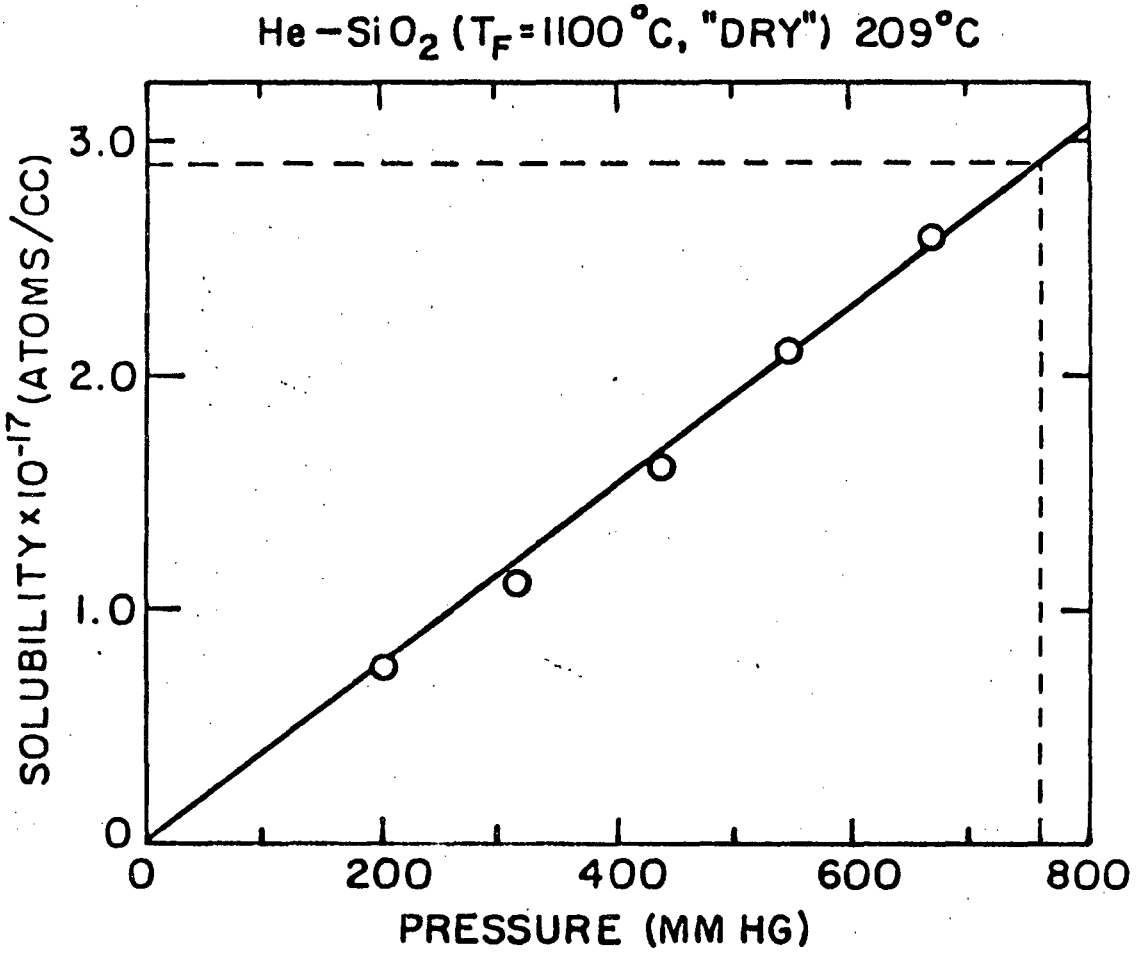
XBL 7012-7418

Fig. 2



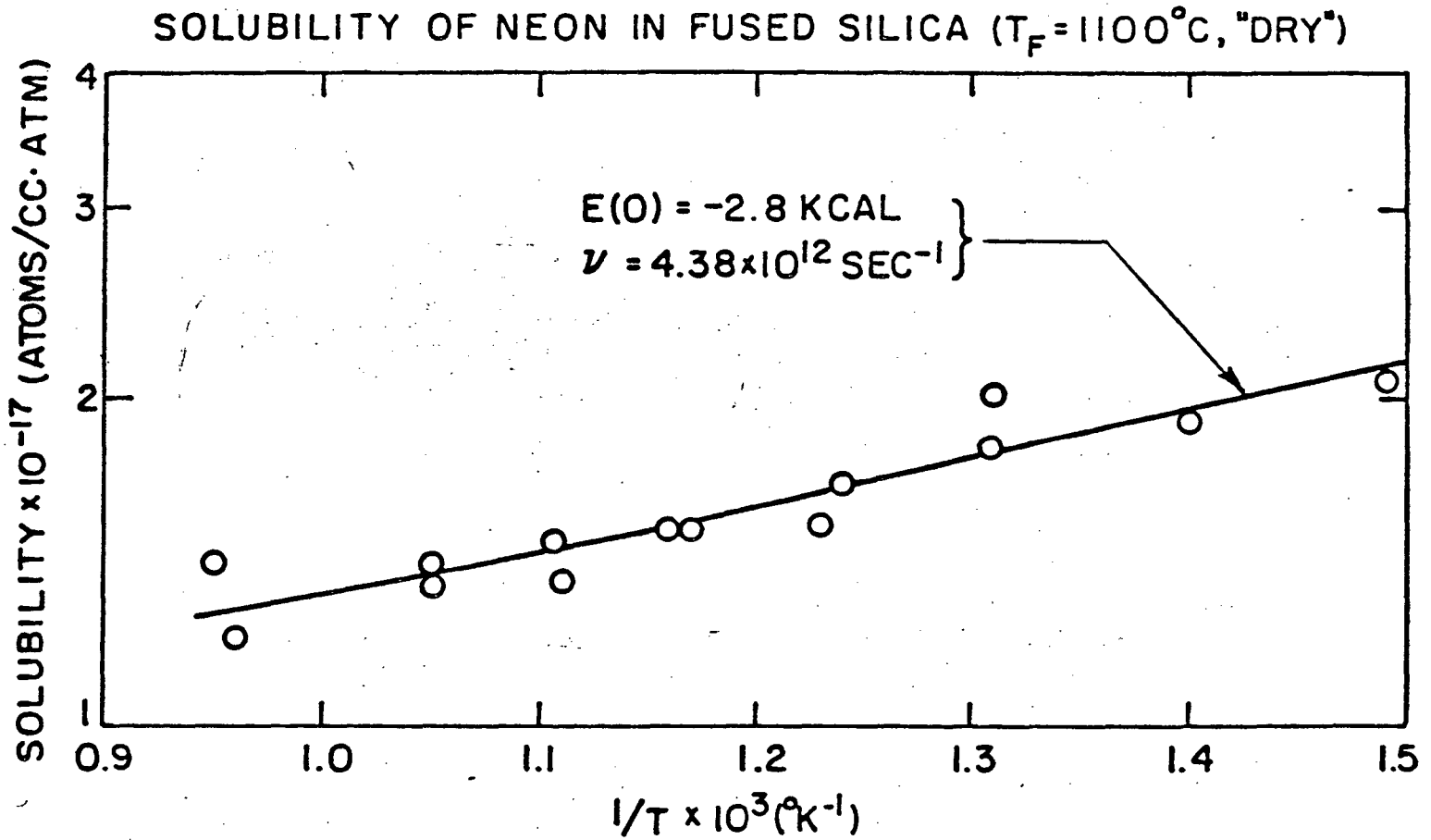
XBL 7012-7421

Fig. 3



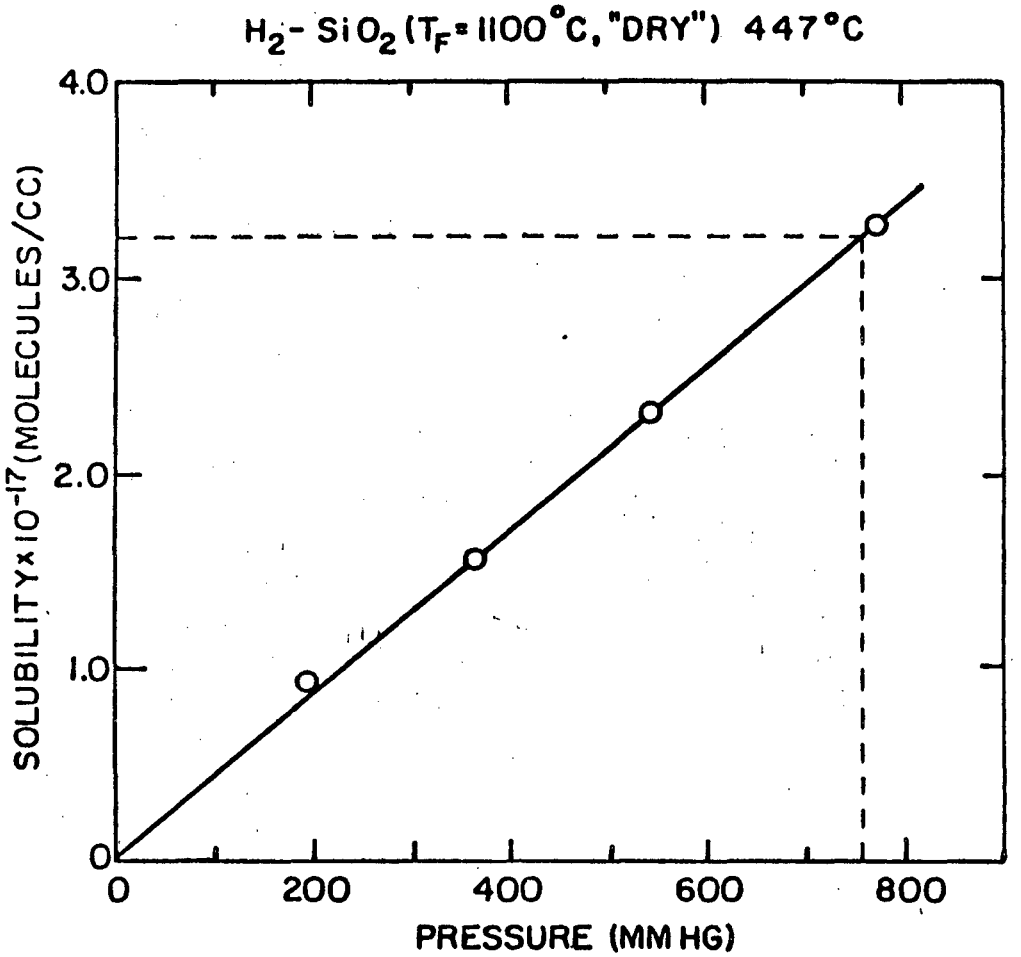
XBL 7012-7420

Fig. 4



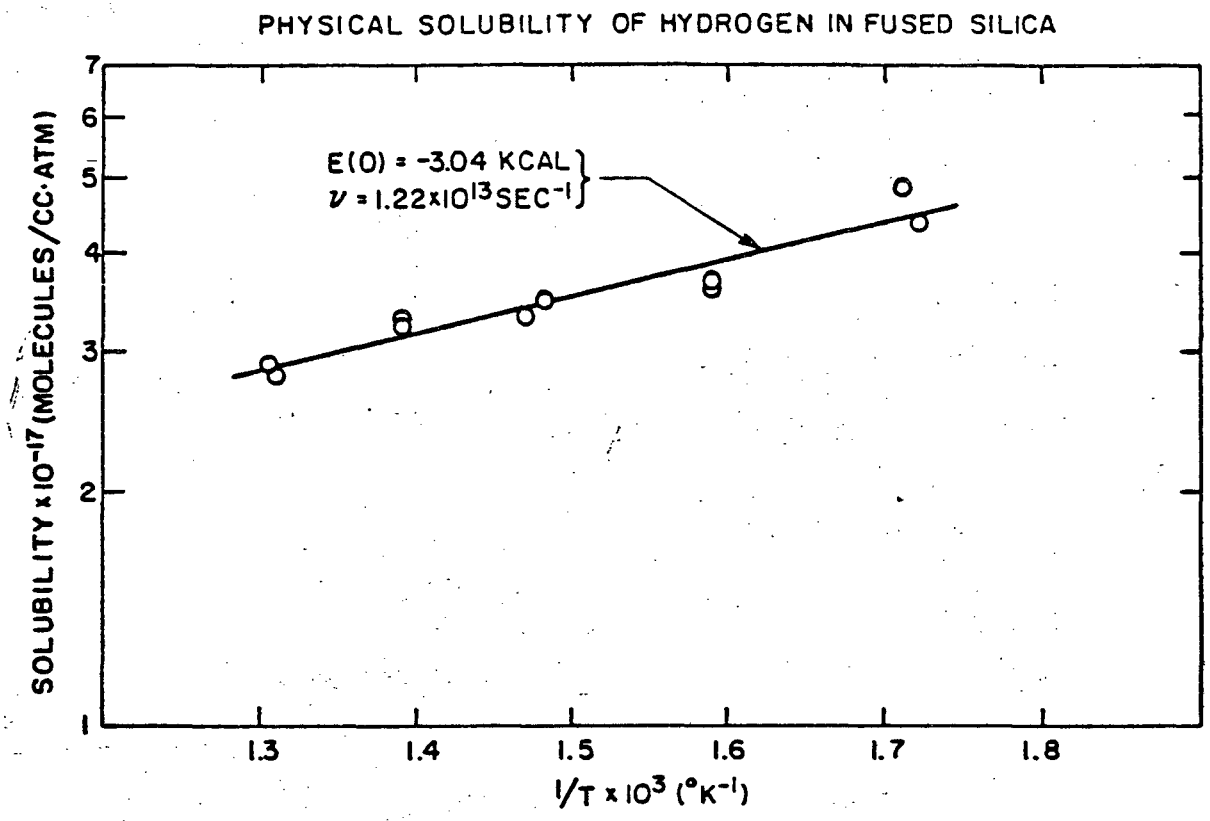
XBL 7012-7423

Fig. 5



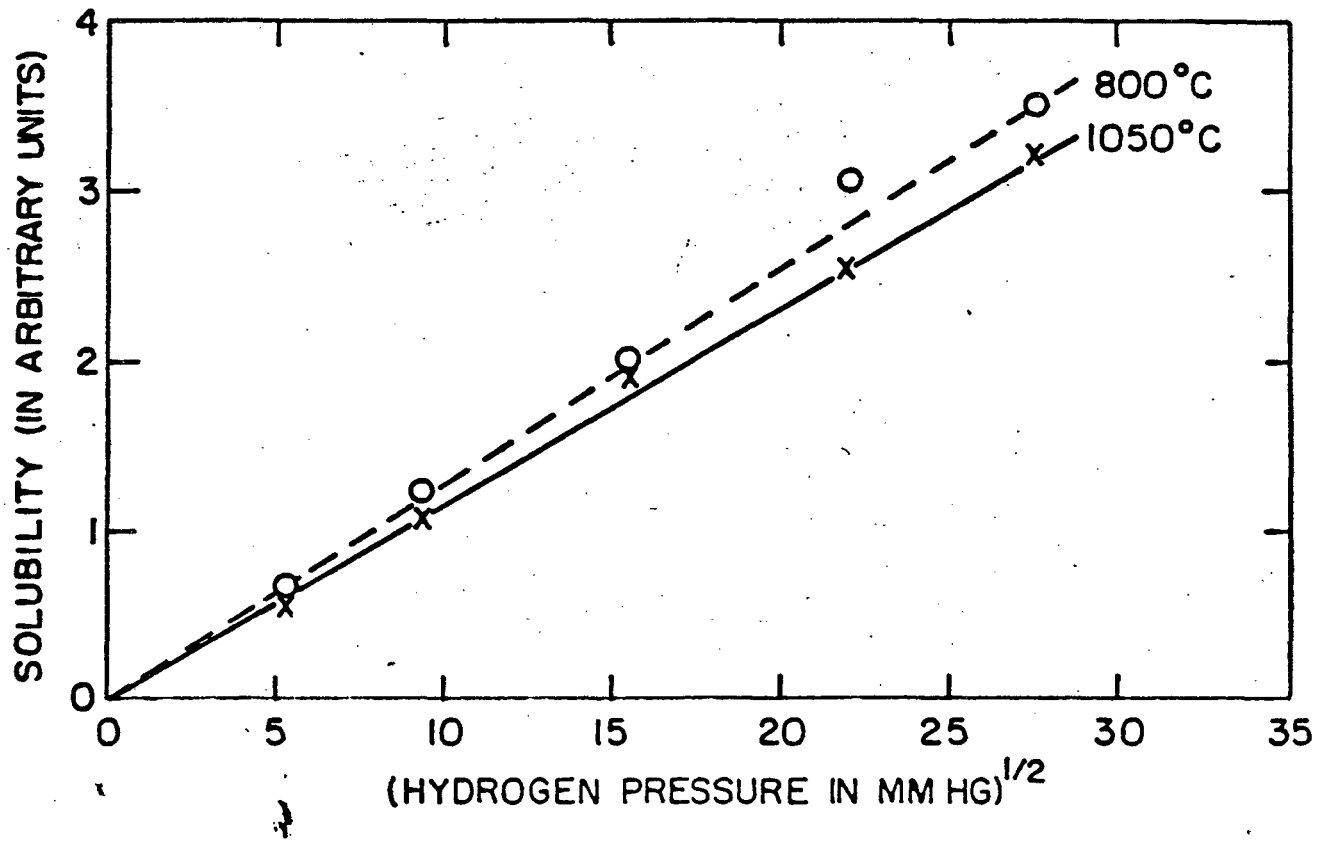
XBL 7012-7425

Fig. 6



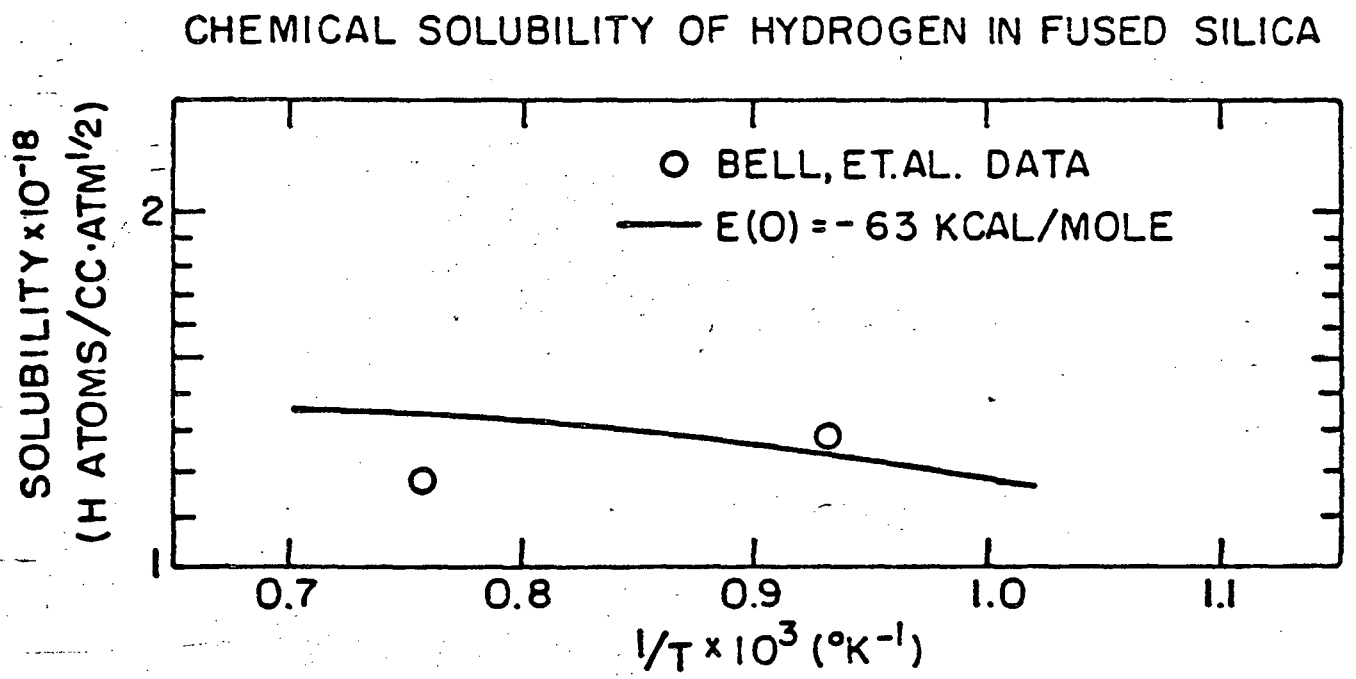
XBL 7012-7426

Fig. 7



XBL 7012-7427

Fig. 8



XBL 7012-7428

Fig. 9

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