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A REDUCED VOLUMETRIC EXPANSION
FACTOR PLOT

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ABSTRACT

A reduced volumetric expansion factor plot has been constructed for simple fluids which is suitable for engineering computations in heat transfer. Volumetric expansion factors have been found useful in correlating heat transfer data over a wide range of operating conditions including liquids, gases and the near critical region.

INTRODUCTION

The volumetric expansion coefficient $(\partial \ln V/\partial T)_P$ has been found useful in heat transfer analyses. Yaskin et. al. (ref. 1) demonstrated its usefulness in grouping helium heat transfer data in the near thermodynamic critical region. Hendricks (ref. 2) demonstrated the usefulness of the energy expansion coefficients $(\partial \ln V/\partial H)_P$ in qualitatively grouping heat transfer data for fluids nitrogen and oxygen in the near thermodynamic critical region; however, quantitative agreement has not yet been achieved. Hendricks et. al. (ref. 3) qualitatively demonstrated the relations between density fluctuations, volumetric expansion coefficient, and turbulent energy and momentum fluxes. The energy expansion coefficient was used in qualitatively grouping gaseous and fluid heat transfer data of several investigators. These data sets for helium, hydrogen, air, nitrogen, carbon dioxide and water cover a large range of experimental conditions.

In the absence of a computer program such as (GASP/WASP) (refs. 4 and 5) these expansion coefficients are quite difficult to calculate and consequently, of little aid to the practicing engineer. The purpose of this paper is to present a single graph which will enable the engineer to determine the volumetric expansion coefficient for a large class of fluids over an extensive temperature-pressure regime.

NORMALIZING PARAMETER

In previous works, on the Joule-Thomson coefficient (ref. 6) the principle of corresponding states was applied and found useful in both qualitatively and quantitatively grouping data sets for not only fluids of simple molecular structure but for fluids with more complex structure and quantum effects.

E-148

Following similar reasoning, the principle of corresponding states has been applied to the volumetric expansion factor $(\partial \ln V/\partial T)_P$. The reduced volumetric expansion factor can be written

$$\beta_R = \frac{\beta}{\beta^*}$$

where

$$\beta^* = (Z_c T_c \psi_c)^{-1} \begin{cases} \psi_c = 1, \text{ for nonquantum fluids and } P_R < 1 \\[2ex] \psi_c = 1 + \dfrac{1.02 - \zeta_c}{30 Z_c}, \text{ for quantum fluids, } P_R \geq 1 \end{cases}$$

$$\zeta_c = \frac{\rho_c}{\rho_{c,neon}}$$

and plotted as a function of reduced temperature,

$$T_R = \frac{T}{T_c} - \varphi_c$$

$\varphi_c = 0$, for nonquantum fluids and for quantum fluids when $P_R < 1$.

$$\varphi_c = \frac{3}{5} \zeta_c (1.02 - \zeta_c)(P_R - 1); \; 1 < P_R < 10$$

$$\varphi_c = 5.4 \; \zeta_c (1.02 - \zeta_c); \; P_R \geq 10$$

The parameters φ_c and ψ_c were determined empirically to account for quantum fluid behavior.

To within engineering requirements, it will be shown that the volumetric expansion factor for simple fluids map onto a single reduced volumetric expansion factor-reduced temperature chart with reduced pressure as a parameter.

The peak value of β_R is anticipated to correspond to T_R^* or the reduced pseduo-critical temperature.[1]

RESULTS AND DISCUSSION

Figure 1(a), called the background curves or background, illustrates the variation of reduced volumetric expansion factor as a function of reduced temperature for selected isobars where fluid nitrogen serves as a basis.[2]

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[1] $C_p - C_v = TV\beta^2/K$, where K is the isothermal compressibility $K = (\partial \ln V/\partial P)_T$ (fig. 1(b)). It should be noted that similar reduced isothermal compressibility factor plots can be established as presented herein for β_R.

[2] To map a function f whose range ϵ to ∞, f^{-1} should be used, but one looses perspective of large and small-see figures 1(c) and (d) - so we use f.

One must note that $P_R = 51.2$ is beyond the range of the curve fit, however it is instructive to illustrate the extrapolated behavior. The saturation locus serves as a guide to the behavior of β_R in the two phase region where it may be assumed that

$$\beta_{R_{2\varphi}} = x\beta_{R_v} + (1 - x)\beta_{R_l}$$

where x is the volume fraction and β_{R_v} and β_{R_l} are the vapor and liquid values, respectively. Figure 1 will be used as a standard for subsequent comparisons to other fluids and will be superimposed as background on subsequent figures. One will note that the value of β_R corresponding to the critical point does not calculate properly and is not expected to be valid as

$$\text{limit} \quad \beta_R \rightarrow \infty$$

$$PVT \rightarrow \text{critical}$$

A further characteristic of these plots is that the peak or maximum value of β_R along a given isobar corresponds to the transposed critical temperature. The transposed critical temperature is also where the specific heat (C_p) attains a maximum.

COMPARISON TO OTHER NONQUANTUM FLUIDS

Methane: Figure 2 illustrates a very good agreement between the points and the background curves - from figure 1(a) - with the exception of one point, the critical point where agreement is not expected to be good as explained previously.

Oxygen: Figure 3 illustrates the behavior of β_R which is not as good as for methane, but still it is quite reasonable. Note in particular that the extrapolations are very good considering the extent that the pressure is extrapolated beyond data.

Argon: Figure 4 when compared to figure 3 illustrates that β_R for argon and oxygen behave in a very similar way and furthermore are in good agreement with the background - figure 1(a).

Fluorine: The points representing β_R for fluorine fall somewhat off the background curves, but only a small amount more than for oxygen and argon. In general the agreement is good as can be seen from figure 5.

Carbon Monoxide: Here the agreement with the background is quite good except at the highest pressure where substantial deviations are noted, see figure 6. Even though the corresponding states equation representing carbon-monoxide has nitrogen as the base fluid (but not the base fluid used to establish the background curves) the carbon-monoxide accuracy and range are limited. The background is preferred at higher pressures.

Carbon Dioxide: As carbon-dioxide does not behave as a corresponding states fluid, only moderate agreement should be anticipated. As illustrated

in figure 7, even though the deviations are quite noticable when compared to the background, the background values still give an adequate representation for the usual heat transfer and fluid flow analyses. A line plot without the background (i.e., fig. 1(a)) for carbon-dioxide may be necessary for some analyses and as such is given as figure 8.

Water: For such a complex molecule, the agreement with the background is quite reasonable as illustrated in figure 9. The values at pressures, $P_R > 6$ are far beyond the capability of the water program and even though agreement is reasonable, the values can not be relied upon. If no other values are available, the background curve can serve as a first order estimate for β_R. More refinement will have to come from the individual curve fit for water, given as figure 10, and in particular β^* may require the effects of dipole moments.

COMPARISON TO QUANTUM FLUIDS

Neon, hydrogen, and helium are quantum fluids and as such, the normalizing parameters are more complex. It is however, quite informative to first look at the departures from the background (fig. 1(a)) with $\varphi_c = \psi_c = 1$ (i.e., as if they possessed no quantum behavior).

Neon: With $\varphi_c = \psi_c = 1$, the agreement between the points and the background of figure 11 is quite good. Only a little gain is made using the pseudo parameters φ_c and ψ_c of equations (1) and (2); however, being that neon is a quantum fluid the pesudo parameters should probably be used. The set of points are now corrected for quantum fluid effects and superimposed on the background as figure 12.

Hydrogen: The departures of β_R for p-hydrogen from the background are quite significant at elevated pressures and lower temperatures, see figure 13. Applying the quantum corrections of equations (1) and (2) to each point and superimposing the points on the background results in satisfactory agreement for the most part, as shown in figure 14, but certainly not as good as for nonquantum fluids.

Helium: The values for β_R for helium at $T_R \leq 1$ requires a better PVT-surface representation than available in GASP (ref. 4), such as (ref. 7). With $\varphi_c = \psi_c = 1$, there is little agreement between the β_R results and the background, see figure 15. Applying equations (1) and (2) to the points which are superimposed on the background shows that the agreement is better, figure 16, but not as good as expected.

Line graphs of hydrogen and helium with $\varphi_c = \psi_c = 1$ are given as figures 17 and 18 to illustrate that even without the empirical quantum fluid correction, the reduced plots are still quite useful.

SUMMARY

A reduced volumetric expansion chart has been produced for simple fluids which is suitable for engineering computations in heat transfer and fluid flow. The normalizing parameter $\beta^* = (Z_c T_c)^{-1}$ does not adequately

reduce the volumetric expansion factor for polar molecules or quantum fluids and should be modified to include such effects or individual charts used; in the absence of data β^* can be used, for the first order calculations.

SYMBOLS

C_p, C_v specific heat

P   pressure

T   temperature

T^* pseudo critical temperature associated with the peak specific heat

V   specific volume

Z   compressibility

β^* volumetric expansion factor normalizing parameter, $(Z_c T_c \psi_c)^{-1}$

ζ_c $\rho_c/\rho_{c,neon}$; $\rho_{c,neon} = 0.483$ g/cm^3

φ_c see equation (2)

ψ_c see equation (1)

Subscripts:

c   critical

ℓ liquid

R   reduced by the critical constant

v   vapor

2φ two-phase region

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2. Hendricks, R. C. (1977), Simulation of the Heat Transfer Characteristics of LOX, ASME Paper 77-HT-9, Heat Transfer Conference.

3. Hendricks, R. C., Yeroshenko, V. M., Yaskin, L. A., Starostin, A. D. (1979), Bulk Expansion Factors and Density Fluctuations in Heat and Mass Transfer. Proposed Paper 18th-National Heat Transfer Conference, San Diego, CA, Aug. 5-8.

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   Fortran W Code for Calculating Water and Steam Properties, NASA TN
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   NASA TN D-6807.

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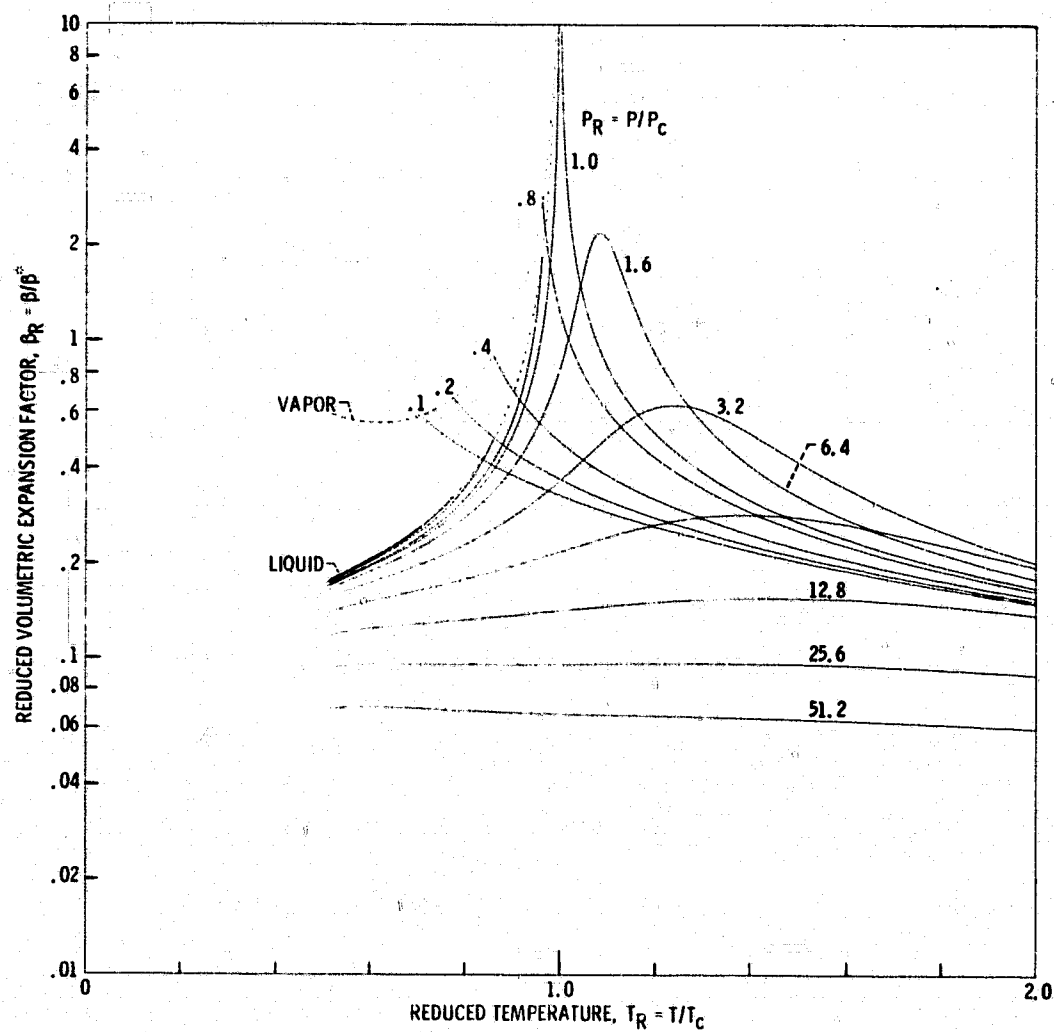   1500 K with Pressures to 1000 Atmospheres, National Bureau Standards
   TN-631.

Figure 1(a). – Generalized reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars.
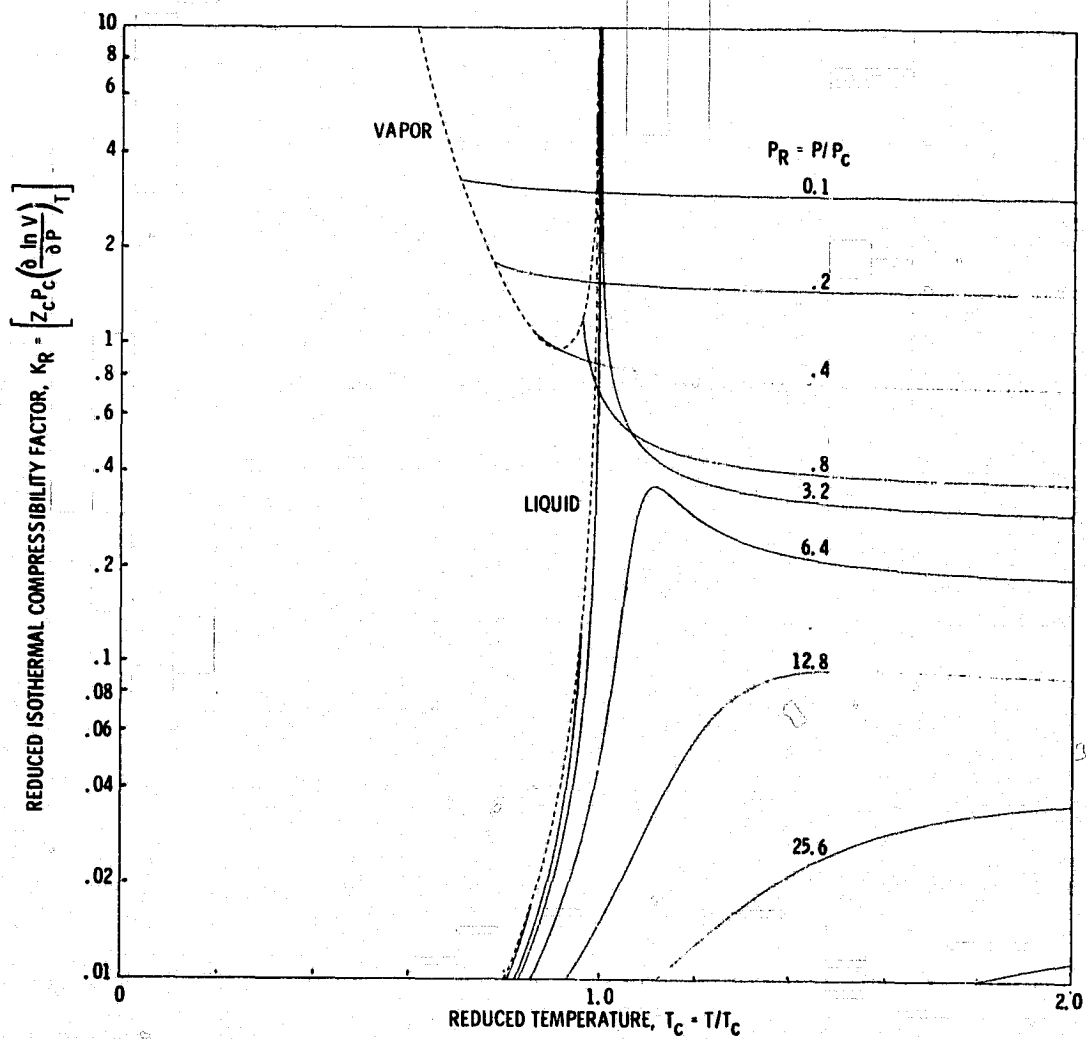
Figure 1(b). – Reduced isothermal compressibility factor as a function of reduced temperature for selected isobars.
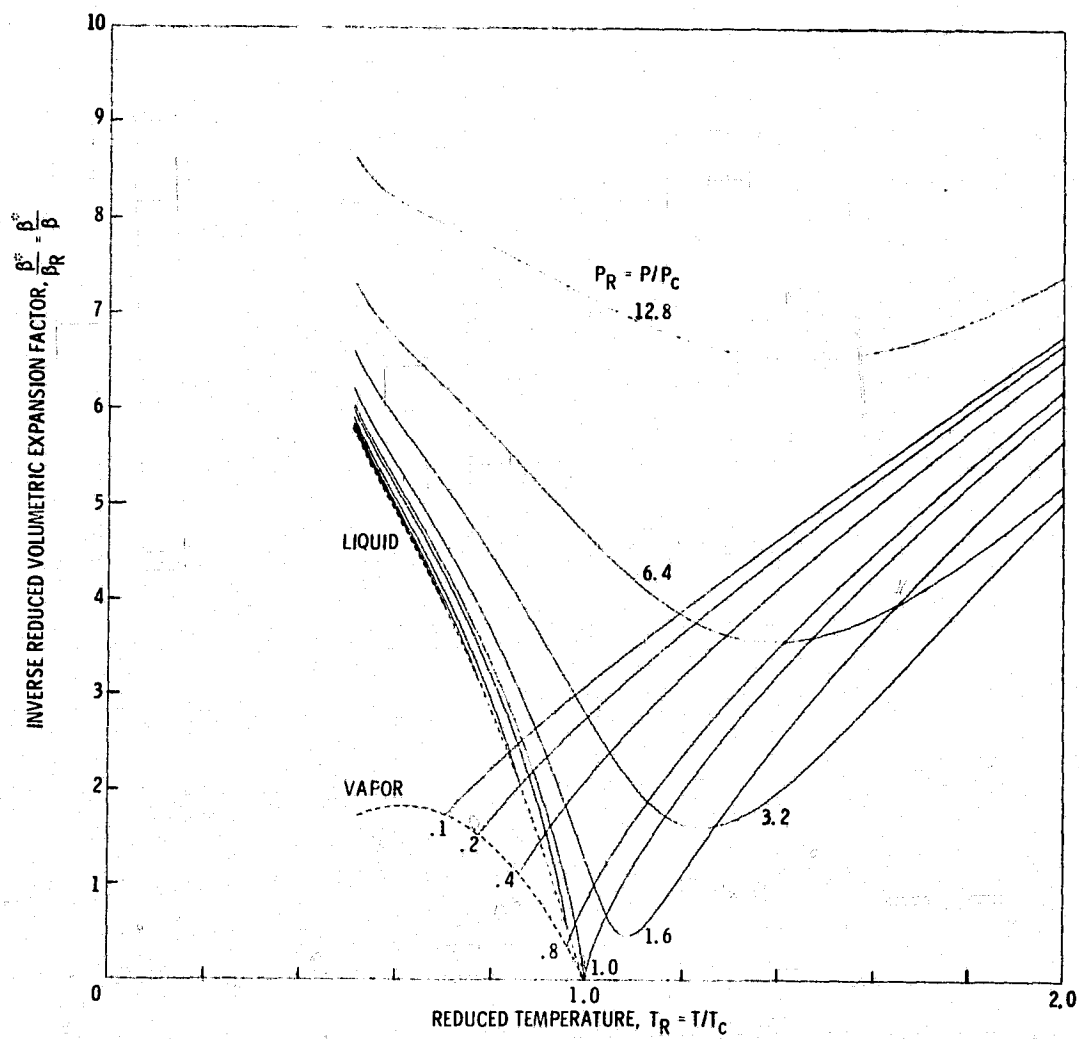
Figure 1(c). - Inverse reduced volumetric expansion factor as a function of reduced temperature for selected isobars (linear plot).
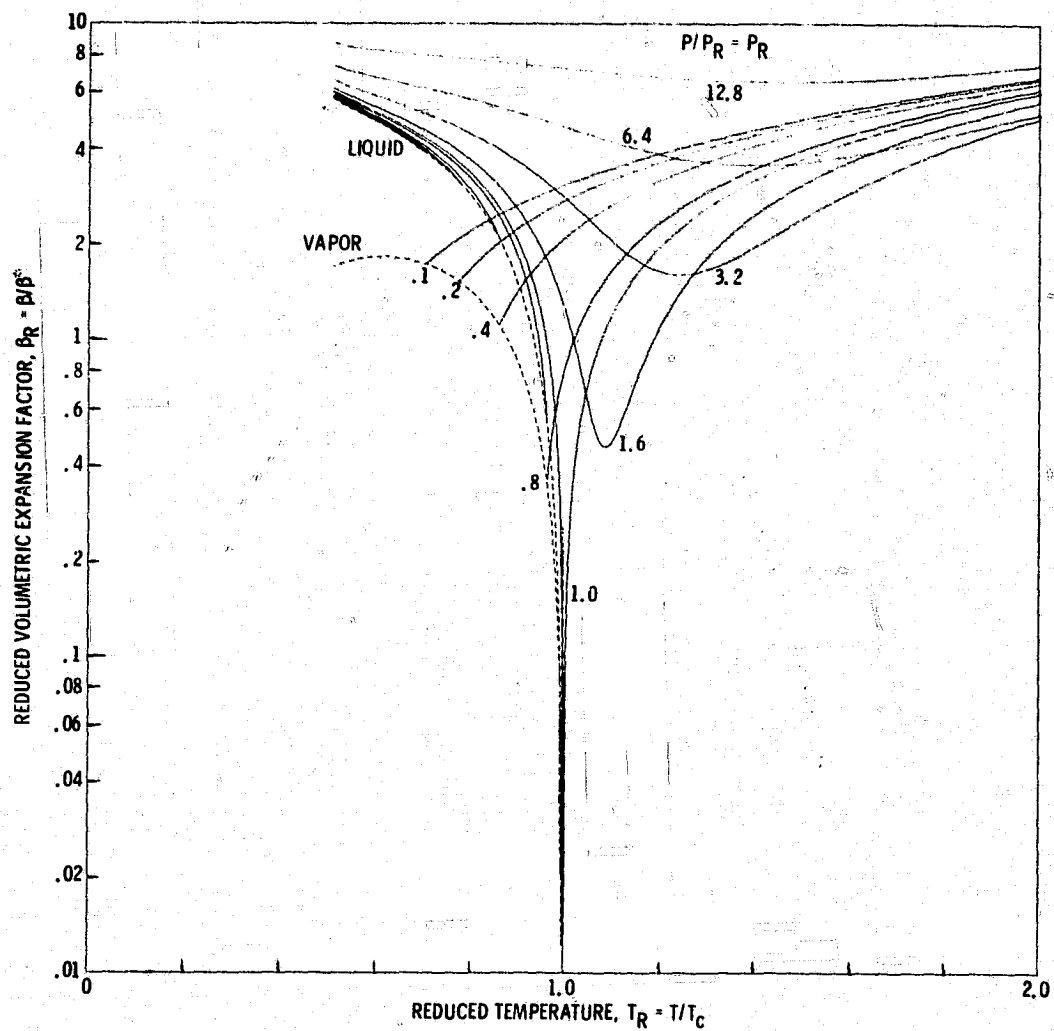
Figure 1(d). - Inverse reduced volumetric expansion factor as a function of reduced temperature for selected isobars (log plot).
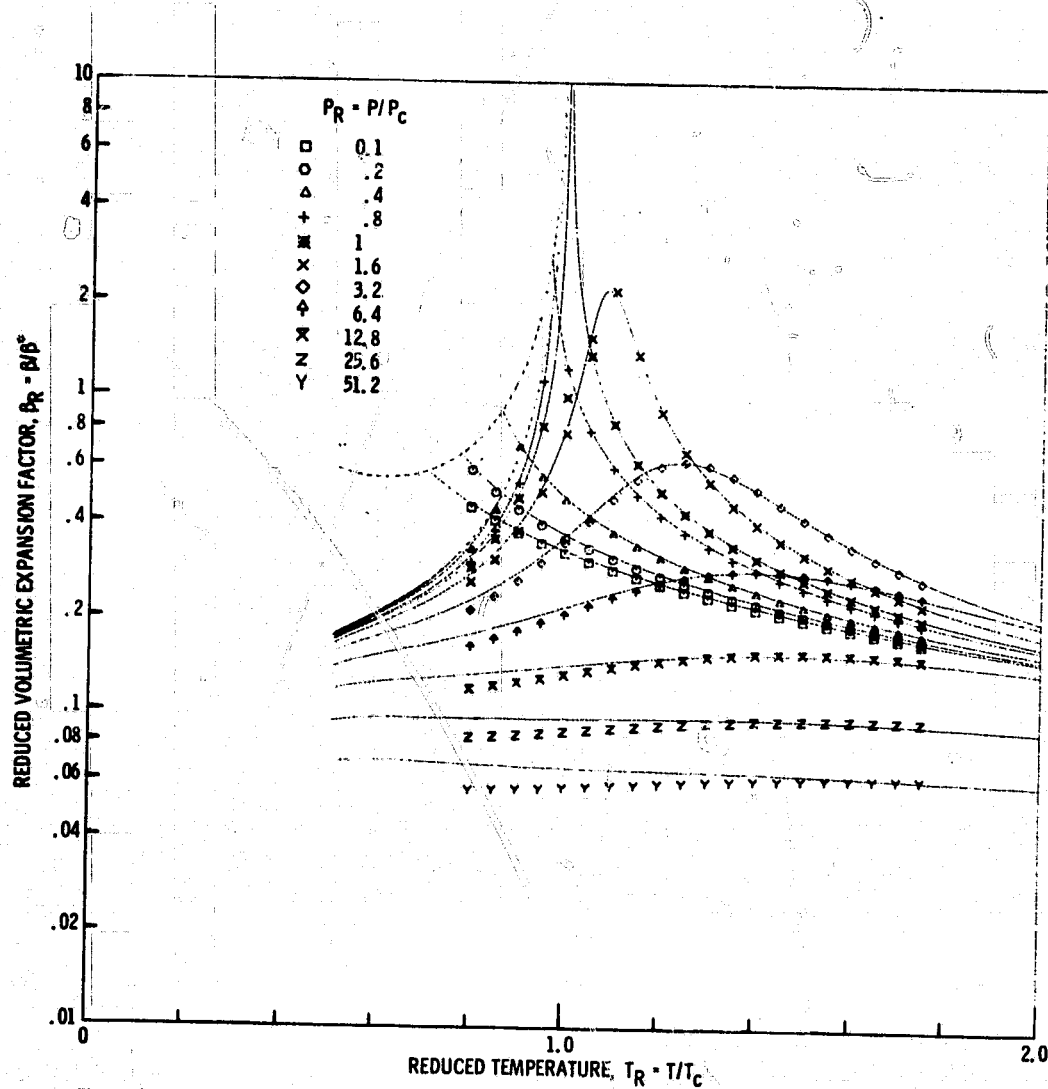
Figure 2. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid methane and the background is figure 1(a).
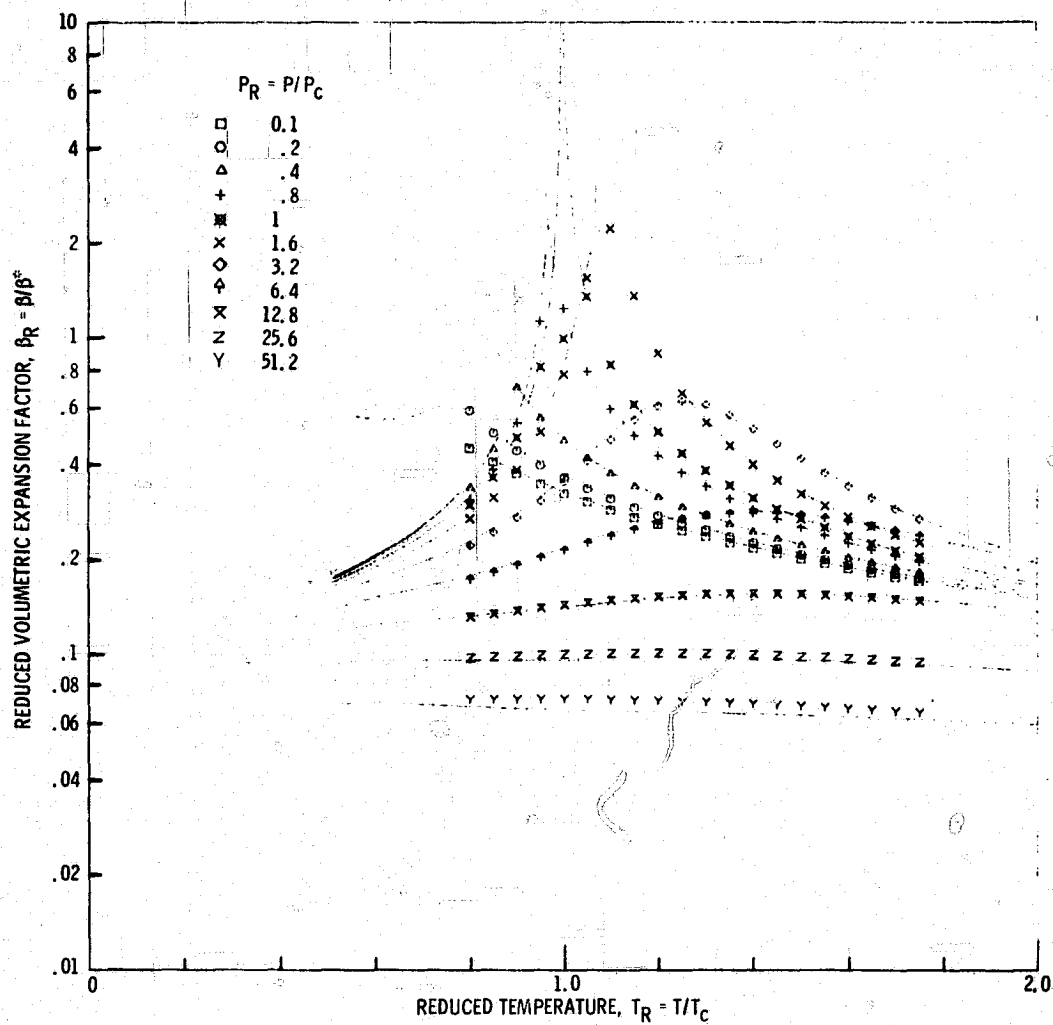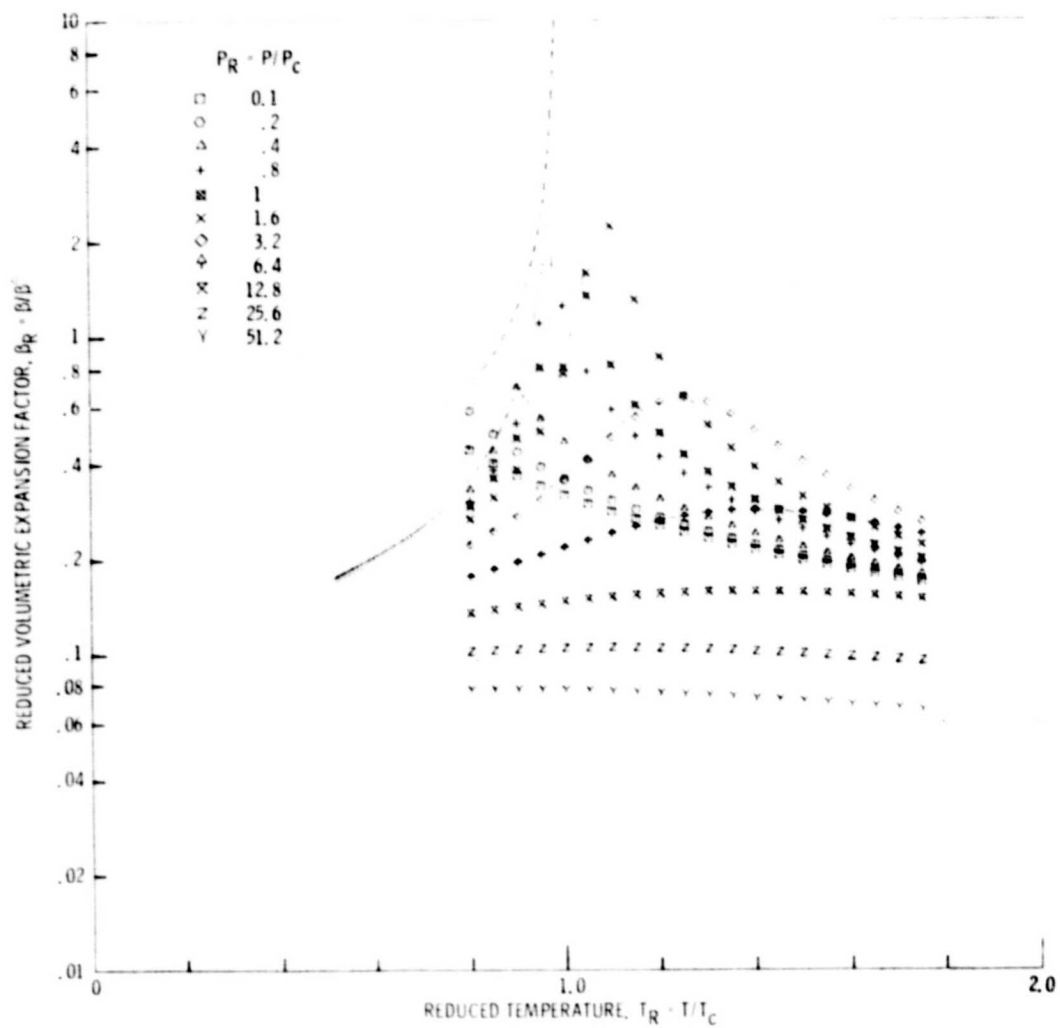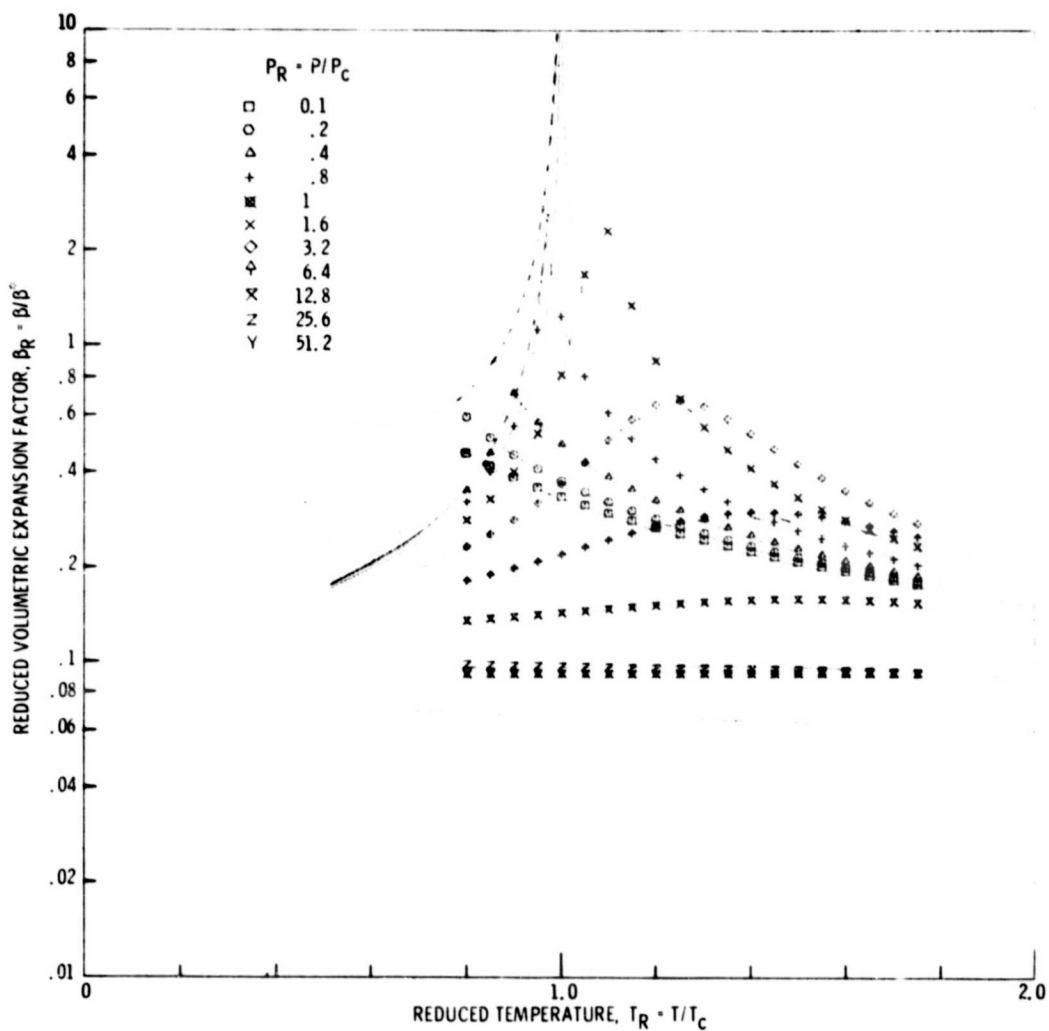
Figure 3. – Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid oxygen and the background is figure 1(a).
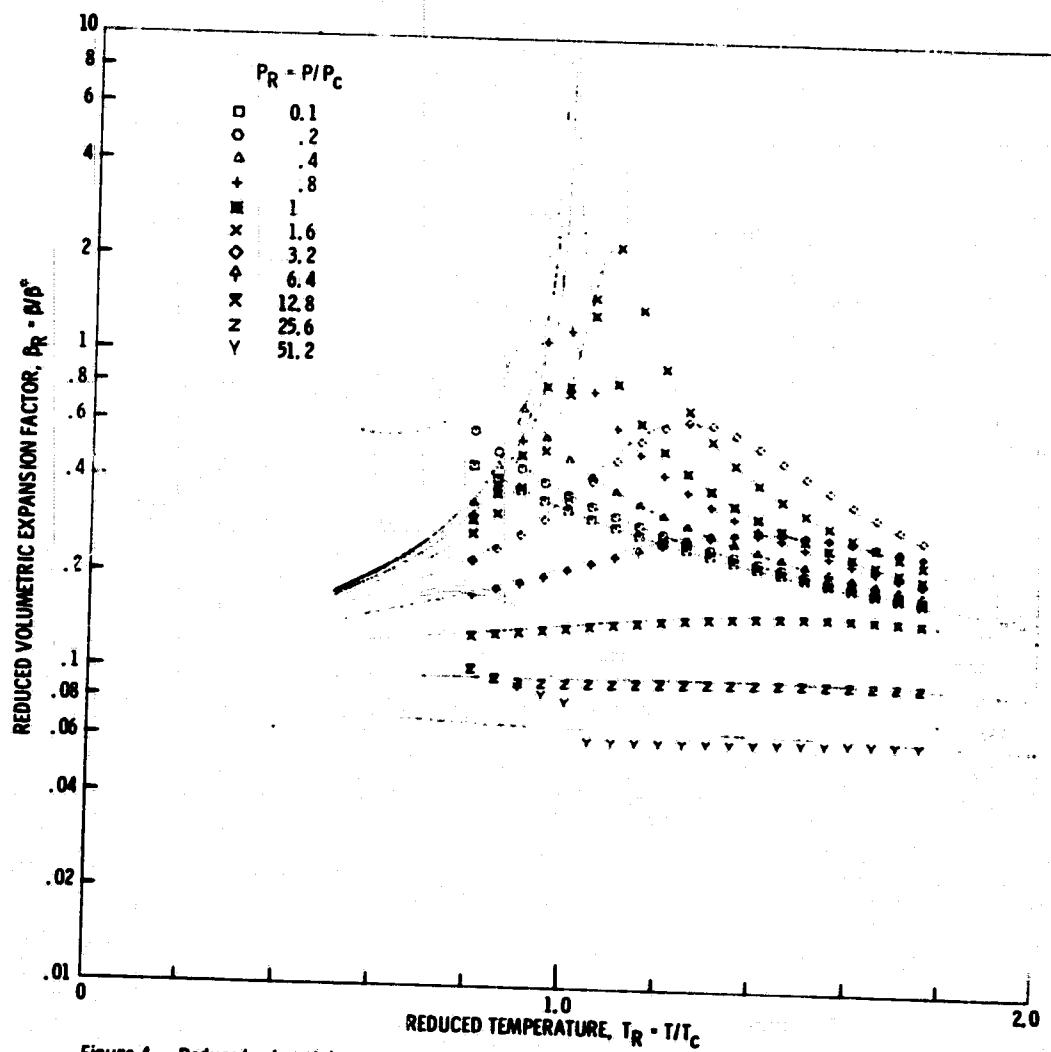
Figure 4. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid argon and the background is figure 1(a).
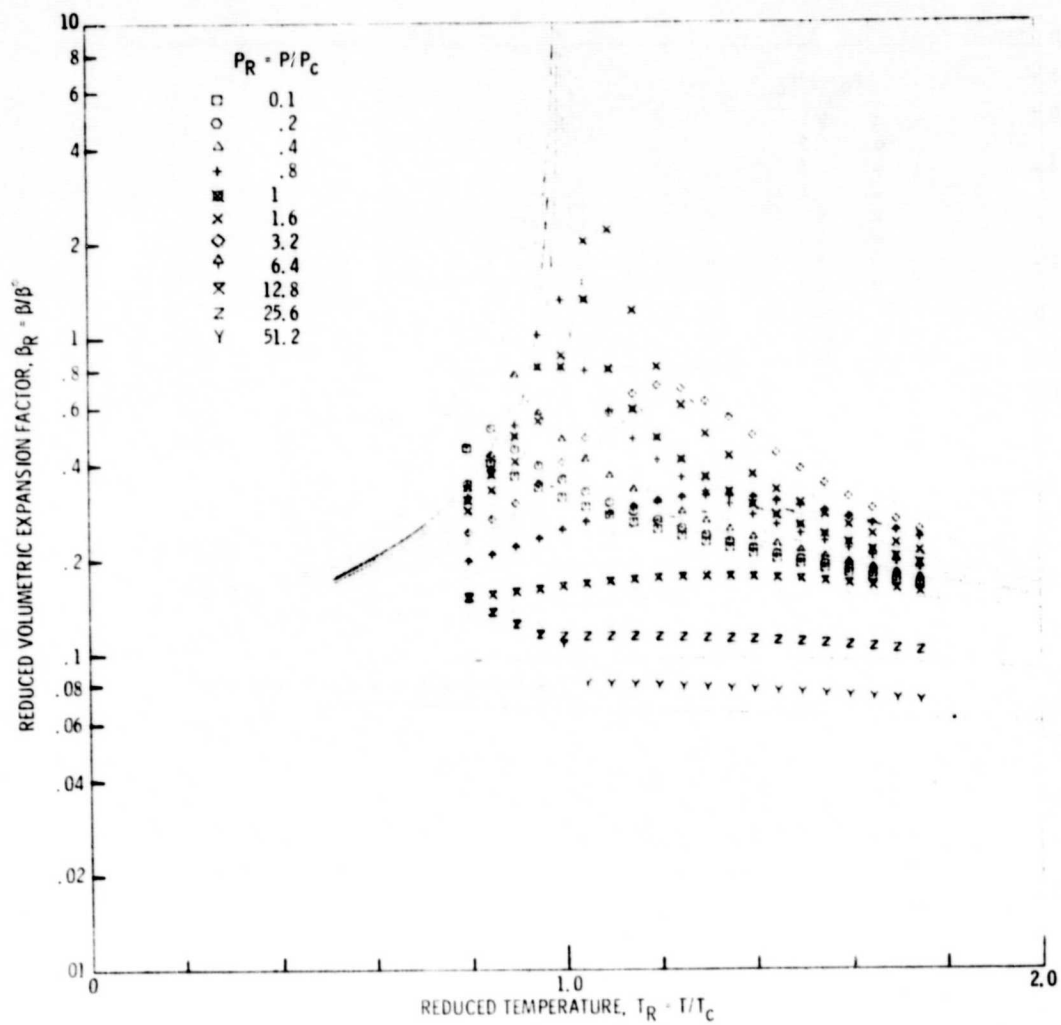
Figure 5. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid fluorine and the background is figure 1(a).

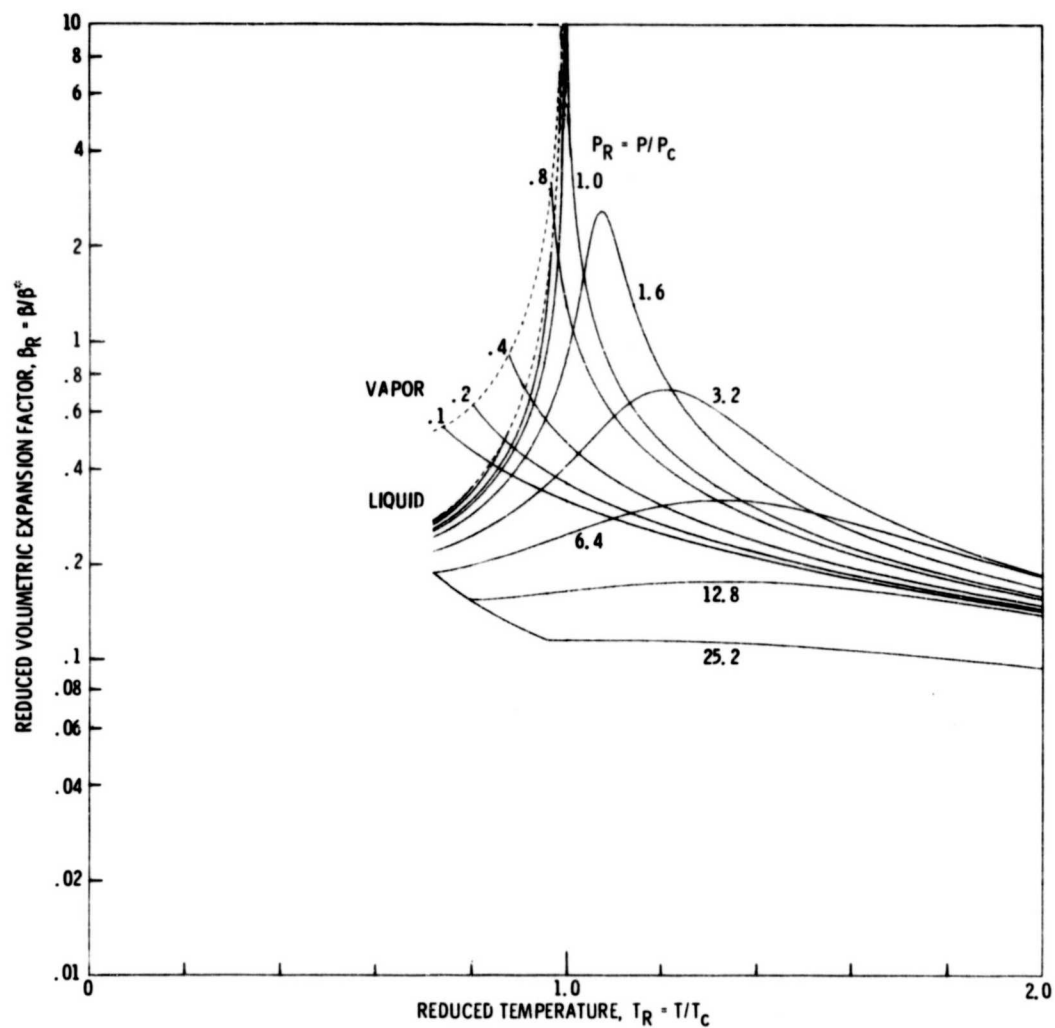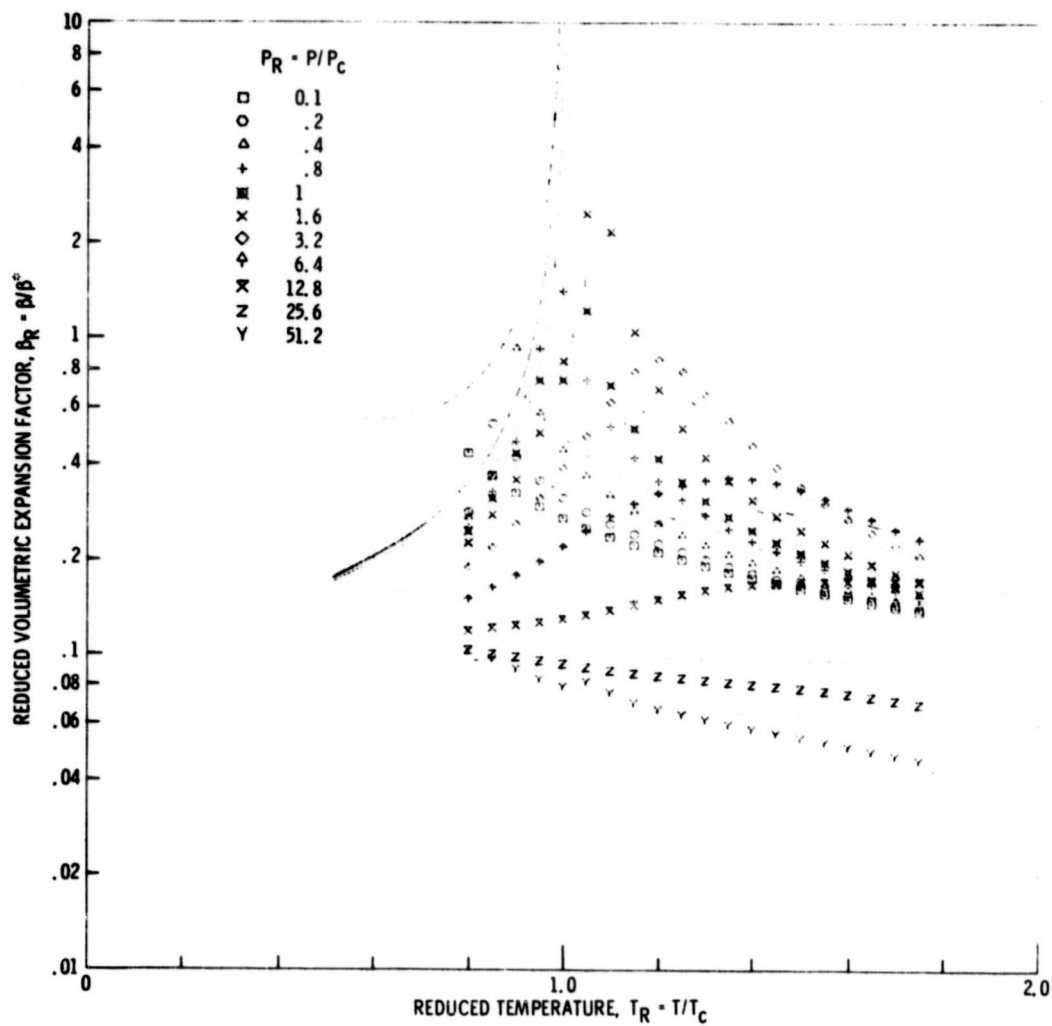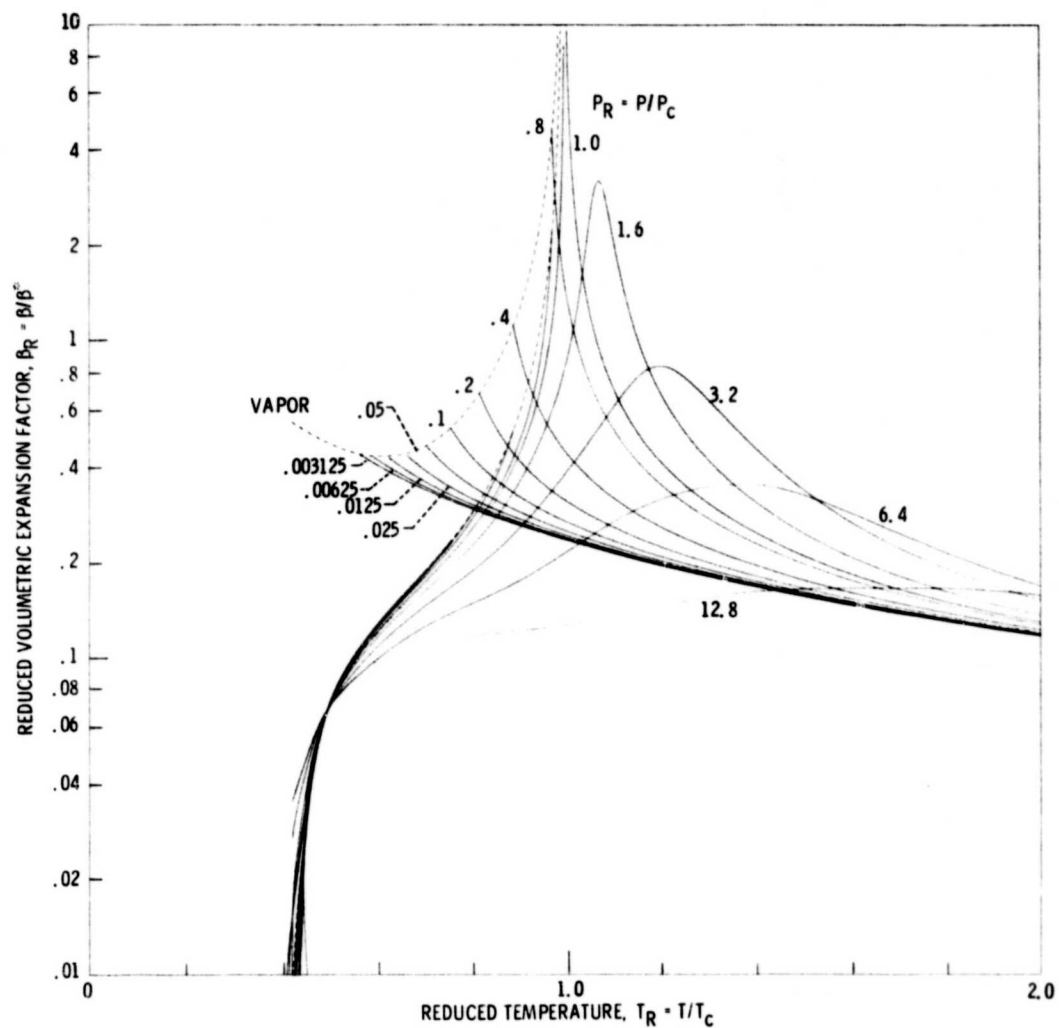REDUCED VOLUMETRIC EXPANSION FACTOR, $\beta_R = \beta/\beta^*$

10
8
6

4

2

1
.8
.6

.4

.2

.1
.08
.06

.04

.02

.01

$P_R = P/P_c$

□	0.1
○	.2
△	.4
+	.8
▧	1
×	1.6
◇	3.2
⟡	6.4
⤬	12.8
Z	25.6
Y	51.2

0   1.0   2.0

REDUCED TEMPERATURE, $T_R = T/T_c$

Figure 6. – Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid carbon-monoxide and the background is figure 1(a).

REDUCED VOLUMETRIC EXPANSION FACTOR, $\beta_R = \beta/\beta^\circ$

10
8
6

4

2

1
.8

.6

.4

.2

.1
.08

.06

.04

.02

01

$P_R = P/P_c$

◻	0.1
○	.2
△	.4
+	.8
▧	1
×	1.6
◇	3.2
✦	6.4
✕	12.8
Z	25.6
Y	51.2

1.0   2.0

0

REDUCED TEMPERATURE, $T_R = T/T_c$

Figure 7. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid carbon-dioxide and the background is figure 1(a).

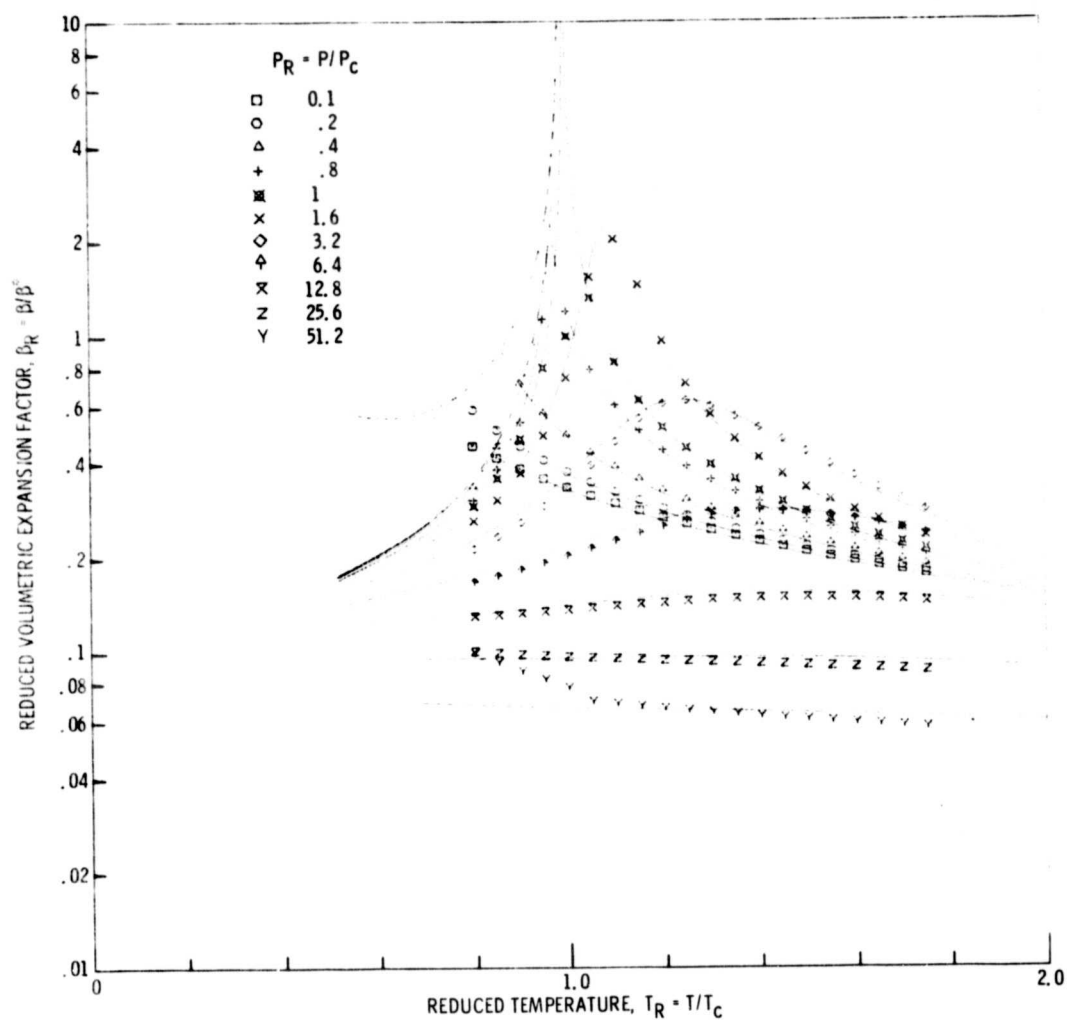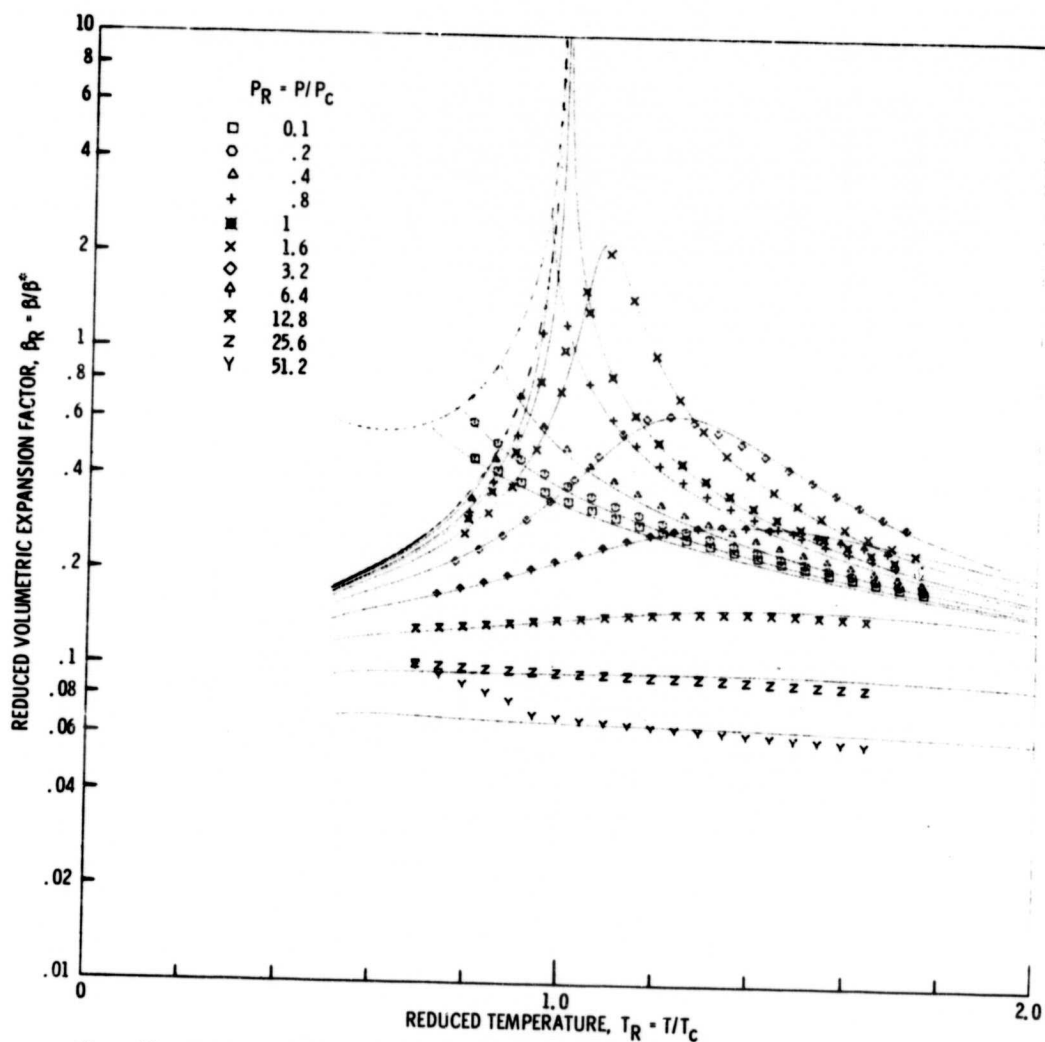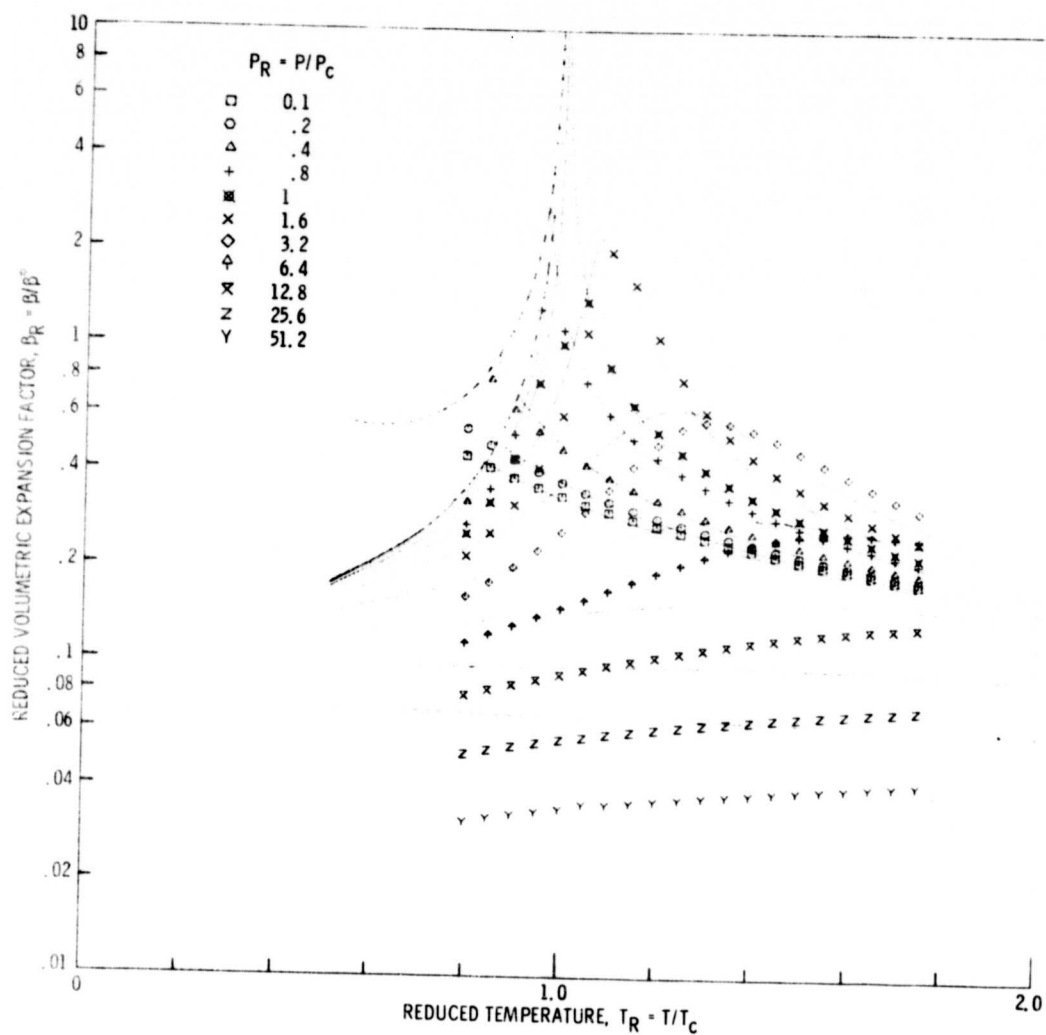Figure 8. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars for fluid carbon-dioxide.

Figure 9. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid water and the background is figure 1(a).

Figure 10. – Reduced volumetric expansion factor plot as a function of reduced temperature with selected Isobars for fluid water.

Figure 11. – Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid neon without quantum corrections and the background is figure 1(a).
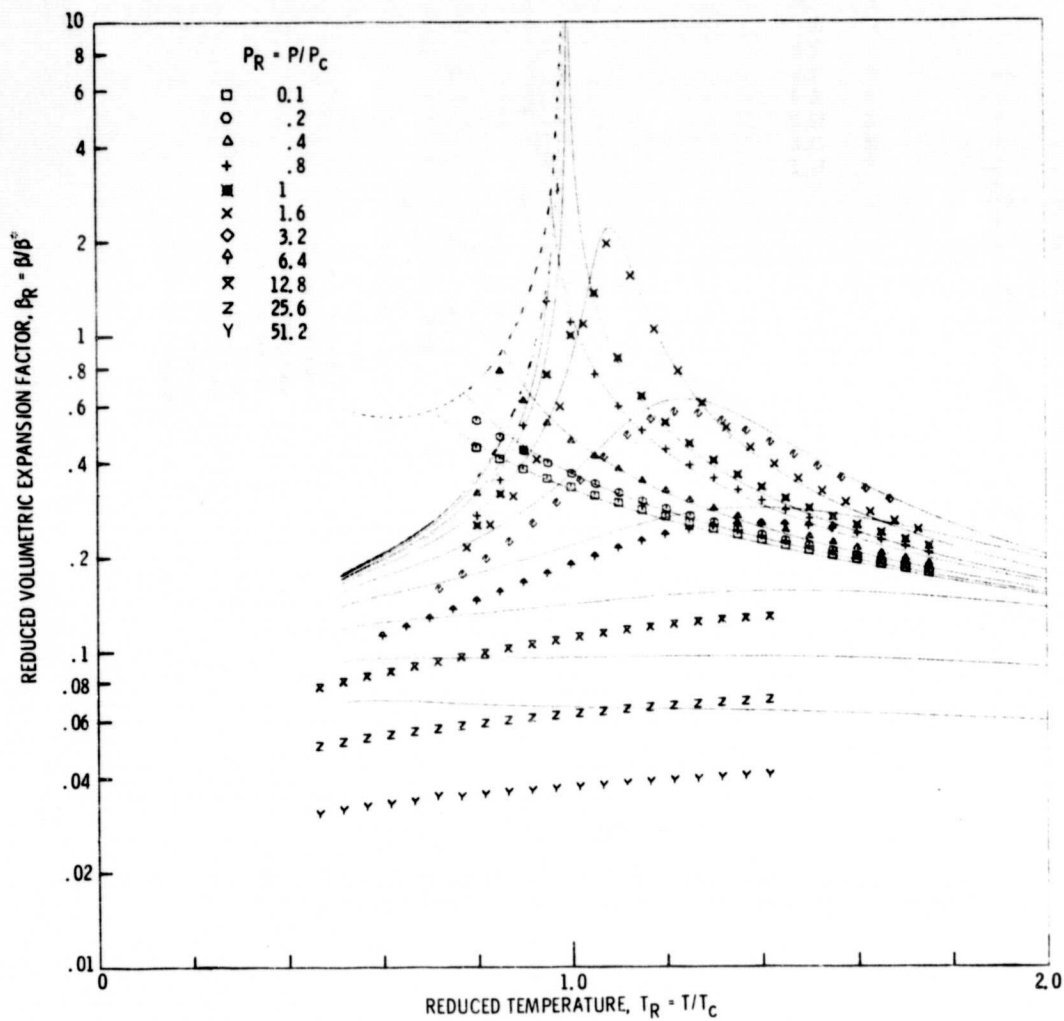
Figure 12. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid neon with points corrected for quantum effects and the background is figure 1(a).

Figure 13. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid hydrogen without quantum correction and the background is figure 1(a).

Figure 14. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid hydrogen with points corrected for quantum effects and the background is figure 1(a).
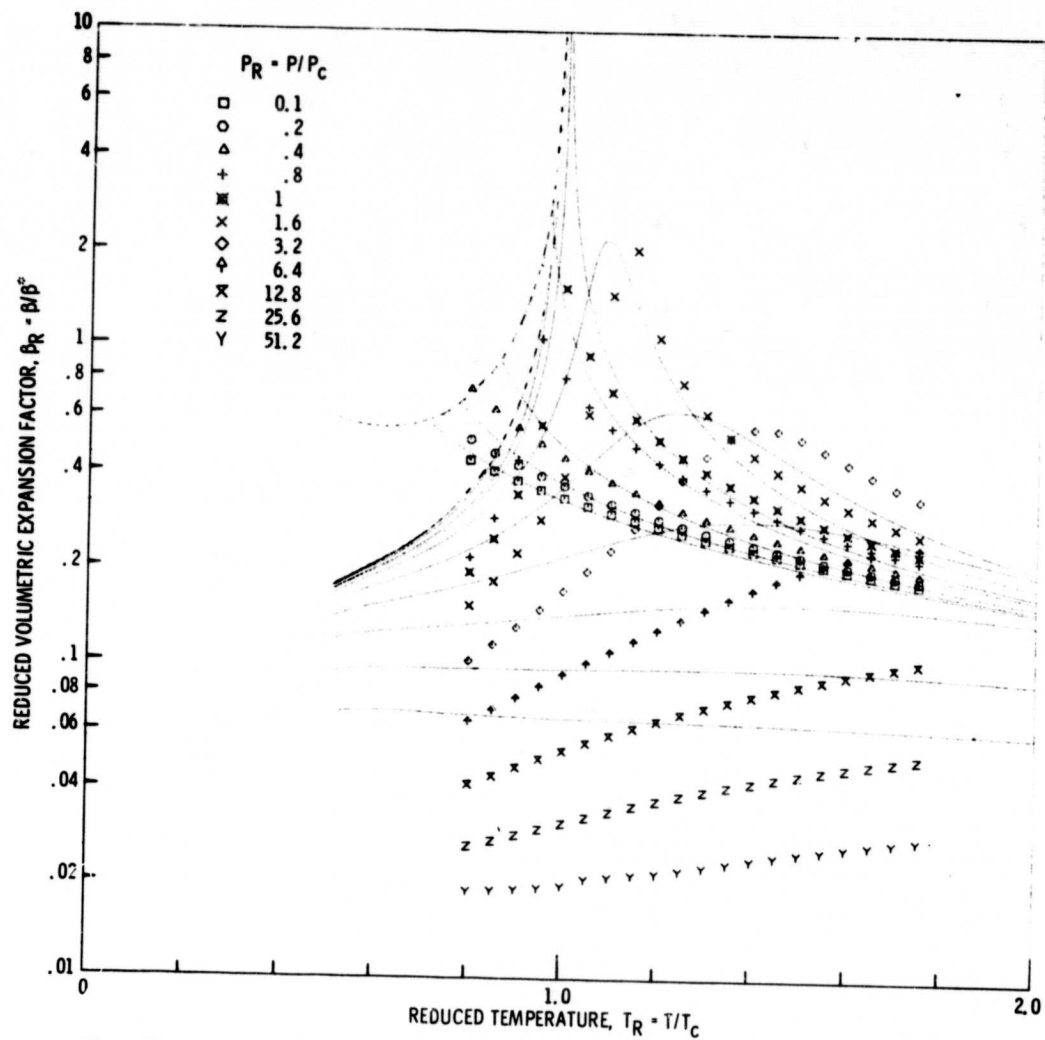
Figure 15. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid helium without quantum corrections and the background is figure 1(a).
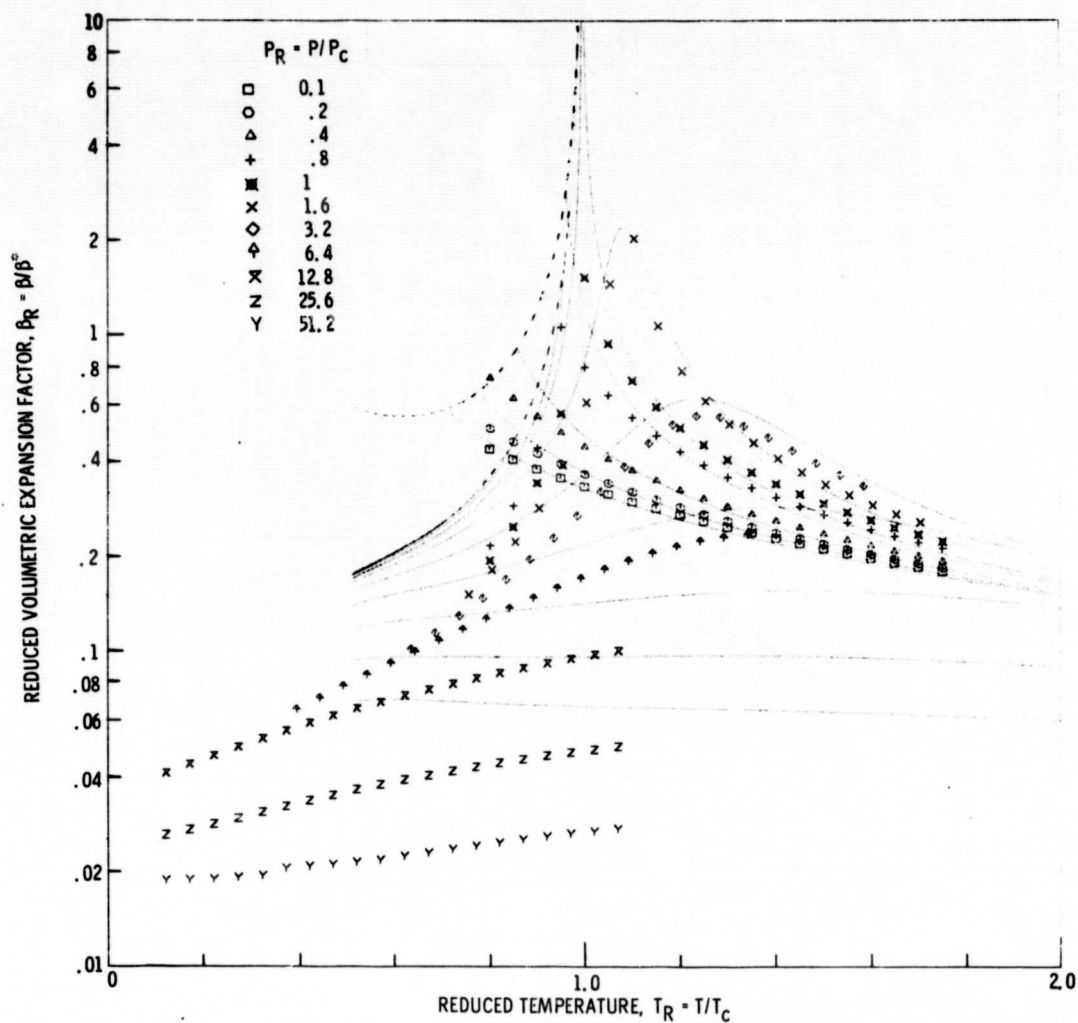
Figure 16. – Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars. Points are for fluid helium with points corrected for quantum effects and the background is figure 1(a).
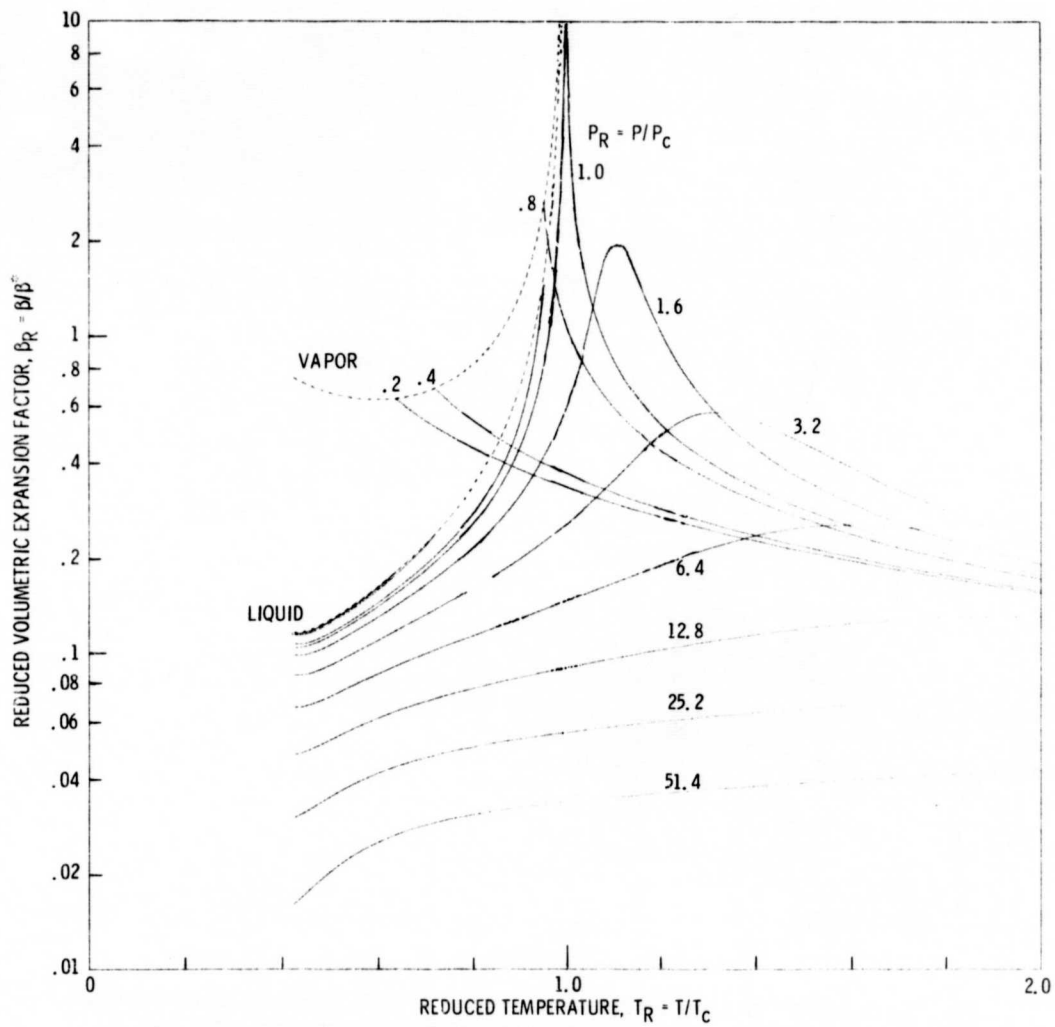
Figure 17. – Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars for fluid hydrogen.
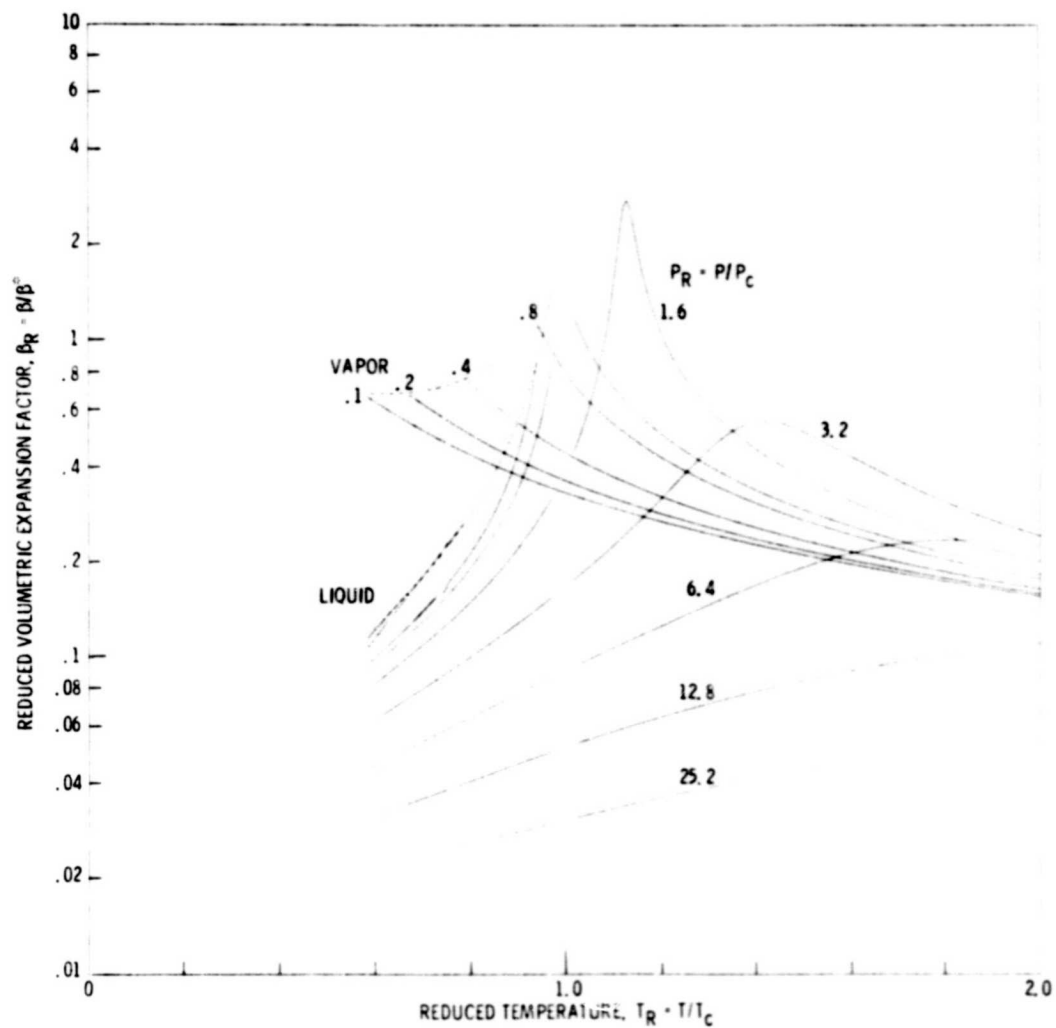
Figure 18. - Reduced volumetric expansion factor plot as a function of reduced temperature with selected isobars for fluid helium.