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**AUTHORS' NAMES:**

O. Buck,<sup>1</sup> O. N. Carlson,<sup>1</sup> H. Indrawirawan,<sup>1</sup> L. J. H. Brasche,<sup>1</sup> and D. T. Peterson<sup>1</sup>

**TITLE OF PAPER:**

Internal Friction Peaks Due to Interstitials in BCC Alloys

**AUTHORS' AFFILIATIONS:**

<sup>1</sup>Ames Laboratory and Materials Science and Engineering Department, Iowa State University, Ames, Iowa 50011

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**ABSTRACT:** Richter's and Snoek's original works established the existence of an anelastic relaxation produced by a stress-induced interstitial reorientation in bcc metals. This anelastic relaxation, now referred to as a Snoek peak, has been studied extensively and well characterized in the past for the interstitials carbon, nitrogen, and oxygen. The existence of a hydrogen Snoek peak in bcc metals has been a matter of some controversy, however.

We have studied relaxation peaks in V, Nb, and V-Nb alloys recently. The alloys have complete mutual solubility and are of interest since they have an extremely high room temperature solid solubility for hydrogen. They also have, over a certain composition range, not shown any hydride phase precipitation at temperatures as low as 4K. Thus, if a hydrogen Snoek peak does exist, it should be found in such alloys. Indeed there is evidence now of a spectrum of hydrogen relaxation peaks below room temperature. Furthermore, there is a large misfit of V in Nb and Nb in V and, possibly, some chemical interaction such that trapping (or antitrapping) of the interstitials at the substitutional sites, causing solute-interstitial peaks, can be characterized.

The present paper provides an overview of our observations regarding: 1. The effect of hydrogen on the oxygen and nitrogen Snoek peaks in pure V and Nb, 2. The oxygen relaxation peaks in V-Nb alloys, 3. The hydrogen relaxation spectrum in V-Nb alloys, and 4. The effect of oxygen on the hydrogen relaxation spectrum in V-Nb alloys.

**KEY WORDS:** vanadium, niobium, oxygen, nitrogen, hydrogen, Snoek peak, anelastic relaxation, trapping, antitrapping

## Introduction

The interest in the stress-induced reorientation of dilute solute interstitials atoms, such as carbon, nitrogen, and oxygen, in bcc metals started with Richter's [1,2] and Snoek's [3] original works. This reorientation gives rise to pronounced internal friction peaks, now called Snoek peaks [4]. In recent years information on these peaks has increased dramatically, particularly for the metals V, Nb, Ta, and Fe [5]. The locations of these peaks with respect to temperature and frequency are relatively well known as are the activation energies and pre-exponential factors such that the identification of the peaks does not present a particular problem. On the other hand, some argument has developed [5-9] as to whether clustering or anticlustering occurs with increasing solute interstitial concentration. The clustering model suggests formation of solute interstitial pairs while anticlustering proposes a long range repulsive interaction between solute interstitials with the possibility of some interaction between different types of solute interstitials [5]. The situation becomes even more complicated in the presence of intrinsic atomic defects or, to be more specific, in the case of substitutional alloying where a substitutional-interstitial interaction may occur. Current models suggest the possibility of trapping or antitrapping [10-12] based on chemical and/or elastic interactions. The criterion that has been used to determine the degree of chemical interaction is the difference in the heats of formation of the oxides whereas the elastic interaction is controlled primarily by the size factor.

In our studies of interstitials in bcc alloys [13-20] we found the V-Nb alloy system to be particularly attractive. First of all, as mentioned earlier, the Snoek peaks of the "heavy interstitials" oxygen and nitrogen in both V and Nb are very well known [5]. Secondly, V and Nb have complete mutual solubility with a relatively large misfit of V in Nb or Nb in V and, possibly, some chemical interaction [16,17]. Thirdly, and from our interest most importantly, the hydrogen solubility in these alloys (in contrast to the pure metals) is extremely large [21] and, therefore, some hydrogen remains in solution in most of these alloys at temperatures as low as 4K. Thus, if a hydrogen peak does exist, it should be present in such alloys. Several independent studies have

confirmed its existence recently [13,14,18,22-24]. It is broader than a single relaxation peak with a distribution of activation energies. A separate study [25] provided activation energies and diffusion coefficients for long range diffusion of hydrogen. The comparison of the "mean" relaxation parameters with those obtained from the diffusion measurements looks very favorable [14,18]. The above observations immediately open the experimental opportunity to study possible interactions between the "light interstitial" hydrogen and the heavy interstitials by determining the activation parameters of one interstitial in the presence of the other. This is important in that there are reports in the literature assigning the appearance of internal friction peaks to the formation of interstitial complexes such as O-H (see for instance Refs. 26 and 27). Hypotheses of this type have been used to explain synergistic effects of interstitials on mechanical behavior of bcc alloys. Such hypotheses may now be confirmed or denied depending on the internal friction results. Since the V-Nb alloy system shows strong H-embrittlement [28,29], the above information may also be useful in interpreting this very practical, and so far not satisfactorily explained, problem.

The following paper provides a brief overview of internal friction studies on the V-Nb system [13-20]. In particular, we will describe the effects of hydrogen in solid solution on the oxygen and nitrogen Snoek peaks in V and Nb [15-19], the effect of substitutional alloying on the oxygen Snoek peak in V-Nb [16,17] as well as the hydrogen Snoek peak in V-Nb [14,18,24] and in oxygen-doped V-Nb [20]. The results serve as a basis for an explanation of some mechanical properties of V-Nb alloys as discussed elsewhere [30] and provide a reasonable self-consistent picture of interstitial and interstitial-solute interactions in this alloy system.

## **Experimental Methods**

Electron-beam melted niobium and vanadium, obtained from Teledyne-Wah Chang formed the basis of these investigations [13-20]. To produce the alloys, desired amounts of vanadium were added to niobium by arc melting in argon atmosphere. For specific details, see Ref. 28. Oxygen, nitrogen or hydrogen was introduced into the specimens by gas-phase charging, followed

by homogenization anneal. The chemical compositions of the alloys, in the following given in atomic percent, were determined by vacuum fusion analysis and confirmed with hardness measurements.

Internal friction measurements were carried out in an inverted pendulum apparatus at a frequency between about 0.1 and about 5 Hz or in a vibrating reed apparatus between about 200 and 2000 Hz, using electrostatic excitation and detection systems [18]. The damping,  $Q^{-1}$ , was obtained from the decay of the amplitude of the freely oscillating sample. In all experiments the maximum shear strains did not exceed  $3 \times 10^{-6}$ .

## Results

### Effects of Hydrogen on the Oxygen and Nitrogen Snoek Peaks in Vanadium and Niobium

The oxygen and nitrogen internal friction peaks in both V and Nb were found to be nearly ideal Debye peaks [15,19]. Figure 1 shows results [15] for the oxygen peak in V, plotted as  $Q^{-1}/Q_m^{-1}$  versus  $T^{-1}$ , where  $Q_m^{-1}$  is the damping at the peak maximum and  $T$  is the absolute temperature. Figure 1 shows that (a) this peak is unaffected by the presence of hydrogen (at least up to 0.45 at% H). Similar results were found for H/O ratios of 0.5, 1.0, and 2.0. The peak is a nearly perfect single relaxation Snoek peak, with an experimentally determined peak width at half maximum of  $1.02 \pm 0.04$  times the calculated width. Results on the oxygen peak in Nb in the presence of hydrogen [15] and on the nitrogen peak in Nb in the presence of hydrogen [19] were similar. Table 1 shows the activation parameters of the Snoek peaks compared to literature values. Overall, the present  $\Delta H$  and  $\tau_0$  results are in good agreement with the literature values, particularly for the oxygen Snoek peak in Nb. The only major discrepancy is a value of  $\Delta H = 1.29$  eV for oxygen in V, estimated by Weller [5] which is based on a combination of internal friction, elastic aftereffect [31] and diffusion [32] measurements. It is assumed [5] that the material apparently had a relatively large nitrogen content with respect to the vanadium used in the present investigation.

For Nb, it is known that nitrogen increases  $\Delta H$  of the oxygen Snoek peak which should also be true for V, thus probably leading to the observed discrepancy.

The major conclusion reached in these studies [15,19] was that there is no effect of the hydrogen on the oxygen and nitrogen peaks in either V or Nb, indicating that there is no interaction of hydrogen with oxygen or nitrogen at the temperatures where the Snoek peaks appear.

Unfortunately, pure V and Nb do not allow measurements to be made below room temperature where one would expect the hydrogen Snoek peak to occur. Hydrogen forms hydride precipitates which lead to a broad low temperature peak [34]. The temperature at which the first internal friction changes occur on cooling define a point on the alpha solid solution phase boundary for each composition. These points fit well on the phase diagram established by other authors [35,36]. Therefore, a true Snoek peak of hydrogen does not exist in pure V and Nb because the hydrogen is out of solution and in the hydride phase.

#### Effects of Substitutional Solutes on the Oxygen Relaxation in Vanadium and Niobium

The oxygen relaxation in V dilutely alloyed with Nb and in Nb dilutely alloyed with V was found to depend on the alloy composition [16, 17]. Figures 2 and 3 show oxygen peaks in Nb-rich alloys with 0.24 and 0.5 at% V. It is seen from Fig. 2 that the Nb-O Snoek peak expected at about 420K at 1 Hz is absent in the Nb-0.24 V alloy containing 0.10 at% O while a different peak,  $P_2$ , appeared at about 500K.  $P_2$  reaches a maximum, as clearly indicated in Fig. 3, reaching its maximum value at an oxygen concentration about equal to the vanadium concentration. Its half-width line broadening increases continuously from about 1.04 in Nb-0.24 V to about 1.35 in Nb-5.0 V [17]. Once it reaches its maximum value, a peak ( $P_1$ ) appears at about 400K at 0.25 Hz with a half-width line broadening that increases from about 1.15 in Nb-0.24 V to about 1.19 in Nb-0.5 V. The peak temperature of  $P_1$ , however, is close to that of the Snoek peak for oxygen in pure Nb as reported in the previous paragraphs.

As the V concentration is increased in the Nb-rich alloys a third peak, P<sub>3</sub>, appears in the vicinity of about 515K at a frequency of 0.6 Hz [17] with a half-width line broadening of about 1.43. As shown in Fig. 4, P<sub>2</sub> is still present in the Nb-5.0 V. It disappears, however, if the V concentration becomes too high. The alloy 90 Nb-10 V, doped with 0.61 at% O, shows only the broad peak P<sub>3</sub>, with a half-width line broadening of about 2.05 [17] at about 0.3 Hz and about 660K.

On the other hand, V-rich alloys with up to 0.5 Nb show only the V-O peak P<sub>1</sub> as shown in Fig. 5 with a half-width line broadening of about 1.25. P<sub>1</sub> was found [16] to be located at about 445K for a frequency of about 0.5 Hz. This peak temperature is close to that of the Snoek peak for oxygen in V as reported earlier. So far no experiments on V-rich alloys with Nb concentrations higher than 0.5 at% have been performed.

Table 2 provides the activation parameters determined in these studies [16,17]. The activation energies and relaxation times for P<sub>1</sub> and P<sub>2</sub> are almost independent of the substitutional and interstitial concentrations, increasing only slightly with alloy concentration, as does the peak broadening. P<sub>1</sub> appears, therefore, to be due to the oxygen Snoek peak in the respective host (Nb or V). P<sub>2</sub> appears to be due to the interaction of vanadium-oxygen pairs, if the vanadium concentration is at or below 5.0 at%. For higher V concentrations, clustering of two or more V atoms is very likely, giving rise to an additional peak, P<sub>3</sub>. With further increase of the V-concentration ( $\geq 10$  at% V) and further clustering of V, P<sub>3</sub> becomes broader with a slight increase in the activation energy [17]. The V-rich alloys that have been investigated thus far do not exhibit a Nb-O interaction peak.

Further evidence for the V-O interaction is provided in Fig. 6 [16]. The figure shows the height of the P<sub>1</sub> and P<sub>2</sub> peaks as a function of oxygen concentration for various alloys. P<sub>2</sub> reaches a maximum height at an oxygen concentration corresponding approximately to the V-concentration of the alloy (Fig. 6b). In Nb-rich alloys with 1.5 and 2.5 at% V, the saturation level was never reached for oxygen concentrations of up to almost 1 at%. P<sub>1</sub> appears as soon as P<sub>2</sub> exhibits saturation (Fig. 6a) with basically the same relaxation strength as that of the oxygen Snoek peak in

pure Nb.  $P_1$  in the V-rich alloys shows the same relaxation strength as the oxygen Snoek peak in pure V.

For the interpretation of the above results [16] the following model was developed. Neutron diffraction and ion channeling studies [37- 40] have shown that oxygen occupies octahedral sites in both V and Nb and it is assumed that they do likewise in the V-rich and Nb-rich alloys. Thus, solute-interstitial (s-i) pairs as shown in Fig. 7a may be created [41]. Assuming that the pairs are more strongly bound (trapping) in the A configuration (Fig. 7a), a jump from A to B would provide a peak ( $P_2$ ) above the Snoek peak ( $P_1$ ). Apparently there is trapping of oxygen at V and anti-trapping (repulsive forces) of oxygen at Nb [16] so that  $P_2$  could only be found in Nb-rich alloys. The results have been explained in terms of an elastic interaction [16, 41, 42]. A quasi-chemical model [43, 44], however, provided similar conclusions [16]. At an O/V ratio of about one the trapping sites become saturated and the almost unperturbed oxygen Snoek peak in Nb appears.

As the V concentration is increased the likelihood of V occupying adjacent or nearby sites as indicated in Fig. 7b is increasing. Three possible configurations for cells having two solute atoms have been discussed in detail by Pick et al [45]. In Nb-2.5 V, for instance, about 0.85% of the octahedral cells, as shown in Fig. 7b-d, contain two V atoms so that the likelihood of an additional internal friction peak ( $P_3$ ) becomes probable. In the Nb-10 V alloy 10% of all cells contain two V atoms and 1.5% contain three V atoms so that most of the oxygen is trapped on these sites. The trapping energies for cells with two V and for cells with three V atoms seem not to be much different [12,46,47] so that only one broad peak  $P_3$  appears, as observed.

### The Hydrogen Relaxation Spectrum in V-Nb Alloys

The existence of a relaxation peak due to hydrogen in solid solution in bcc alloys has been reported by a large number of investigators. We restrict our discussions to the V-Nb system only where some background information is now in existence [13,14,18,22-24].



The base alloys ranged from 70 V-30 Nb to 10 V-90 Nb [18,24]. An example of the internal friction as a function of temperature is shown in Fig. 8 for 70 V-30 Nb with hydrogen-concentrations as high as almost 1.8 at%. In the V-rich alloys above 70 V a second peak (in the vicinity of about 200K) may appear [18, 34] which has been attributed to hydride precipitation as expected from the phase diagram [21].

General observations on V-Nb alloys are that if the hydrogen is in solid solution, the peak height increases proportional to the H-concentration and that the temperature at which  $Q^{-1}$  is a maximum, shifts to slightly lower values with increasing H-concentration. Both effects can be seen in Fig. 8. It may also be noted that the temperature of maximum  $Q^{-1}$  depends, for the same hydrogen concentration, strongly on the alloy composition, with 30 V-70 Nb showing about the highest peak temperature [14, 18, 24]. Furthermore, we should add that deuterium shows similar results as does hydrogen [18,24]. The investigations [18,24] verified that the hydrogen internal friction peak is not a single relaxation peak as noted earlier [22]. In 70 V-30 Nb it is roughly a factor of three larger than the theoretical value as indicated by Fig. 9. However, the width depends on the alloy composition. A single relaxation analysis as applied to the oxygen and nitrogen peaks  $P_1$  and  $P_2$  therefore does certainly not apply. For this reason we selected the Direct Spectrum Analysis (DSA), developed by Cost [48-50], to analyze the hydrogen results. In this case the internal friction,  $Q^{-1}$ , is assumed to be a series of individual relaxation processes

$$Q^{-1}(T) = \sum \Delta_i \frac{\omega\tau_i}{1 + (\omega\tau_i)^2} \quad (1)$$

where

$$\tau_i = \tau_{oi} \exp (\Delta H_i/kT). \quad (2)$$

$\Delta_i$  is the relaxation strength of the  $i^{\text{th}}$  process and  $\omega$  is the frequency in rad/sec. To solve Eq. 1 one has to assume that either  $\tau_{oi}$  or  $\Delta H_i$  in Eq. 2 is constant. We chose to estimate a value  $\tau_o$  from the frequency shift of the measured internal friction peak (at 250 Hz and 1500 Hz) for at least one hydrogen concentration in each given alloy. We also estimated  $\tau_o$  at one frequency for two hydrogen concentrations. Since the resulting  $\tau_o$  values agreed very well with each other as well as with  $\tau_o$  values determined from diffusion measurements [25], we proceeded by assuming that all  $\tau_{oi} = \tau_o$  for each alloy.  $\Delta_i$  was chosen to be  $\Delta/n$  where  $\Delta$  is twice the measured peak height and  $n$  is the number of processes. The final step is an iteration procedure that chooses  $\Delta H_i$  such that the experimentally measured internal friction curves are matched by Eq. 1 to a desired precision. An example of such a DSA analysis for 70 V-30 Nb is shown in Fig. 10 indicating that the resulting internal friction spectrum is basically Gaussian and that the mean activation energy shifts to lower values with increasing hydrogen concentration.

Table 3 presents the mean activation energies (the activation energy at which the Gaussian peaks) - extrapolated to zero hydrogen concentration - and  $\tau_o$ , as obtained from internal friction measurements (including data from Ref. 22). Also given are these values for the 70 V-30 Nb containing 0.2 at% O, to be discussed later. The activation parameters are compared to those obtained by long range diffusion measurements [25] performed over a temperature range between 230 and 473K. In the latter case, it was assumed that the hydrogen jumps from tetrahedral to tetrahedral sites to convert  $D_o$  to  $\tau_o$  values [18,24]. Overall comparison of the activation parameters, determined by internal friction, with those obtained by long range diffusion measurements is very favorable. A comparison of the mean internal friction activation energies with those obtained by diffusion measurements are also shown in Fig. 11. Note that the internal friction results are found to be consistently higher by about 0.03 eV than the diffusion activation energies. However, both results show a similar trend with alloy composition and, therefore, there is little doubt that this low temperature hydrogen relaxation peak is a spectrum of H-relaxation peaks. Other investigators [22,23] reached similar conclusions for the 50 V- 50 Nb alloy.

Our preliminary conclusions, therefore, are as follows. The distribution of activation energies is probably due to a distribution of cells, similar to those shown in Fig. 7. In contrast to oxygen and nitrogen, the hydrogen occupies mostly tetrahedral sites [51]. Using slow neutrons, quasielastic scattering measurements on pure Nb indicate [51] that the hydrogen does not simply jump between nearest neighbor sites. In the alloys this situation is further complicated by the random distribution of host atoms so that, as the hydrogen jumps it will find a multitude of host environments. It is thus not surprising to find a peak which is much broader than a Debye peak. Based on this observation it may, therefore, not surprise one to find the activation energy for long range diffusion to be slightly lower than the average activation energy of the relaxation. It is possible that this difference is a result of slight trapping of the hydrogen by substitutional atoms at the lower temperatures. Evidence for this effect is shown in Fig. 12 [20]. Measurements at higher frequency yield higher activation energies for the 10 V-90 Nb alloy. A similar and more general observation can be made by a comparison of the low frequency data ( $\approx 1$  Hz) reported by Owen et al [14] with higher frequency data ( $\approx 200$  Hz) as shown in Table 3 and Fig. 11 on a variety of V-Nb alloys. The higher frequency data yield  $\Delta H$  values that are consistently higher than those obtained at lower frequencies. Thus, the data suggest that different jumps are operative in the different frequency ranges. A more extensive discussion is provided in Ref. 20.

#### Effects of Oxygen on the Hydrogen Relaxation Spectrum in V-Nb Alloys

Although we have clearly demonstrated that hydrogen does not affect the oxygen (and nitrogen) peak and that, therefore, there is no interaction at temperatures where those heavy interstitial Snoek peaks occur, such an interaction may still be possible at lower temperatures. The hydrogen Snoek peaks discussed in the previous paragraphs certainly provide an opportunity to study such an interaction. We selected a V-rich (70 V-30 Nb) and a Nb-rich alloy (10 V-90 Nb) for these studies [18,20].

The 70 V-30 Nb alloy contained 0.2 at% O and up to 1.3 at% H [18]. We did not observe, within the accuracy of our results, any effect of the oxygen on the DSA results both in height, broadness, mean activation energy or  $\tau_0$ . As an example, Fig. 13 shows the peak height  $Q^{-1}$  as a function of hydrogen concentration for the pure and the oxygen-doped 70 V-30 Nb alloy and for this alloy containing only residual oxygen (0.03 at% O). As seen, the oxygen does not affect the relaxation strength. Table 3 presents  $\Delta H$  and  $\tau_0$  for the alloy with and without oxygen, also showing no difference.

The 10 V-90 Nb alloy studied [20] contained up to 0.7 at% O and almost 1 at% H. Again, no significant differences in the internal friction activation parameters of the oxygen-doped and undoped alloys were observed. Therefore, based on the results obtained on V-Nb alloys, we do not believe that a strong interaction of oxygen and hydrogen occurs, in contrast to earlier reports on O-H complexes in unalloyed Nb [26,27]. This is not inconsistent with an observed interaction at temperatures far below the present hydrogen relaxation spectrum where quantum tunneling has been found [52].

## Summary and Conclusions

The present paper provides an overview of our findings in V, Nb and their alloys which may be summarized as the follows:

1. An internal friction peak much broader than a single Debye peak is generated by hydrogen in solid solution. The broadening occurs in the alloys due to a distribution of V in Nb or Nb in V which creates different energy levels for hydrogen and therefore a spectrum of activation energies. This broadened peak is interpreted to be due to a spectrum of Snoek peaks.
2. Nitrogen and oxygen produce single relaxation energy Snoek peaks in pure V and Nb, in agreement with previous observations.

3. In V-Nb alloys, oxygen produces the same Snoek peaks as well as solute-interstitial peaks (trapping) if V is the solute. Thus far, no solute-interstitial peaks have been found if Nb is the solute.

4. For low interstitial concentrations (< 1 at%) there is no synergistic effect of hydrogen and oxygen or nitrogen in these materials, as indicated by the insensitivity of the Snoek peaks to the presence of the other interstitial solute.

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TABLE 1--Activation parameters for the oxygen and nitrogen Snoek peaks in V and Nb, compared with literature values.

	Present results, including results in the presence of hydrogen			Literature (no hydrogen added)	
Alloy	$\Delta H(\text{eV})$	$\tau_0 \times 10^{15}(\text{s})$	Evaluation Method	$\Delta H(\text{eV})$	$\tau_0 \times 10^{15}(\text{s})$
V-O	1.16*	27*	Single Relaxation Analysis [5]	1.29†	1.0†
	1.14*	39*	Frequency Measurements	1.17 - 1.20††	10 - 28††
Nb-O	1.12*	7*	Single Relaxation Analysis [5]	1.15†††	2.7†††
	1.13*	4*	Frequency Measurements		
Nb-N	1.51**	7**	Single Relaxation Analysis [5]	1.58†††	1.2†††

\* Ref. 15

\*\* Ref. 19

† Ref. 5

†† Ref. 31

††† Ref. 33

TABLE 2--Activation parameters for P<sub>1</sub>, P<sub>2</sub>, and P<sub>3</sub> in Nb-rich and V-rich alloys.

Alloy	P <sub>1</sub>		P <sub>2</sub>		P <sub>3</sub>	
	$\Delta H_1(\text{eV})$	$\tau_{01} \times 10^{15}(\text{s})$	$\Delta H_2(\text{eV})$	$\tau_{02} \times 10^{15}(\text{s})$	$\Delta H_3(\text{eV})$	$\tau_{03} \times 10^{15}(\text{s})$
Nb-rich	1.17*	2.8*	1.41*	4.7*	...	...
			1.40†	6.2†	1.9 ± 0.1†	1.3†
V-rich	1.23*	3.2*	...	...	...	...

\* Ref. 16

† Ref. 17

TABLE 3--Activation parameters for hydrogen in V-Nb alloys from internal friction at 200 Hz[18, 24] and long range diffusion [25].

Alloy	Internal friction	Diffusion	$\Delta H(\text{eV})$	$\tau_0 \times 10^{15}(\text{s})$
	$\Delta H(\text{eV})$	$\tau_0 \times 10^{15}(\text{s})$		
100 Nb	...	...	0.08	80
10 V-90 Nb	0.20	84	0.17	23
25 V-75 Nb	0.25	66	0.23	11
50 V-50 Nb	0.25	64	0.22	13
	0.21 *	443 *		
60 V-40 Nb	0.23	94	...	...
	0.23	75		
70 V-30 Nb	0.20	580	...	...
70 V-30 Nb - 0.2 at% O	0.20	790	...	...
75 V-25 Nb	...	...	0.14	21
80 V-20 Nb	0.19	37	...	...
90 V-10 Nb	...	...	0.09	40
100 V	...	...	0.04	47

\* Ref. 22

## Figure Captions

FIG. 1--Normalized  $Q^{-1}$  as a function of  $T^{-1}$  for the V—0.2 at.% O alloy. Full line: theoretical Snoek peak curve. Note the absence of an effect of hydrogen in solid solution. [15]

FIG. 2--Internal friction peaks for Nb-0.24 at.% V containing different concentrations of oxygen. Frequency  $\sim 0.25$  Hz. [16]

FIG. 3--Internal friction peaks for Nb-0.50 at.% V containing 0.65 to 0.90 at.% O. Frequency  $\sim 0.35$  Hz. [16]

FIG. 4--Internal friction peaks for Nb-5.0 at.% V alloy containing different oxygen concentrations. Frequency  $\sim 0.55$  Hz. [17]

FIG. 5--Internal friction peaks for V-0.50 at.% Nb containing different oxygen concentrations. Frequency  $\sim 0.5$  Hz. [16]

FIG. 6--Plots of  $Q_{\text{mix}}^{-1}$  vs oxygen concentration for P1 (Fig. 6a) and P2 (Fig. 6b) peaks for Nb, V, Nb-0.24 at.% V and Nb-0.50 at.% V alloys. [16]

FIG. 7--Schematic representation of octahedral cells of types  $n = 1$  and  $n = 2$  in b.c.c. lattice. (A to F octahedral sites, • solute atom, ○ host atom). [17]

FIG. 8--Experimental data for the 70 V-30 Nb alloy at various hydrogen concentration. All results have been corrected to a frequency of  $\sim 270$  Hz. [18]

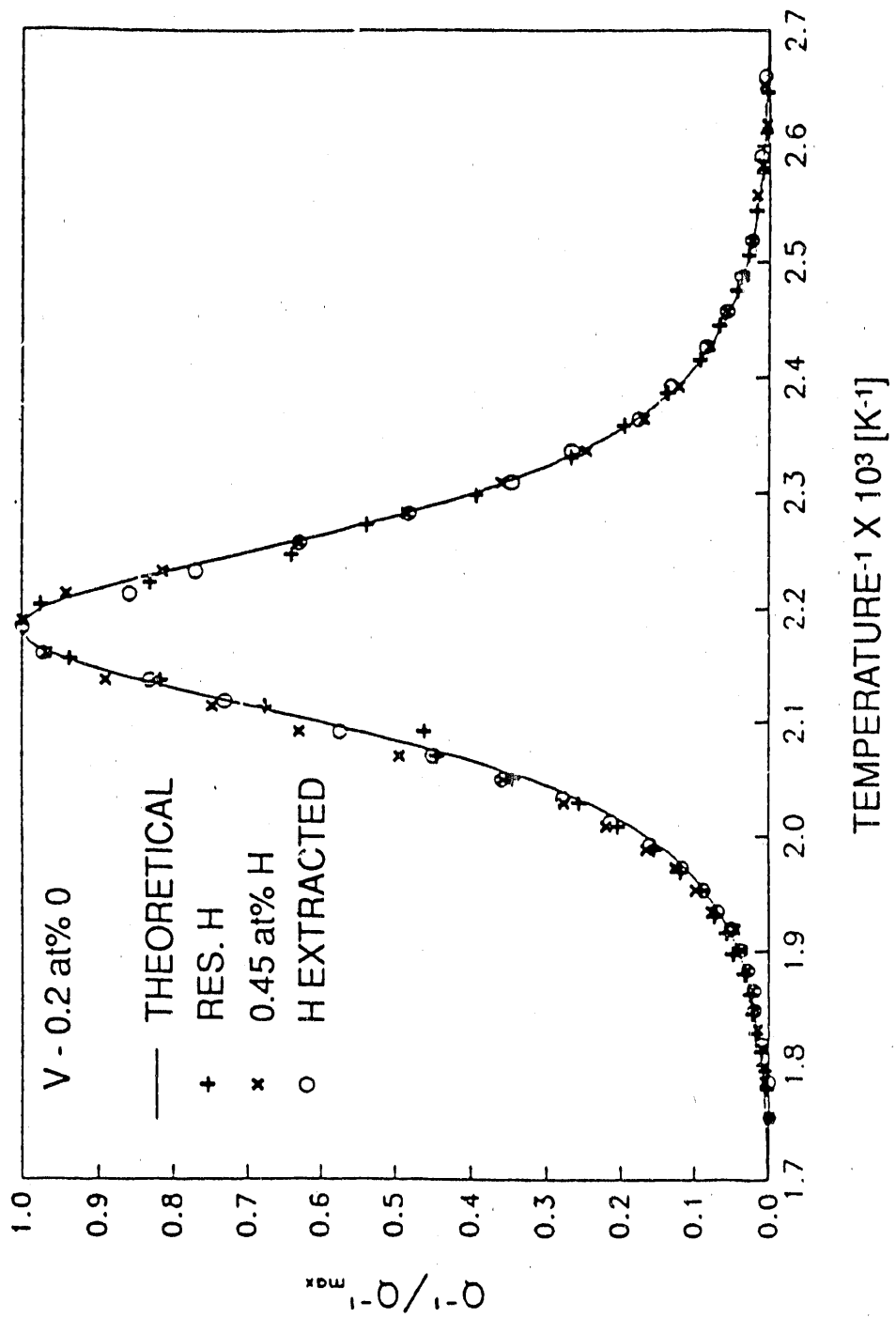
FIG. 9--Comparison of the 70 V-30 Nb - 0.55 at.% hydrogen internal friction peak to the theoretical Debye peak calculated for an activation energy of 0.188 eV. [18]

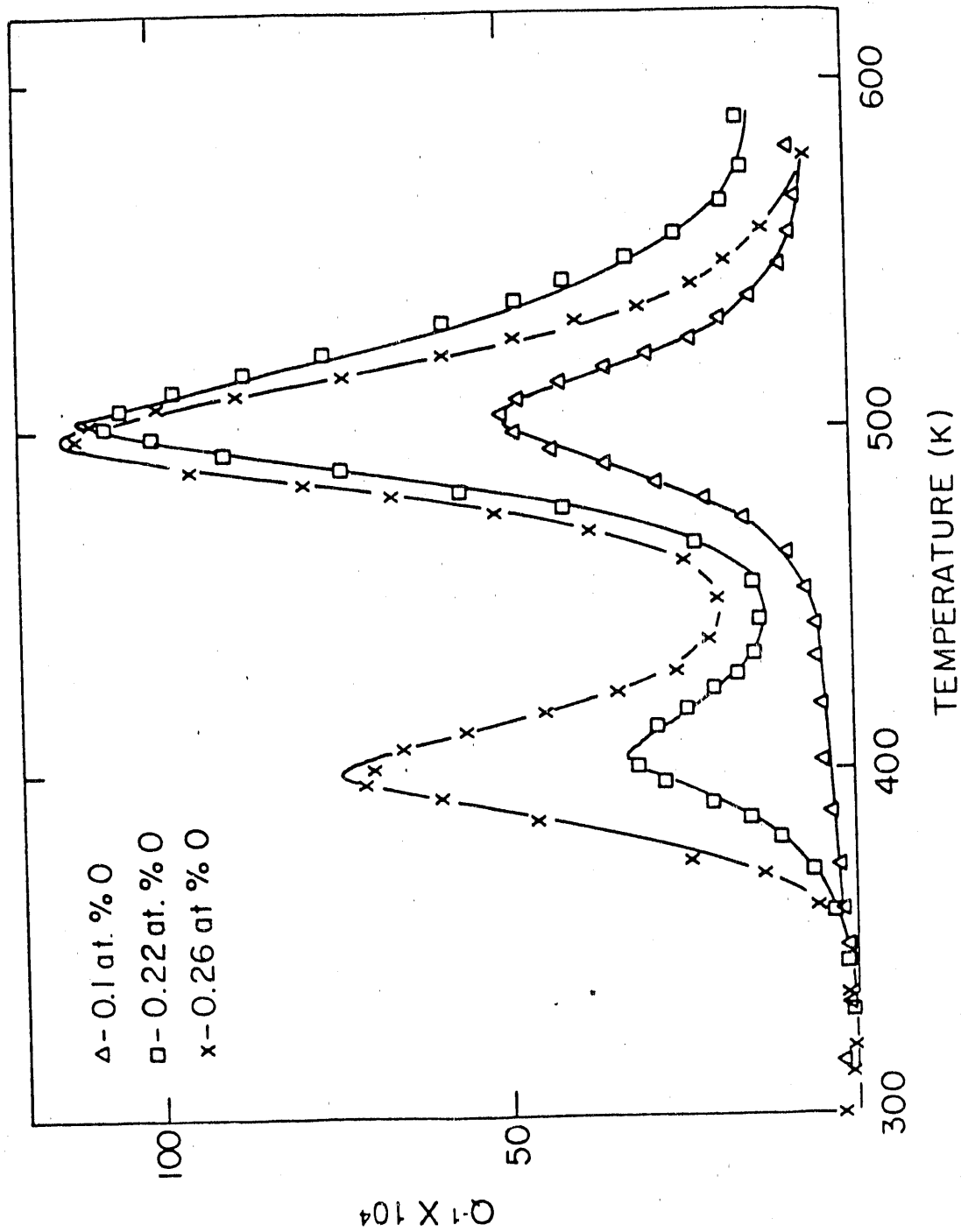
FIG. 10--DSA results for the 70 V-30 Nb alloy.  $\tau_0 = 5.9 \times 10^{-13}$ s. Envelopes are generated using Gaussian distribution function. [18]

FIG. 11--Comparison of activation energies found by internal friction to those found by diffusion measurements. [18, 24]

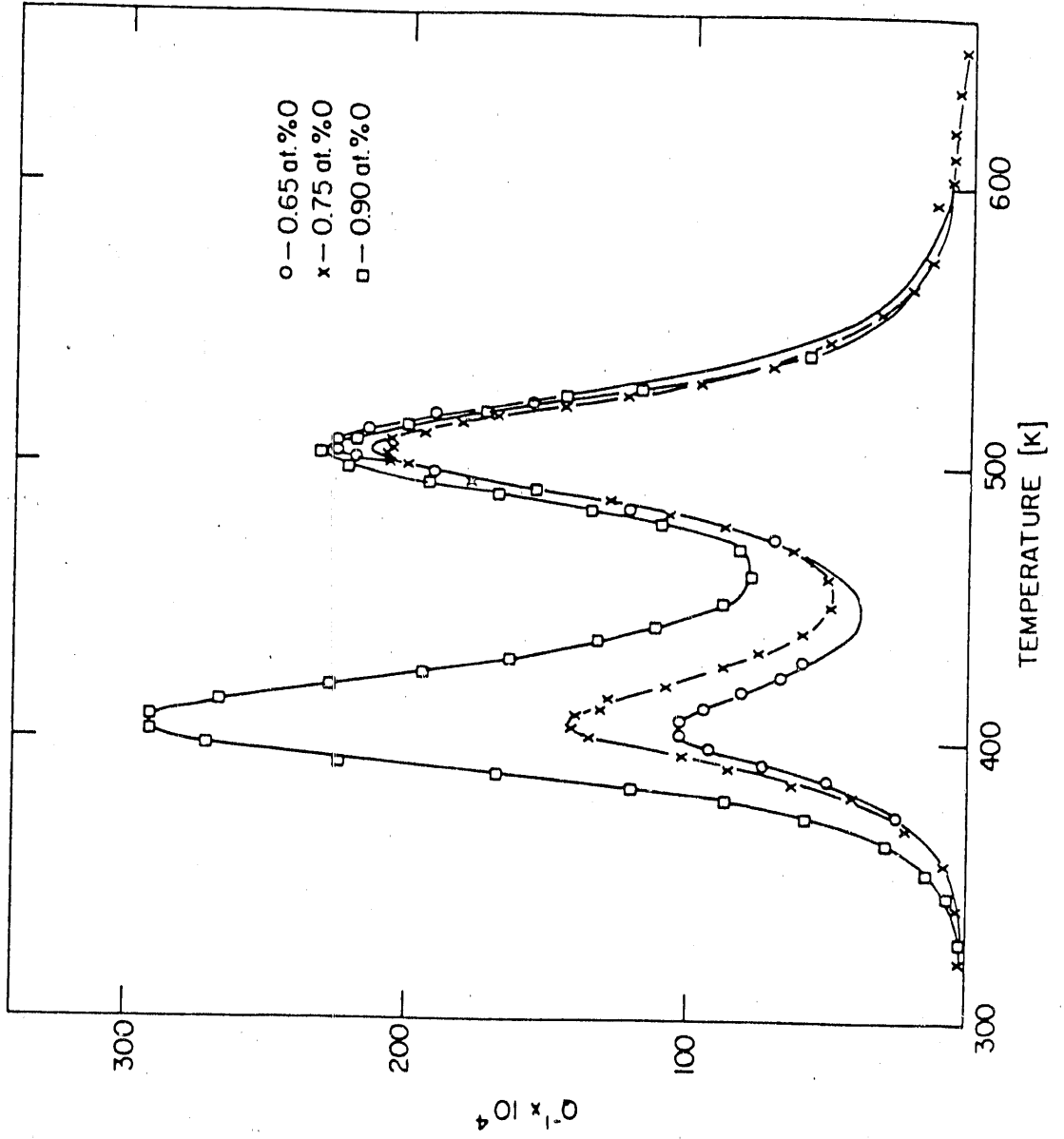
FIG. 12-- $\ln f$  vs  $1/T_p$  plot for Nb-10 V-0.5 at.% H with and without oxygen addition.  $T_p$  is the peak temperature of the H peak. [20]

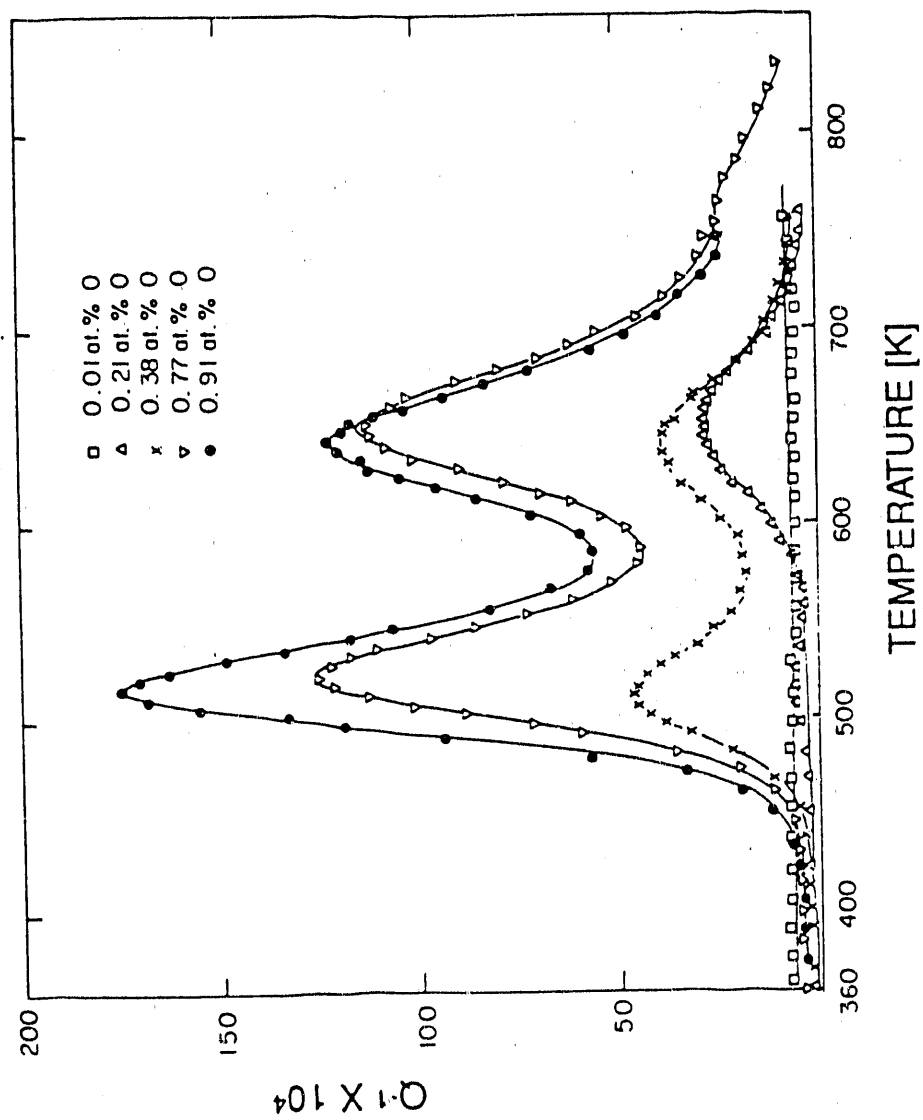
FIG. 13--Comparison of  $Q_{mi}$  for 70 V-30 Nb charged with and without oxygen at hydrogen concentrations listed. [18]











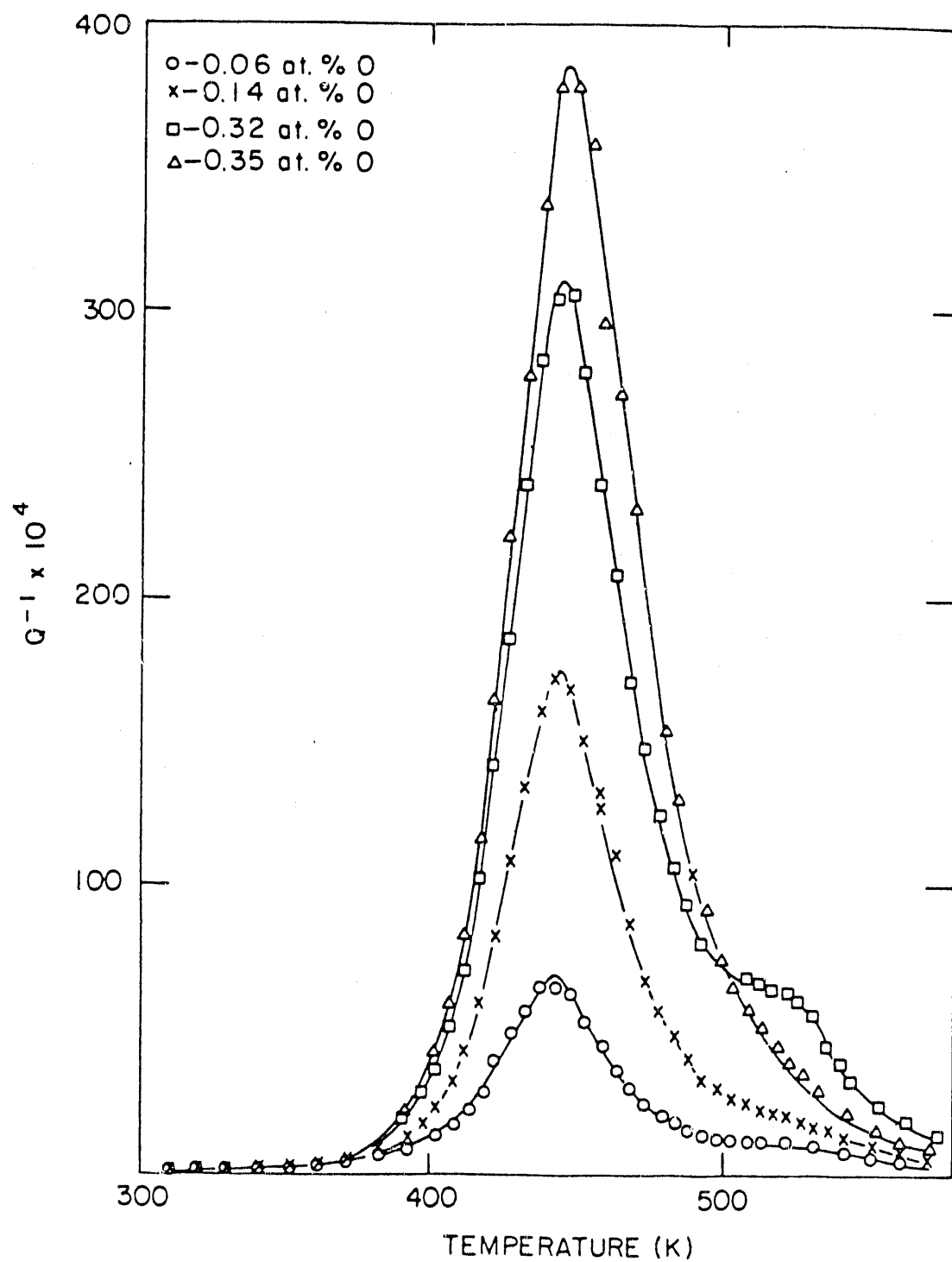


Fig 5

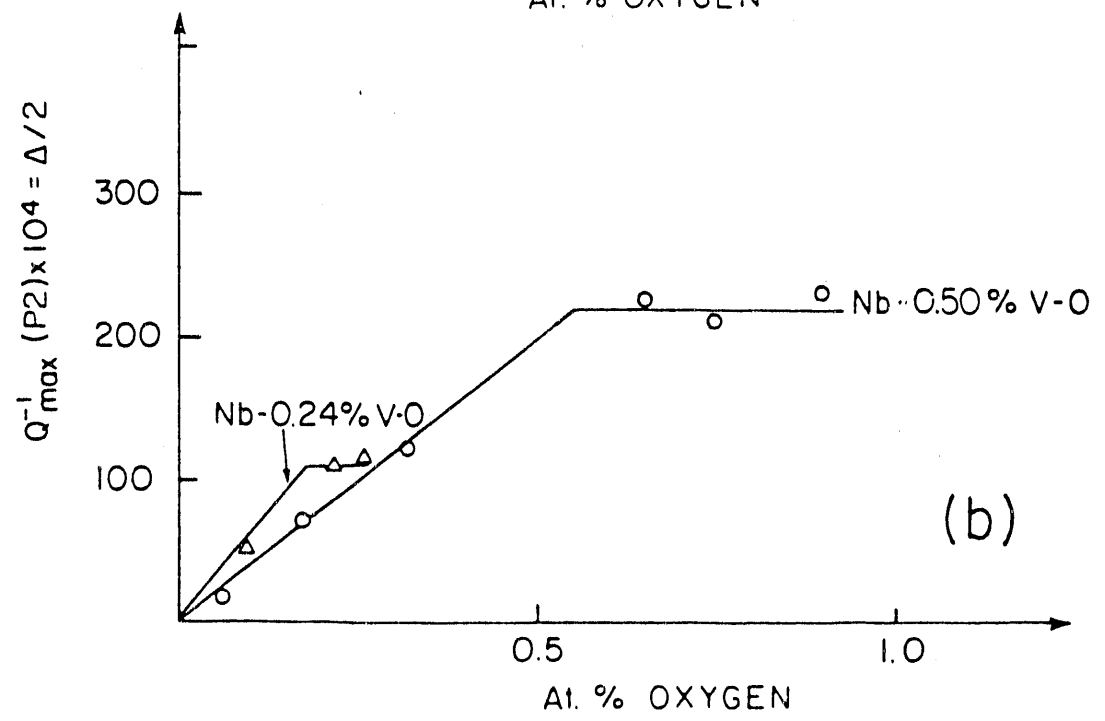
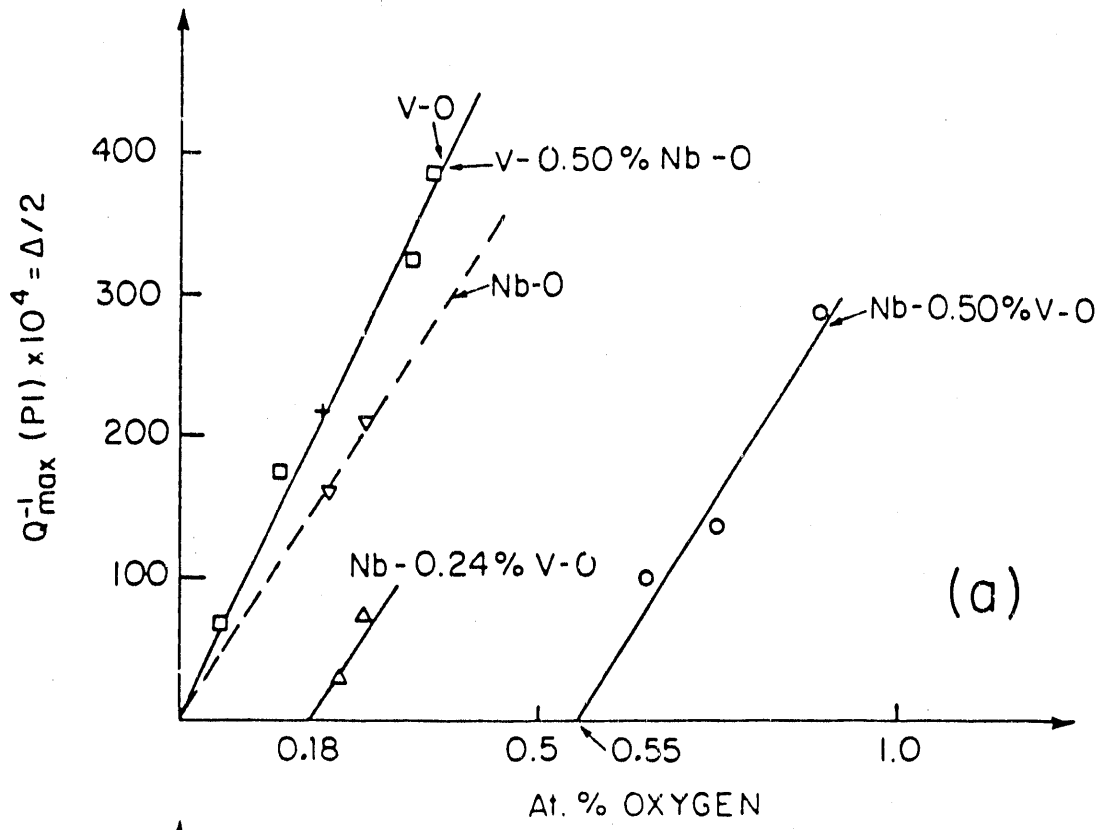
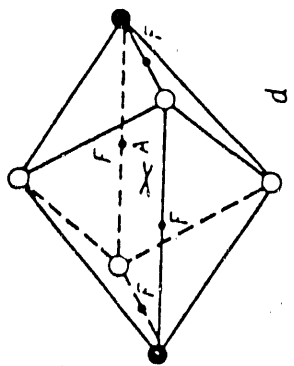
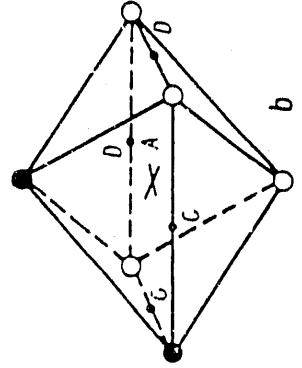
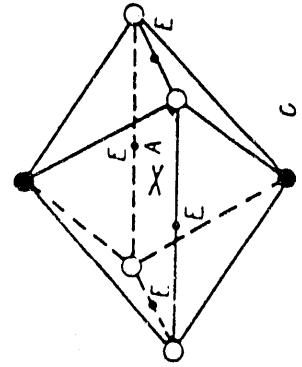
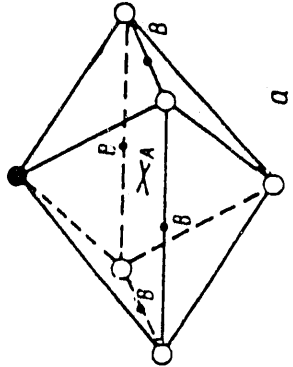
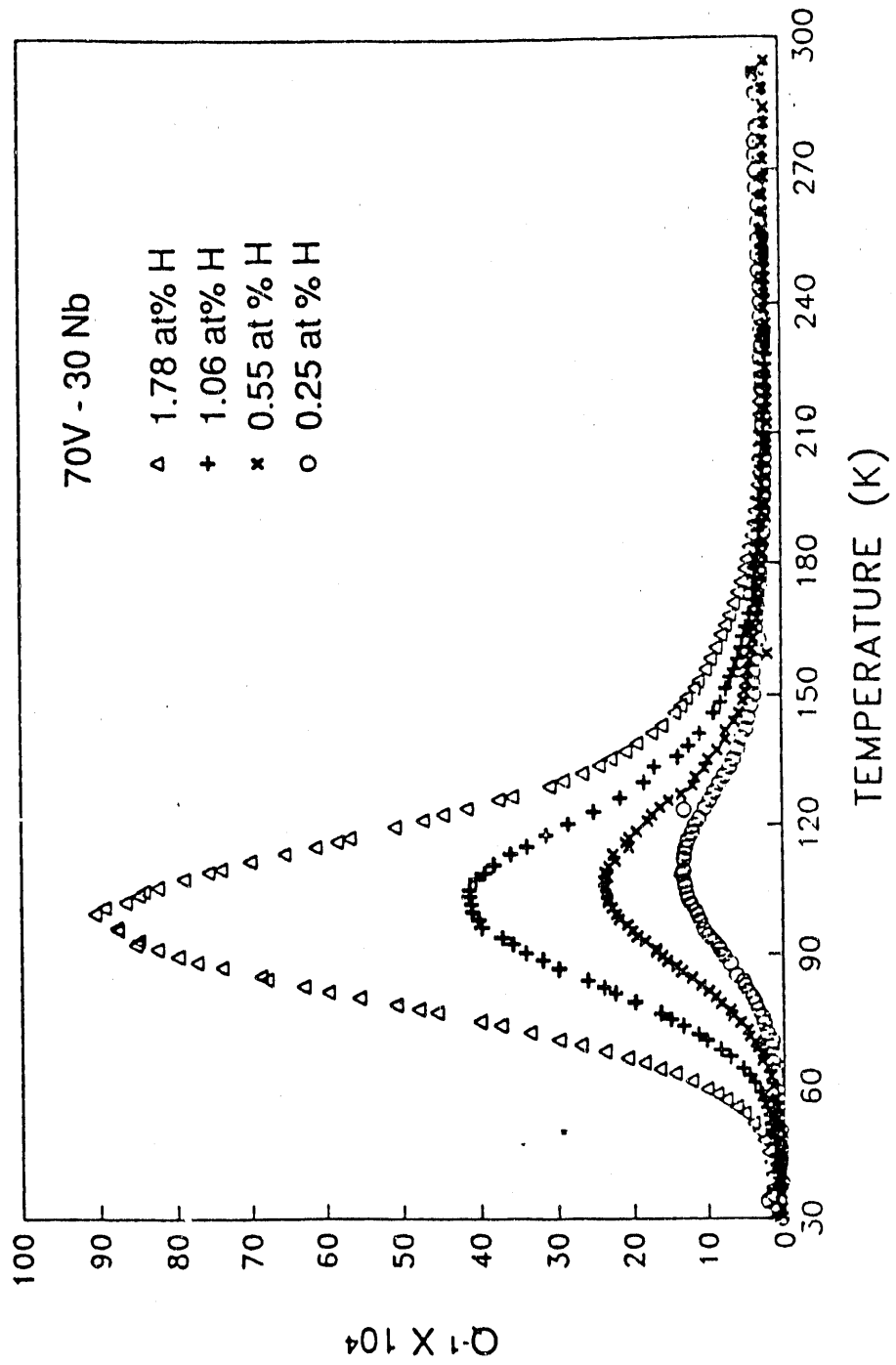
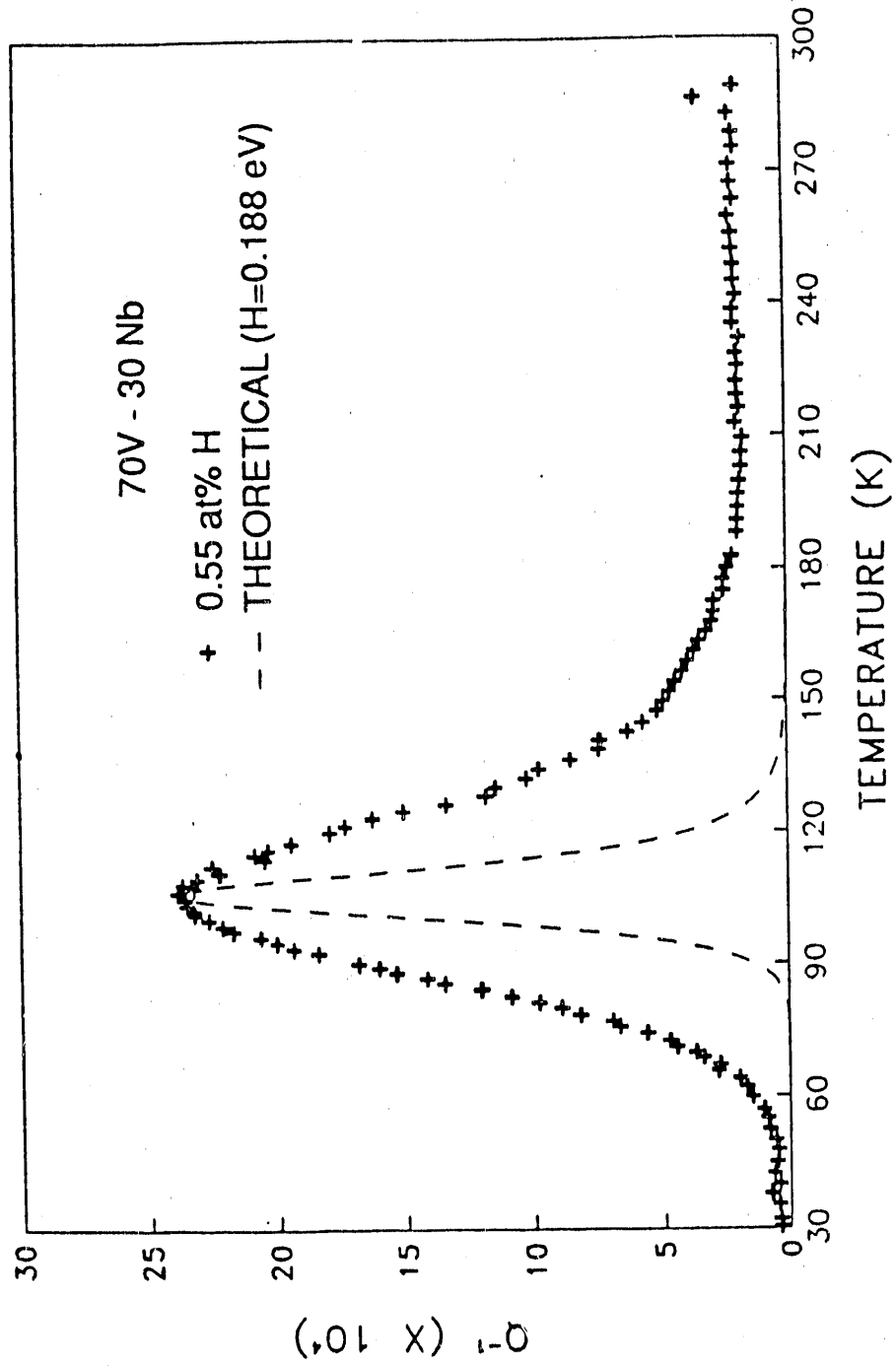
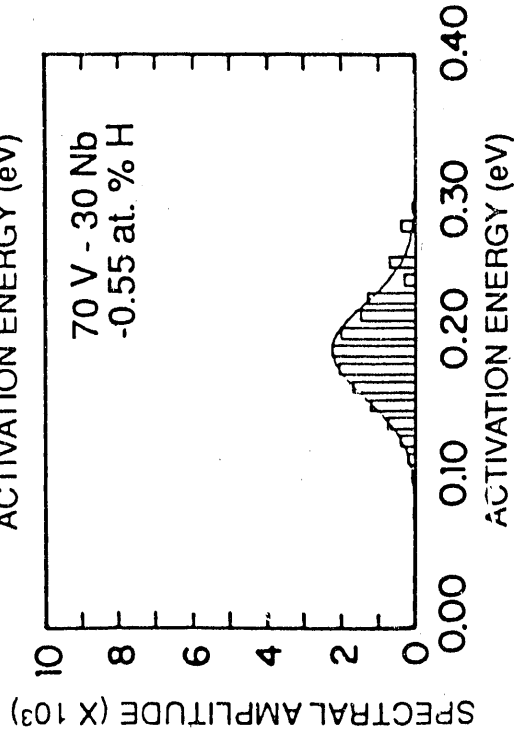
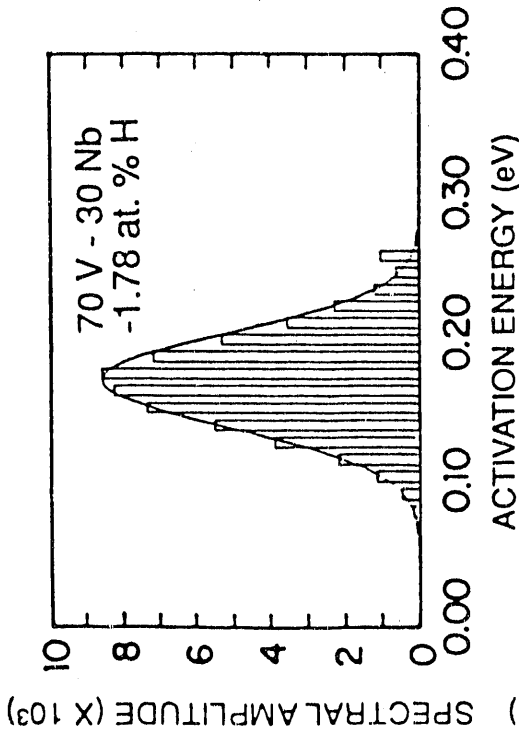
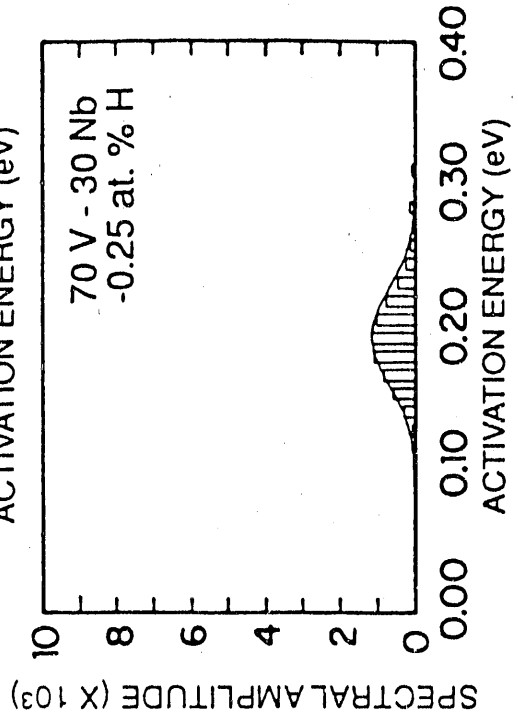
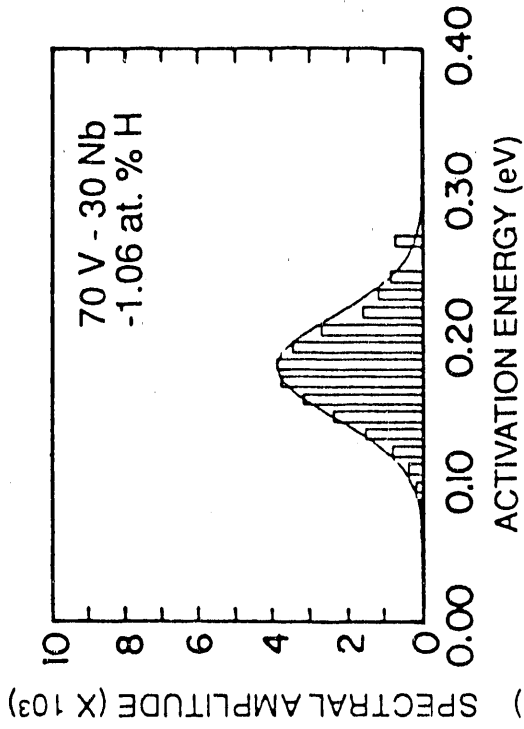


Fig 6

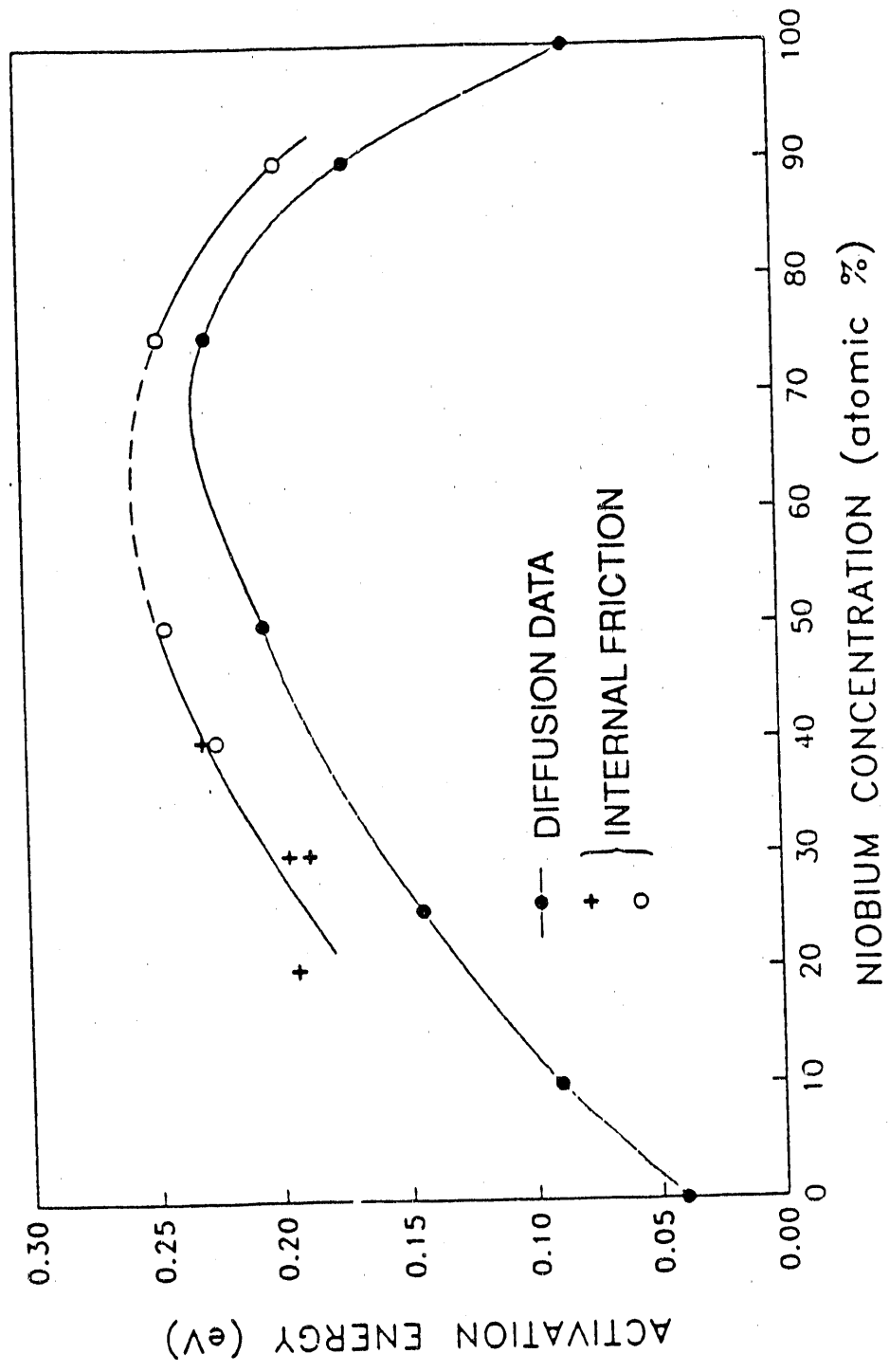












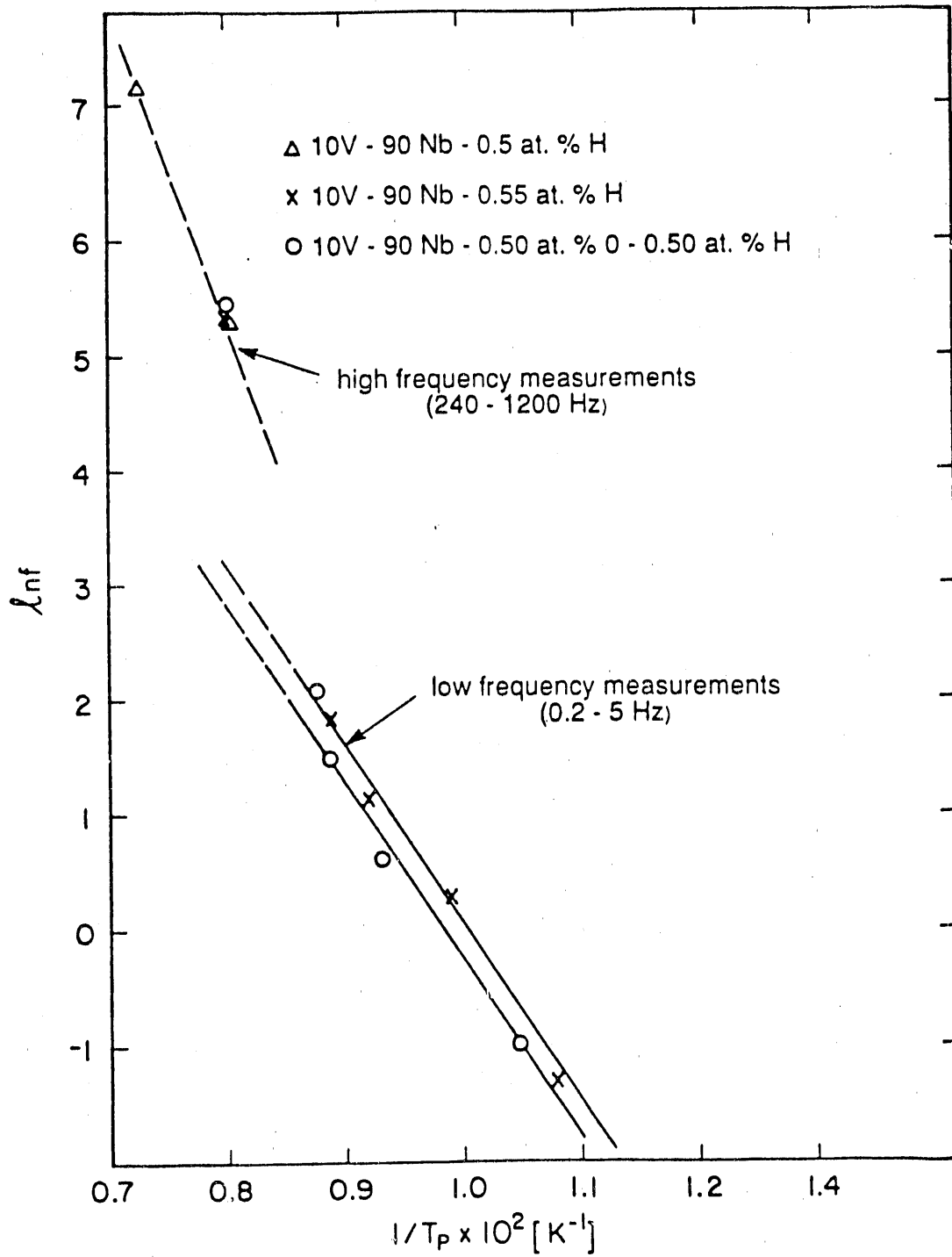


Fig. 12

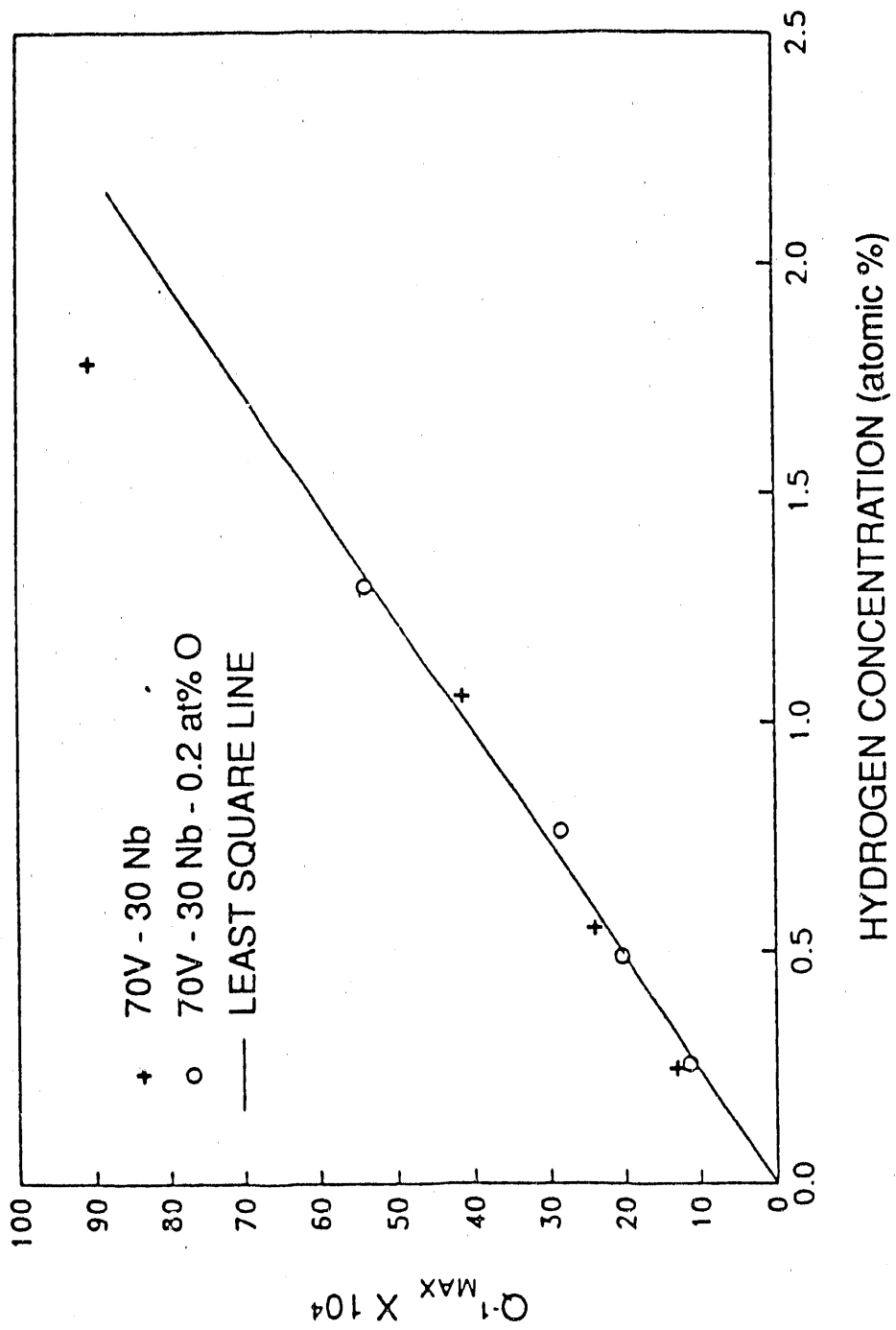


Fig. 13

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