Westinghouse
Electric Corporation

Energy Systems

Box 355
Pittsburgh Pennsylvania 15230-0355

NSD-NRC-96-4754
DCP/NRC0538
Docket No.: STN-52-003

June 21, 1996

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ATTENTION: T. R. QUAY

SUBJECT: WESTINGHOUSE RESPONSES TO NRC REQUESTS FOR ADDITIONAL INFORMATION ON THE AP600

Dear Mr. Quay:

Enclosed are three copies of the Westinghouse responses to NRC requests for additional information on the AP600. Responses to RAIs 440.376, 440.377, 440.379, 440.382, 440.384, 440.393, 440.394 and 440.584 on the Long Term Cooling Tests at OSU are included in this transmittal. A response to RAI 410.289 on the hot water system is also included.

The NRC technical staff should review these responses as a part of their review of the AP600 design. These responses close the nine RAIs.

Please contact Brian A. McIntyre on (412) 374-4334 if you have any questions concerning this transmittal.

Brian A. McIntyre, Manager
Advanced Plant Safety and Licensing

/nja

Enclosures

cc: T. Kenyon, NRC (w/o enclosures)
N. Liparulo, Westinghouse (w/o enclosures)

E004 1/1

2809A

9606280254 960621
PDR ADOCK 05200003
A PDR

Question 410.289

The staff has previously requested additional information on the hot water heating system (RAI Q410.261) regarding the information on (1) the pressures and temperatures of the hot water system piping that supply hot water to major areas of the plant, (2) the system line routed into the containment, (3) the potential consequences of a break of the system piping and the protection measures, and (4) whether the system lines run over or through the control room. The response to the RAI from Westinghouse was reviewed. Explain whether the response is still valid following the design changes as addressed in Revision 3 of the SSAR. Provide an updated response for RAI Q410.261 if needed (see Open Item No.3 in AP600 Open Item Tracking System Database Executive Summary).

Response:

The response to RAI 410.289 is still valid following the issue of Revision 3 and Revision 7 of the SSAR. That is:

(1) The operating pressure and temperature of the hot water heating system (VYS) is about 300 °F (supply), 220 °F (return) and 120 psig. The piping system design conditions are 320 °F and 200 psig.

(2) No VYS lines are routed inside containment. However, hot water from VYS is routed into containment via VWS. This allows heating of the containment with fan coolers when the reactor is shutdown. This mode of operation represents less than 2% of overall operation time.

(3) No VYS piping is routed in rooms that contain safety-related equipment. There are no adverse consequences on safety-related components or equipment due to postulated breaks in the VYS piping routed in nonsafety-related areas.

(4) The VYS lines are not routed over or through the main control room.

SSAR Revision: NONE

Question 440.376

Re: OSU Scaling Report

One infers from the discussion of p. 5-2 (and, in fact, from other scaling relationships and from an examination of the data) that the APEX scaling rationale essentially makes a transition from pressure scaling to property scaling during a single experiment. Discuss how the point of transition is determined, and how the transition is taken into account in computer code assessments of the test data.

Response:

The transition from pressure scaled to property scaled conditions has been selected to be the pressure at which the ADS 4 valves are opened. Because of this, the ADS 4 valves have been sized assuming property scaled conditions. This is typically about 50 psia for SBLOCA's without additional ADS failures. The actuation of ADS 4 overwhelms the depressurization process and permits a transition to the IRWST injection phase and the long term recirculation cooling phase. It is recognized that subsequent to ADS 4 actuation, the break and ADS 1-3 flow areas are somewhat oversized relative to the properly scaled scaling requirements because they have been sized according to pressure scaled conditions. However, during this time period, the flow rate through the break and ADS 1-3 is extremely low relative to the flow rate through the ADS 4 valves. Therefore, ADS 4 flow should dominate the behavior.

With respect to computer code assessments of APEX data, the codes should predict the actual evolution of the transient. The scaling transition is not a physical transition. It is the reference region at which those interpreting the data should recognize that pressure scaling is no longer required to estimate conditions in the full scale AP600. Time scaling for APEX is always required to properly interpret the data.

SSAR Revision: NONE

Question 440.377

Re: OSU Scaling Report

The development of the equations in Section 5.2.1 is somewhat confusing. What does the term "uniform fluid properties" mean — is this simply an indication of no significant temperature or pressure gradients in the control volume ? Also, Eq. (5-5) is not entirely clear. Since there is no such thing as two-phase density at a point (the point is either liquid or vapor), the term ρ_{tp} is necessarily averaged over a volume, so that the development of the equations on p. 5-4 appears somewhat redundant. Clarify this information.

Response:

The control volume being considered (Figure 5-3) has two main regions; a single-phase vapor bubble region and a two-phase, liquid-vapor mixture region. The term "uniform fluid properties" is intended to mean that the liquid and vapor densities are constant throughout the mixture and that the void fraction profile within the mixture is flat. For example, if a bubbly mixture is being considered, it would be assumed that the bubbles are the same size and homogeneously dispersed.

Although the concept of a two-phase mixture implies some type of volume averaging, often the averaging is performed on a region-wise basis so that a void fraction profile is obtained. The reason for including this subtlety in this analysis is that the author was seeking to define the "elastic compliance" for more general problems, as given by equation (5-9). (This particular approach to defining the two-phase elastic compliance has not been presented previously.) Because void fraction profiles are sometimes present and measured in some problems of interest, (although not considered in this application) the apriori assumption of homogeneous conditions for all cases for the development of equation (5-9) would limit its applicability.

SSAR Revision: NONE

Question 440.379

Re: OSU Testing

In Section 5.3.1 (starting on p. 5-8). It appears that the development of this part of the model ignores wall heat transfer. It would seem that wall heat transfer to the mixture would also have an influence on the rate of expansion. Explain or justify this apparent exclusion.

Response:

This is correct; wall heat transfer is neglected in the development of the analytical model for depressurization from saturated liquid conditions. The model presented in Section 5.3.1 was specifically developed for, and therefore limited to, the case where the mass and energy leaving the system through the break dominates the depressurization process. That is, an order of magnitude analysis revealed that the energy flow rate through the break would be orders of magnitude larger than the core decay heat, the wall heat transfer or the energy flow rate associated with the mass injected into the system.

Performing the order of magnitude analysis for the AP600 indicates that for breaks larger than 2 inches in diameter, the energy leaving the system through the break, would greatly exceed the remaining energy transport terms. This is illustrated in the enclosed order of magnitude analysis. This simple model, therefore, could be used to understand the dominant depressurization processes for purposes of scaling a wide range (i.e., > 2 inches) of blowdown transients. The model could also be easily assessed against simple experimental data, such as Marviken blowdowns, and numerical calculations such as that provided by RELAP.

Although intentionally neglected in the model development in Section 5.3.1, the wall heat transfer was not neglected in the scaling analysis. Equation 5-61includes a vapor generation rate ratio (Π_Γ). Equations 5-78 and 5-79 show how the wall heat transfer (q_{metal} energy release rate from the metal) was included in the vapor generation rate ratio. This scaling group was assessed as part of the scaling analysis and is further considered in Sections 5.6.7 and 5.6.8.

The effect of wall heat transfer and other energy transport terms becomes important for the very small breaks (i.e. ,< 1"). As indicated in Section 5.7.2, special attention was given to the Π-groups containing these transport terms.

SSAR Revision: NONE

Question 440.382

Re: OSU Scaling Report

In the development of Eq. (5-103), explain how the first term of Eq. (5-102) can be approximated by P_p/P_m.

Response:

Requiring that the first term of equation (5-102) be unity was based on a study of the physical properties of water. This relation is only true for most fluids for the range of dimensionless saturation temperature 0 to 0.8. Reference 440.382-1 provides detailed supporting information for water and several other fluids.

References

440.382-1 Reyes, *A Theory of Decompression of Two-phase Fluid Mixtures in Equilibria*, Section 7.1, "Self-Similarity of Fluids in Phase Equilibria," OSU NE-9407, (1994)

SSAR Revision: NONE

Question 440.384

Re: OSU Scaling Report

After Eq. (5-119) on p. 5-32, it stated that ". . . the volumetric vapor fraction in the model will be the same as that in the AP600 . . . if the power is scaled accordingly." On what basis is the power scaled ? What ensures that this scaling will be consistent over the range of "reduced" pressures being scaled ?

Response:

For the two-phase natural circulation phase of a transient, the power scaling criterion given by equation (4-138) on p. 4-72 should be used to establish the proper volumetric void fraction conditions at the core exit during reduced pressure operations. It should be noted however, that for the tests that have been performed, equation (4-145) on p. 4-73 has been implemented. For the two-inch break tests and larger diameter simulations, use of equation (4-145) will yield good results because the two-phase natural circulation period is very short. For the very small breaks (1" and smaller) use of equation (4-145) to scale power will result in higher than prototypical void fractions at the core exit; thus producing somewhat higher natural circulation flow rates.

SSAR Revision: NONE

Question 440.393

Re: OSU Testing

The discussion in the first paragraph of Section 5.7.1 (p. 5-55) requires clarification. Apparently, because the area of the smallest ADS valve is greater than an equivalent break diameter of 2", once ADS opens, the system is break flow dominated (based on the claim that for 2" and greater the system break flow dominated; see RAI 440.375). However, the logic as stated in this paragraph is difficult to follow. Clarify this matter.

Response:

The staff's assessment is correct.

The first paragraph will be clarified by inserting the following:

> "All cases of ADS operation result in the opening of a valve having a throat diameter of at least 2 inches in diameter. Therefore, based on the previous analysis of depressurization behavior, scaling of the ADS flow area should be dictated by the same rationale used to scale the system breaks having diameters larger than two inches."

An errata will be issued.

SSAR Revision: NONE

Question 440.394

Re: OSU Scaling Report

The basis for the statement in the fourth paragraph of Section 5.7.2 (p. 5-56) needs to be further explained. Aside from considerations of "steam accumulation in the CMT balance lines" (which needs to be tied more explicitly into "system volumetric expansion") there appears to be no accounting for recirculatory operation of the CMTs (which continues for a significant period in the 1" break discussed in this section), nor for the possibility of flashing in the CMT-- due to accumulation of hot water during recirculation and the gradual decrease in system pressure--as an initiating mechanism for CMT draining. If this subject is discussed elsewhere in the report, provide a cross reference to this information. Otherwise, address this matter.

Response:

The detailed discussion on CMT recirculation and draining is included in Sections 6.1 through 6.3 of the scaling analysis.

SSAR Revision: NONE

Question 440.584

Re: Long Term Cooling Test SB5

Staff analysis of data from Westinghouse OSU Test SB5 has revealed an apparent anaomaly in the break flow. The integrated flow from the break, as determined from the instrumentation on the primary sump tank, appears to be apprximately twice as large as would be expected, based on comparison to a similar NRC confirmatory test using the same nominal break size (1") as well as comparison to other Westinghouse tests of different sizes. For instance, Test SB19, with a 2" break (4 times SB5 nominal break area), appears to show about twice the break flow of SB5, rather than 4 times the flow. Please review the data from SB5 and explain the apparent anomalous flow data.

Response:

As discussed in Section 1.5 of the OSU Test Analysis Report (Reference 440.584-1), the original scaling for the OSU test breaks used the break-dominated depressurization process described in Section 5.4.1 of the Facility Scaling Report (Reference 440.584-2). This scaling approach was used for all breaks modeled in the OSU tests given in the OSU Test Analysis Report as well as the OSU Final Data Report (Reference 440.584-3). This scaling process is valid for break sizes of 2 in. or more, but was found to be inaccurate for smaller breaks. Therefore, the 1-in. cold-leg break (SB05) and the 1/2-in. cold-leg break (SB23) are oversized when considering the system energy and volumetric scaling methodology. The ratio of the break diameter scale factors between the two methods is given in Table 5-6 in the Facility Scaling Report, and is 1.5 and the ratio of the integrated break flow between tests SB19 and SB05 is expected to be about a factor of two as observed.

The break areas used for the Westinghouse tests with break sizes less than 2 incles were greater than the scaled values; therefore, the timing of the events for these 1-in. and 0.5-in. tests will be distorted from the properly scaled values, and the events and total transient will be shorter than the revised scaling would predict. Revision of the scaled break diameters is the only significant re-scaling for the OSU test facility. This distortion only affects a few tests; the remaining tests have the properly scaled break diameter. Data for the affected tests are still suitable for the purposes of computer code validation, since the break area used in the test can be simulated in the code prediction of the test.

Reference

440.584-1 WCAP-14292, Revision 1, "Low Pressure Integral System Tests at OSU Test Analysis Report"

440.584-2 WCAP-14270, "Westinghouse AP600 Long Term Cooling Test Facility Scaling Report"

440.584-3 WCAP-14252, "AP600 Low Pressure Integral System Test at OSU: Final Data Report"

SSAR Revision: NONE

7.0 SCALING CONSIDERATIONS

7.1 *Self-Similarity of Fluids in Phase Equilibria*

The success of scaling depressurization behavior in reduced pressure test facilities ultimately lies in the fact that several properties of fluids in phase equilibria exhibit "self-similarity" over a wide range of conditions. As explained by Briggs and Peat (1989) in their discussion on Mandelbrot fractals, self-similarity is a "repetition of detail at descending scales." In applying this concept to certain fluid properties at saturation conditions, I have found that there exists a region, bounded by a dimensionless temperature range, in which continuous subsets of certain fluid properties can be scaled by a single constant to re-create a set of fluid properties applicable to a much wider range of conditions. In this section, I present a criterion that defines the "self-similar" region for fluids in phase equilibria. I also describe how saturation pressures and temperatures in systems undergoing similar processes at different spatial and temporal scales can be related.

7.1.1 *Liquid-Vapor Phase Change Fluid Properties*

The ratio of the pressure work associated with phase change to the total energy associated with phase change can be written as a dimensionless group as follows:

$$\psi = \frac{P v_{fg}}{h_{fg}} \qquad (7\text{-}1)$$

Where P is the saturation pressure, v_{fg} is the change in specific volume and h_{fg} is the latent heat of vaporization. If one graphs this quantity against the corresponding saturation temperature a linear trend is observed beginning at the triple point temperature, T_t, and extending nearly to the critical point temperature, T_c. The saturation temperature can be expressed as a dimensionless quantity as follows:

$$\theta = \frac{T - T_t}{T_c - T_t} \qquad (7\text{-}2)$$

Figures 7-1 through 7-7 are graphs of ψ versus θ for a variety of fluids at saturated conditions. These figures illustrate that the data is quite linear for the range of dimensionless temperatures given by:

$$0 \le \theta \le 0.8 \qquad (7\text{-}3)$$

As the critical point is approached, for values of θ greater than 0.8, the trend becomes non-linear. The intercept is the value of ψ evaluated at the triple point. That is:

$$\psi(0) = \psi_t \tag{7-4}$$

The slope is a constant given by:

$$\frac{d\psi}{d\theta} = c_l \tag{7-5}$$

Figure 7-8 summarizes the results for all of the fluids by plotting $(\psi-\psi_t)$ versus θ.

Based on the results, the equation relating ψ and θ is given by:

$$\psi = c_l\theta + \psi_t \tag{7-6}$$

Table 1 summarizes the values of c_l and ψ which are applicable over the range given by equation (7-3).

Table 1
Constants for Equation (7-6)

Fluid	c_l	ψ_t
Water	0.0926	0.05038
Oxygen	0.1302	0.05822
Nitrogen	0.0988	0.08567
R-11	0.0976	0.06601
R-12	0.0900	0.07476
R-113	0.0823	0.07272
R-500	0.0695	0.0898

7.1.2 Equation of State for Saturated Pressure and Temperature

The Clausius-Clapeyron equation is the classical differential equation that defines the slope dP/dT for a phase equilibrium curve. It is derived by assuming that the Gibb's free energies for the two phases being considered are equal., e.g. Lay, J.E. (1990). Using the standard definition for the Gibb's free energy and relating the change in entropy to the latent heat of vaporization and the saturation temperature yields the well-known result Clausius-Clapeyron equation:

$$\frac{dP}{dT} = \frac{h_{fg}}{v_{fg}T} \tag{7-7}$$

The Clausius-Clapeyron equation can be used with equation (7-6) to obtain an equation of state for the saturation pressure and temperature. Let us rewrite equation (7-6) as follows:

$$\frac{P v_{fg}}{h_{fg}} = bT + a \tag{7-8}$$

where

$$a = \psi_i - bT_i \tag{7-9}$$

$$b = \frac{c_i}{\left(T_c - T_i\right)} \tag{7-10}$$

Rearranging equation (7-8) yields:

$$\frac{h_{fg}}{v_{fg}} = \frac{P}{(bT + a)} \tag{7-11}$$

Substituting equation (7-11) into the Clausius-Clapeyron equation yields:

$$\frac{dP}{dT} = \frac{P}{T(bT + a)} \tag{7-12}$$

Separating the variables and integrating both sides yields an equation of state equation for saturation pressure in terms of saturation temperature. That is:

$$\int_{P_t}^{P} \frac{dP}{P} = \int_{T_t}^{T} \frac{dT}{T(bT + a)} \tag{7-13}$$

the solution of which is:

$$P = P_t \left[\left(\frac{a + bT_t}{a + bT} \right) \left(\frac{T}{T_t} \right) \right]^{\frac{1}{a}} \tag{7-14}$$

Where P_t and T_t are the saturation pressure and temperature at the triple point respectively. Equation (7-14) is the state equation that relates saturation pressure to saturation temperature.

Comparisons of equation (7-14) to the tabulated values of saturation pressure and temperature for various fluids indicates excellent agreement; having R^2 values greater than 0.994.

7.1.3 Scaled Processes Using Similar Fluids in Phase Equilibrium

Let us now turn our attention to the problem of relating the saturation pressure and temperature in a reduced pressure test model to the same properties in a full pressure prototype. Let us suppose that the same working fluid is used in the model as in the prototype. We would need to relate the fluid properties in the full pressure plant to those in the reduced pressure model. If we assume that the depressurization process evolves along the saturation curve, then equation (7-14) is directly applicable.

Equation (7-14) has been normalized using the saturation pressure and temperature corresponding to the triple point of the fluid. However, the saturation pressure and temperature corresponding to any point between θ equal to zero and 0.8 would serve equally well. For depressurization processes, it is convenient to select the initial saturation pressure and temperature as the "reference" parameters. Thus, equation (7-14) becomes:

$$P = P_o \left[\left(\frac{a + bT_o}{a + bT} \right) \left(\frac{T}{T_o} \right) \right]^{\frac{1}{a}} \tag{7-15}$$

where the subscript "o" denotes a reference property evaluated at the initial phase equilibrium conditions and the constants "a' and "b" are as defined previously. Equation (7-15) can be written as a scaling ratio as follows:

$$\left(\frac{P}{P_o}\right)_R = \left[\left(\frac{a+bT_o}{a+bT}\right)_R \left(\frac{T}{T_o}\right)_R\right]^{\frac{1}{a}} \tag{7-16}$$

where the subscript "R" denotes the ratio of model to plant properties. Because the same fluid is used in both cases, the coefficients a and b are identical in the model and the plant.

Substituting equation (7-8) into (7-16) and rearranging yields:

$$\left(\frac{P}{P_o}\right)_R = \left[\frac{\left(h_{fg}\ T/v_{fg}\right)}{\left(h_{fg}\ T/v_{fg}\right)_o}\right]_R^{\frac{1}{a+1}} \tag{7-17}$$

Figure 7-9 reveals that the right hand-side of equation (7-17) is essentially unity for all values of pressure ratios (P/P_o) in the model and the prototype. Thus:

$$\left[\frac{\left(h_{fg}\ T/v_{fg}\right)}{\left(h_{fg}\ T/v_{fg}\right)_o}\right]_R = 1 \tag{7-18}$$

Substituting this result into equation (7-17) yields:

$$\left(\frac{P}{P_o}\right)_R = 1 \tag{7-19}$$

or in terms of model parameters, denoted by the subscript "m" and the plant parameters, denoted by the subscript "p",

$$P_p = \left(\frac{P_{o,p}}{P_{o,m}}\right) P_m \tag{7-20}$$

Equation (7-20) relates the saturation pressure in the model to the saturation pressure in the plant. This same result can be obtained using the graphical approach presented by Kocamustafaogullari and Ishii (1986).

Substituting equation (7-19) into (7-16) yields an equation that can be used to relate the saturation temperatures in the model to those of the plant. After some algebra, one obtains:

$$T_p = \frac{a}{\left[\dfrac{(a+bT)_m}{T_m}\;\dfrac{(T_o)_R}{(a+bT_o)_R} - b\right]} \tag{7-21}$$

7.1.4 Conclusions

The results herein are applicable to the range of dimensionless temperatures, θ, between zero and 0.8. Equation (7-14) presents a state equation that relates saturation pressure to saturation temperature. It has a sound theoretical basis and can be used to replace empirical correlations currently used in computer codes.

Equation (7-20) and (7-21) relate the saturation pressures and temperatures of a reduced pressure scale model to those of a full pressure prototype. This allows direct data comparisons when the process being examined evolves along the phase equilibrium curve.

The property of "self-similarity" is demonstrated by equations (7-18) and (7-19). That is, any continuous subset of these fluid properties can be scaled by a single constant to re-create an equivalent set of fluid properties applicable to a wider range of pressures.

Figure 7-1

WATER PROPERTIES

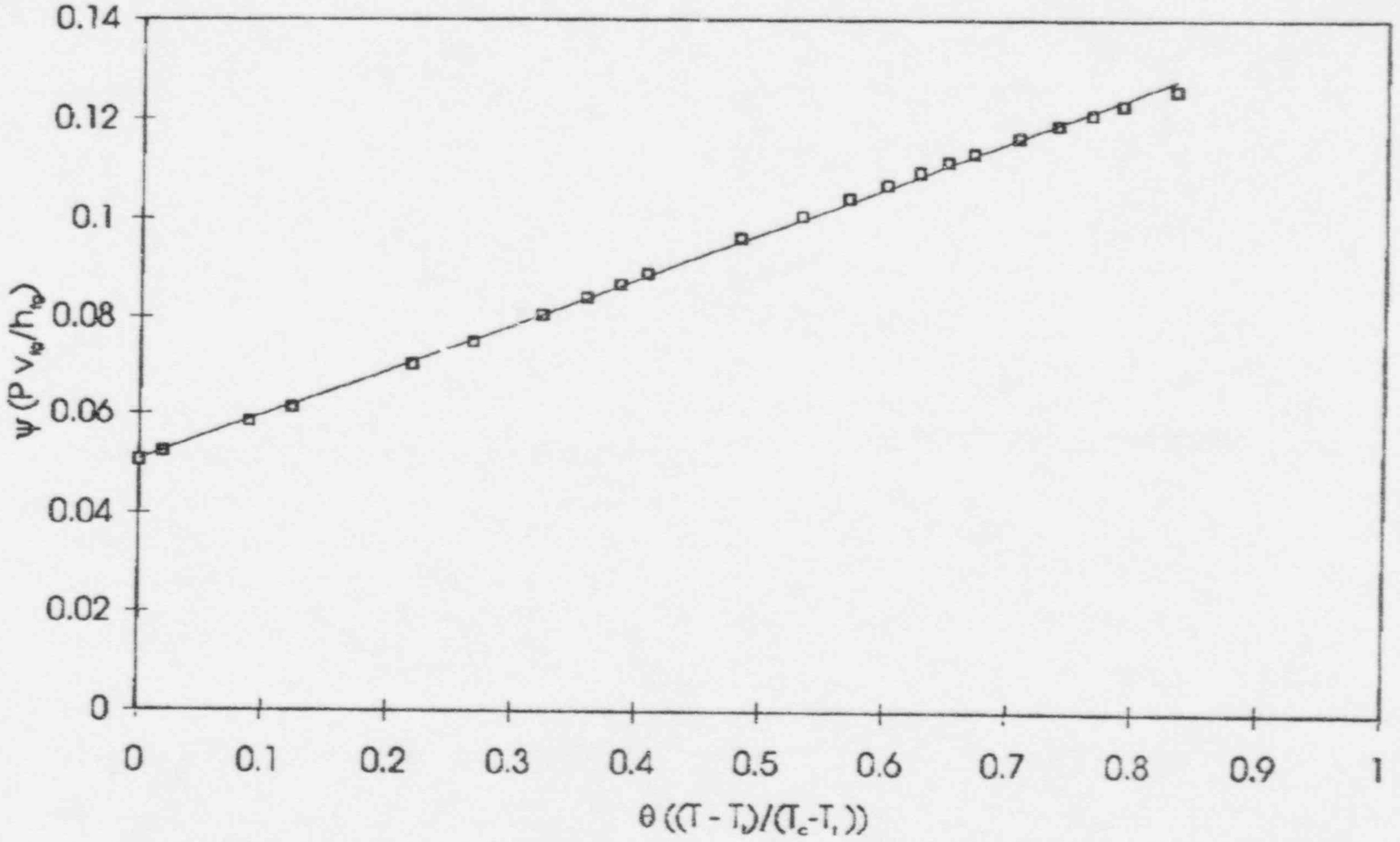


Figure 7-2

OXYGEN PROPERTIES

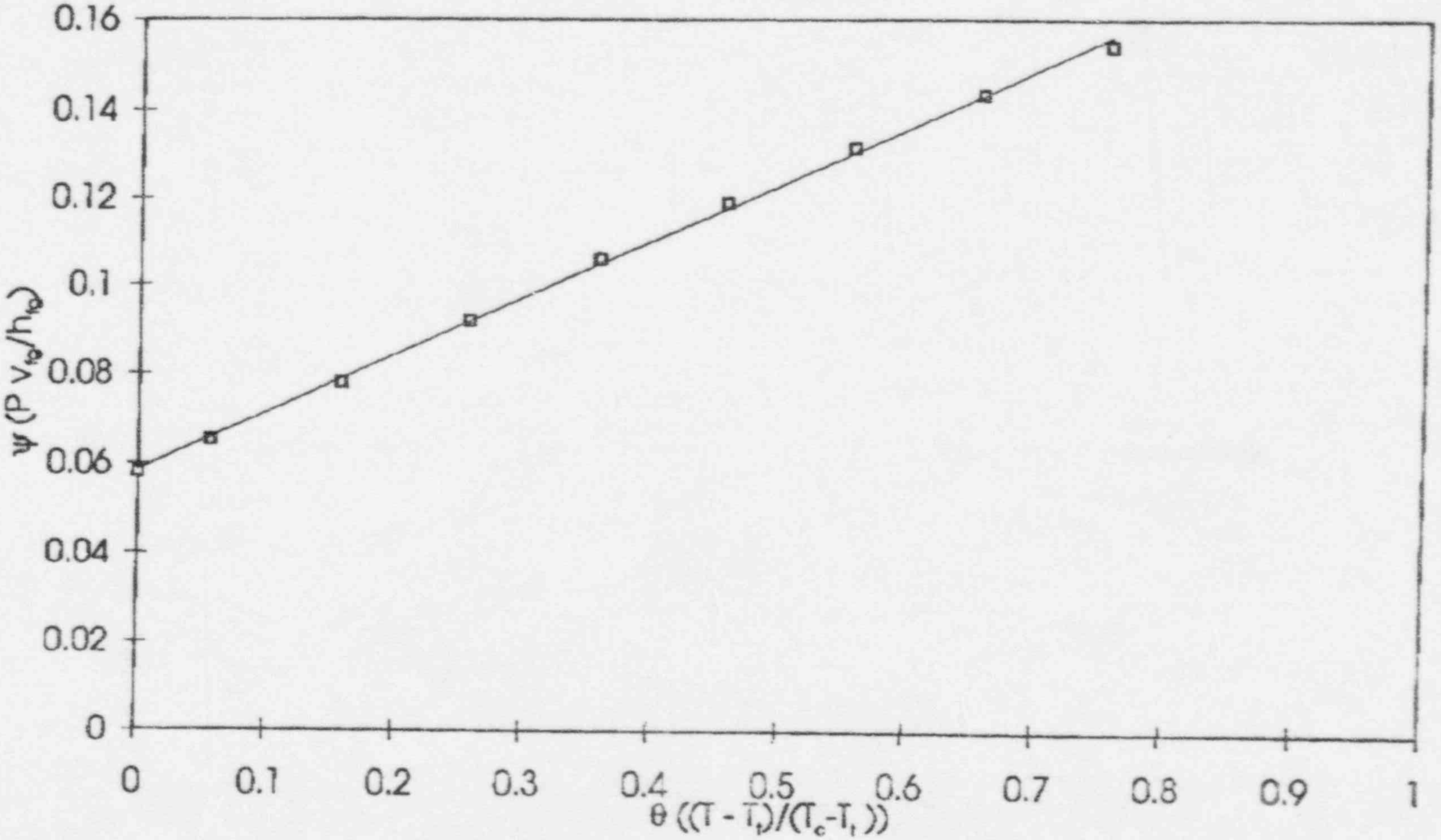


Figure 7-3

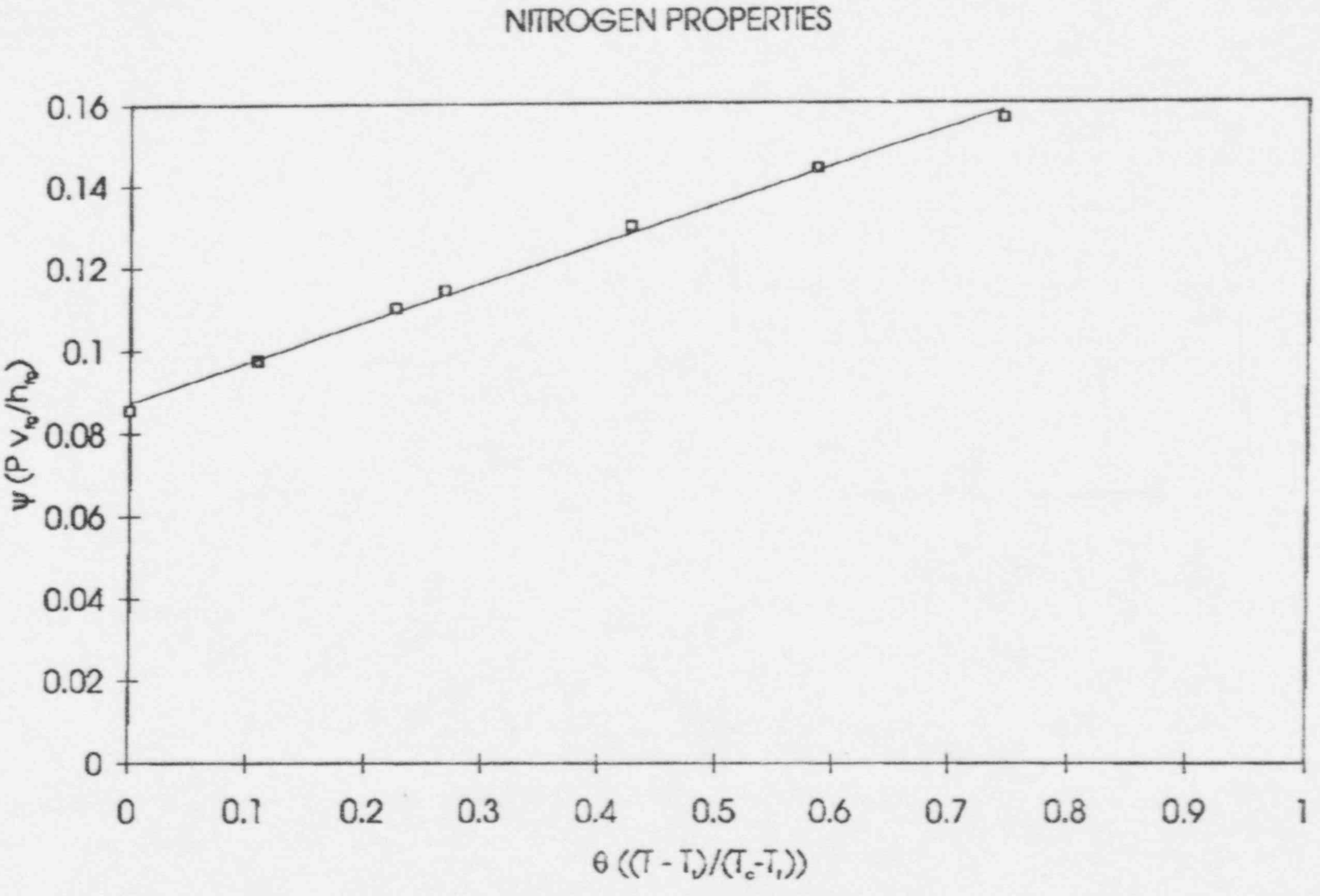

NITROGEN PROPERTIES
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ψ (P v_{fg}/h_{fg})
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
θ ((T - T_t)/(T_c-T_t))

Figure 7-4

R-11 PROPERTIES

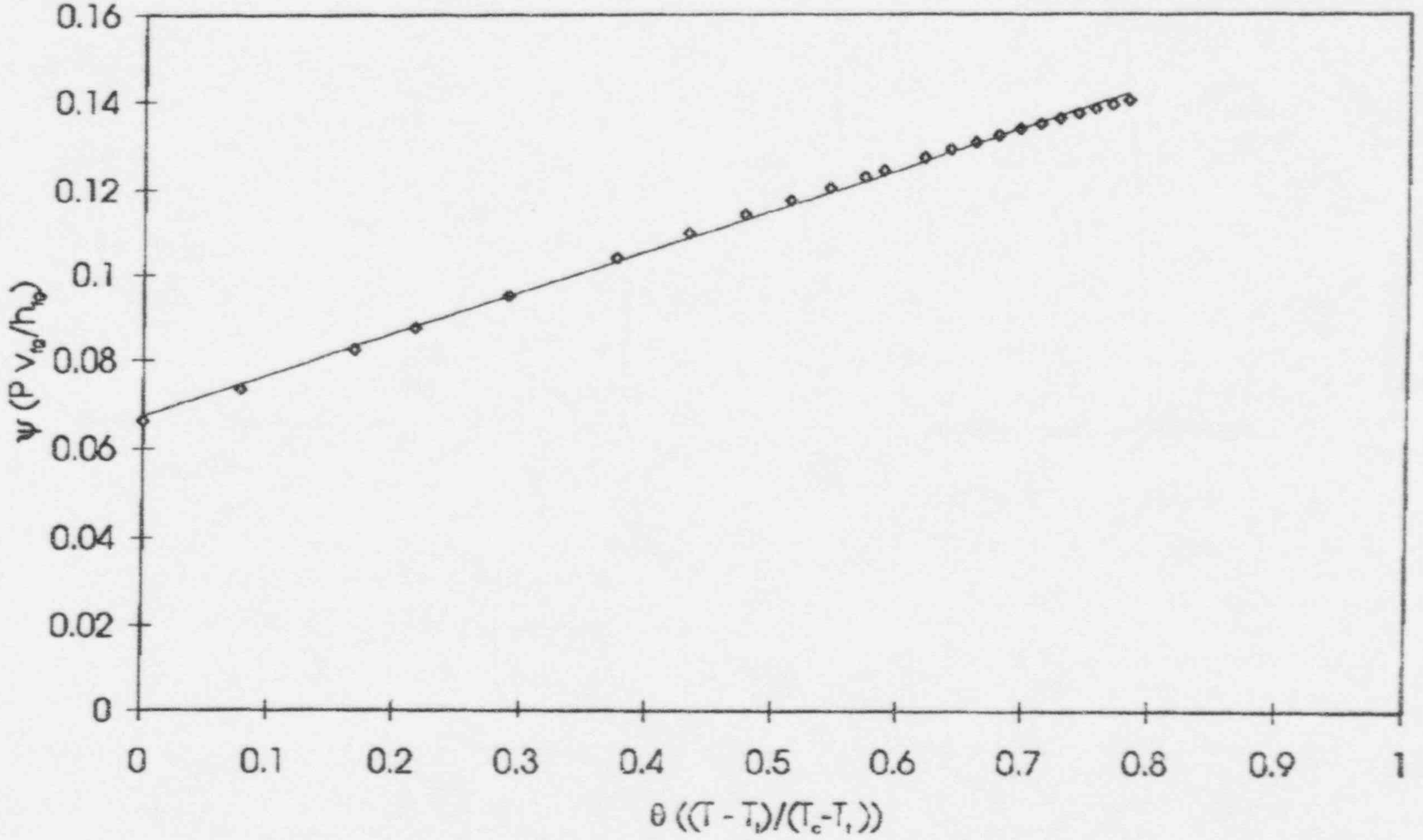


Figure 7-5

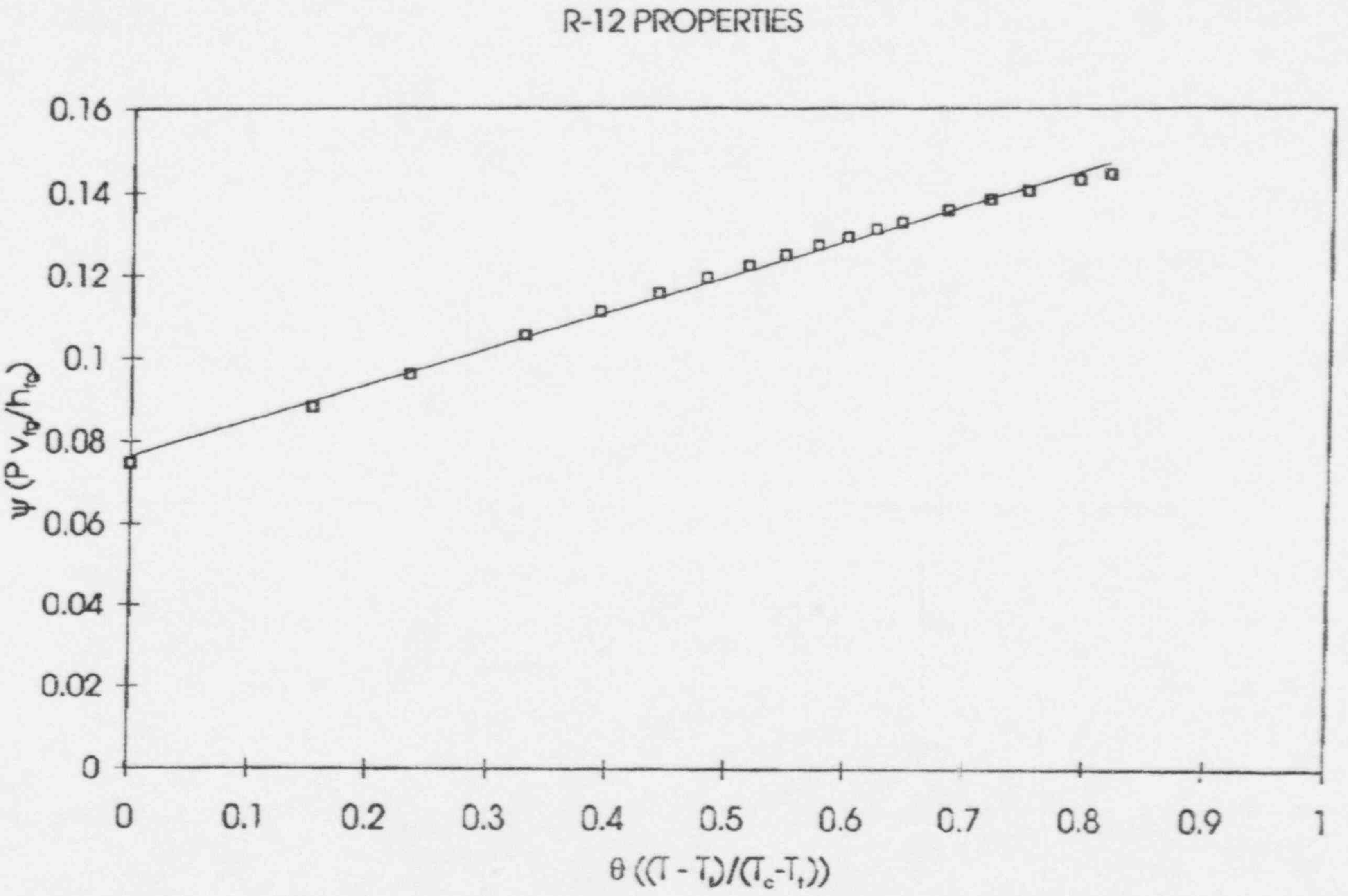

R-12 PROPERTIES
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ψ ($P v_{lg}/h_{lg}$)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
θ (($T - T_t$)/(T_c-T_t))

Figure 7-6

R-113 PROPERTIES

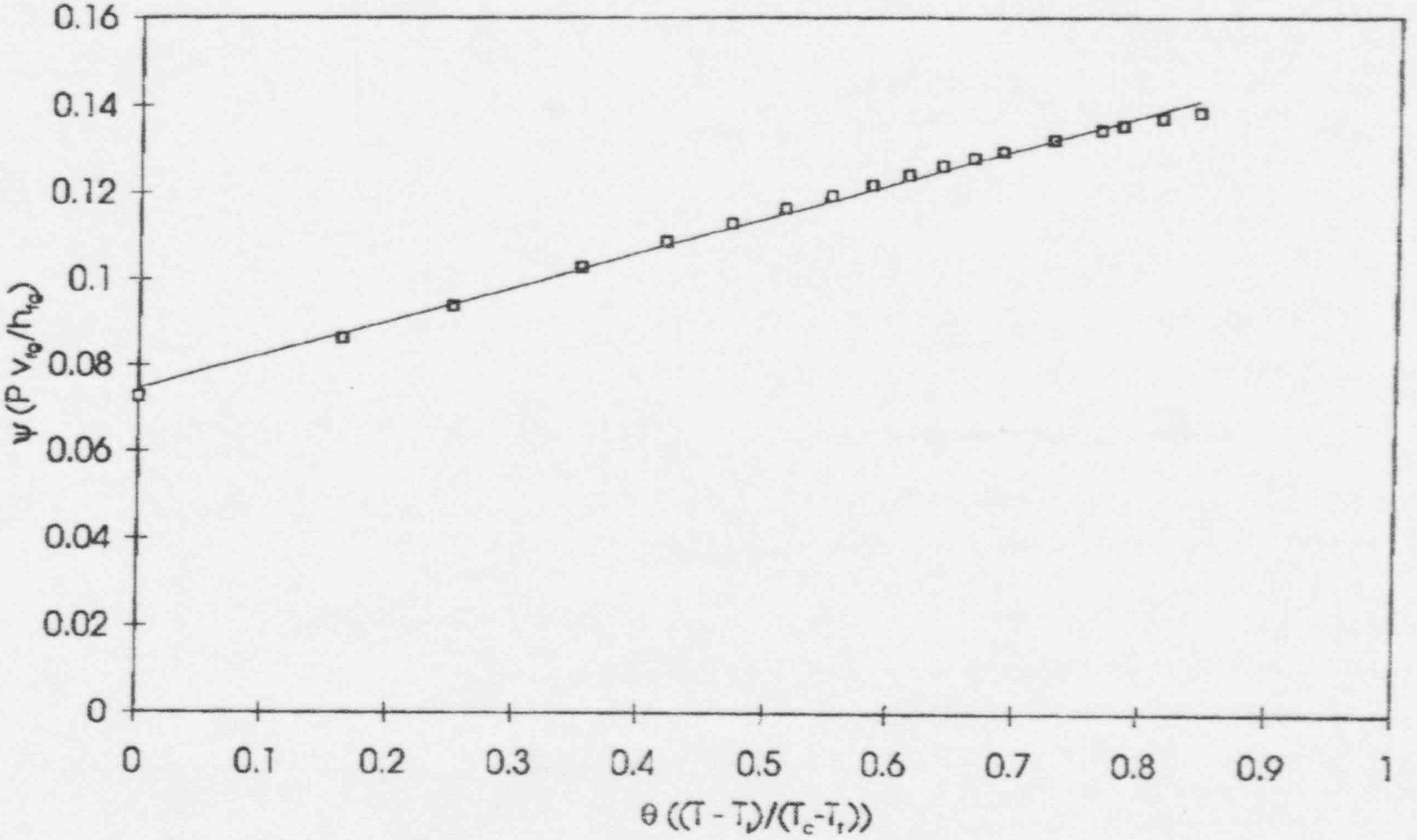


Figure 7-7

R-500 PROPERTIES

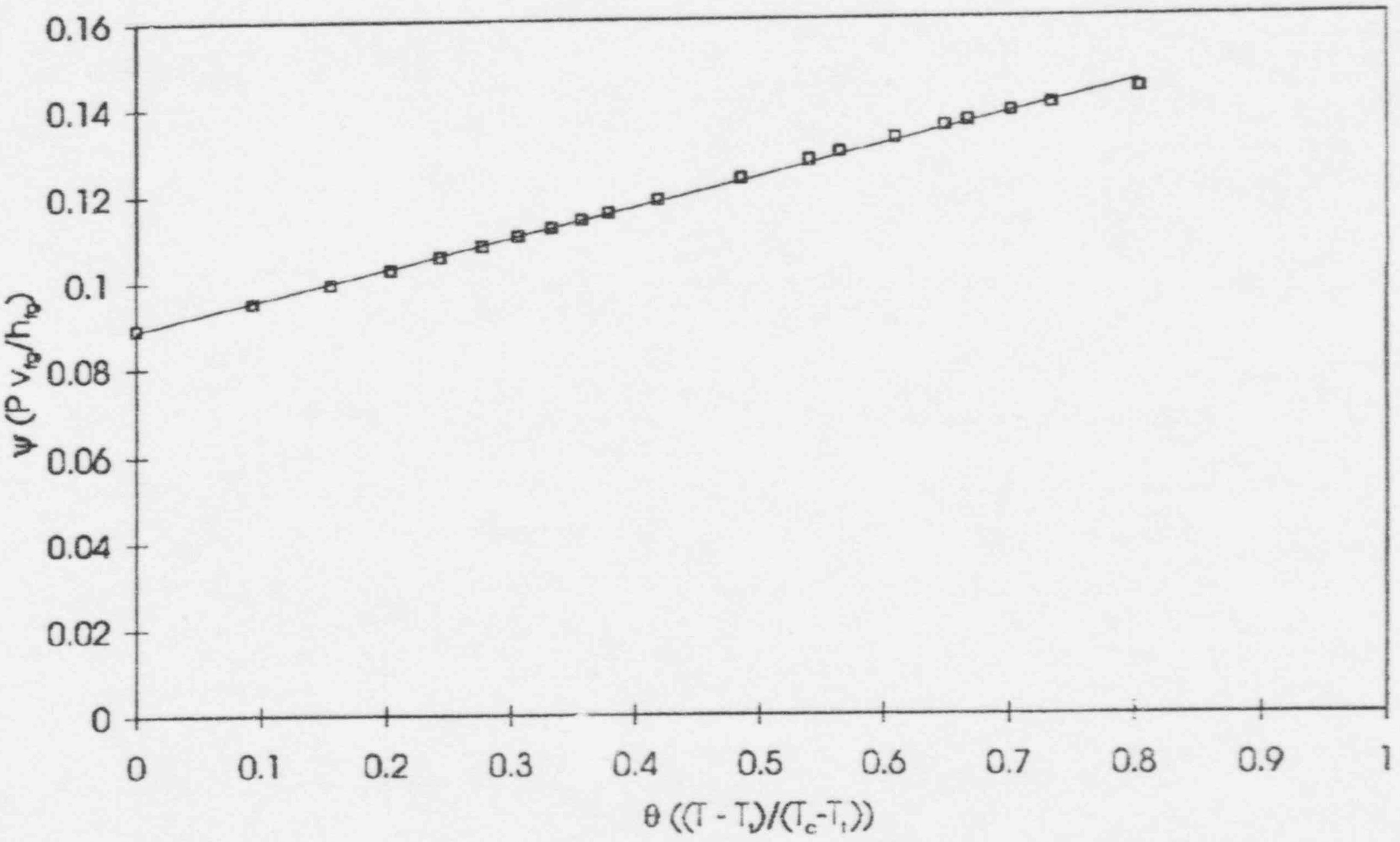


Figure 7-8

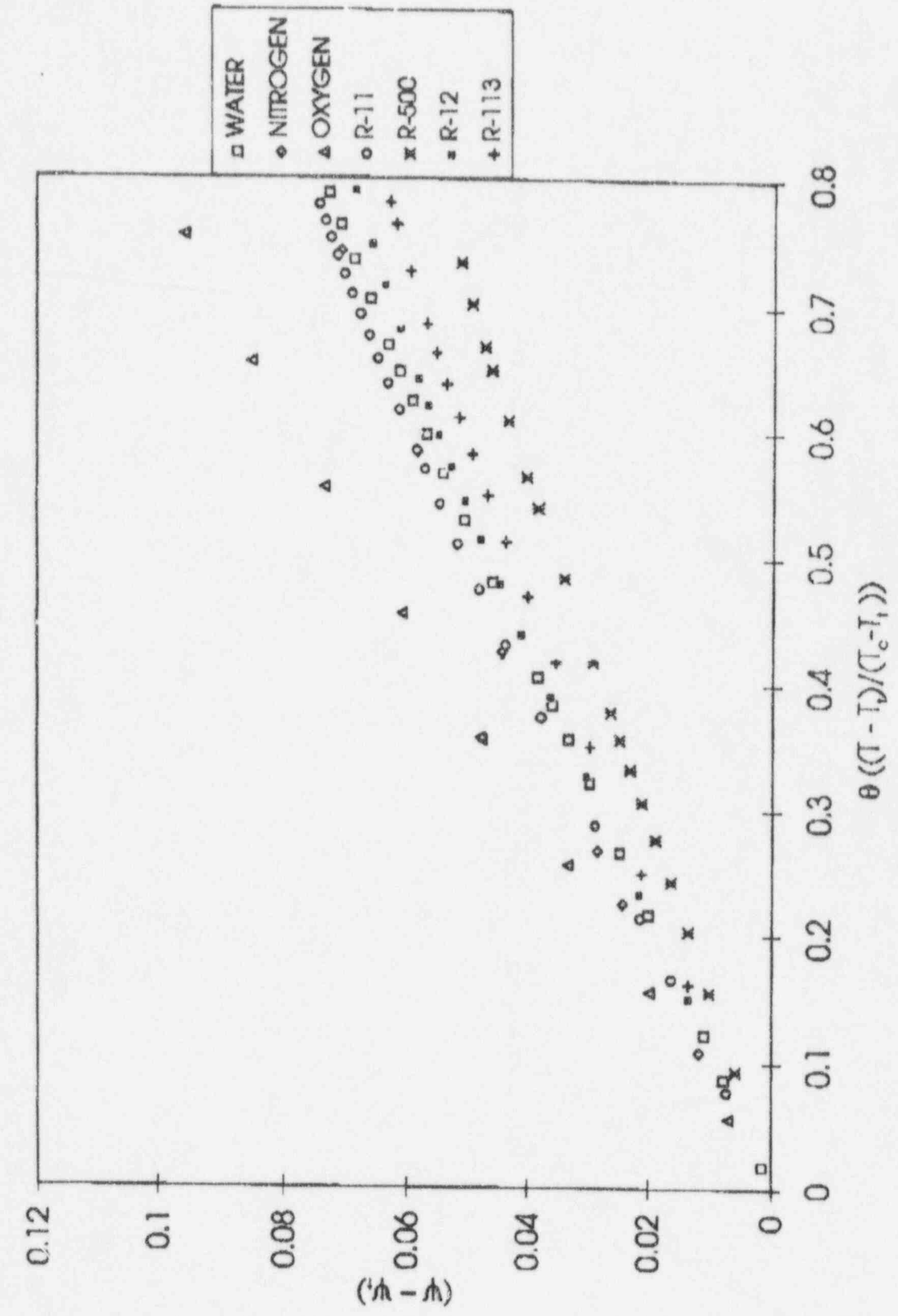
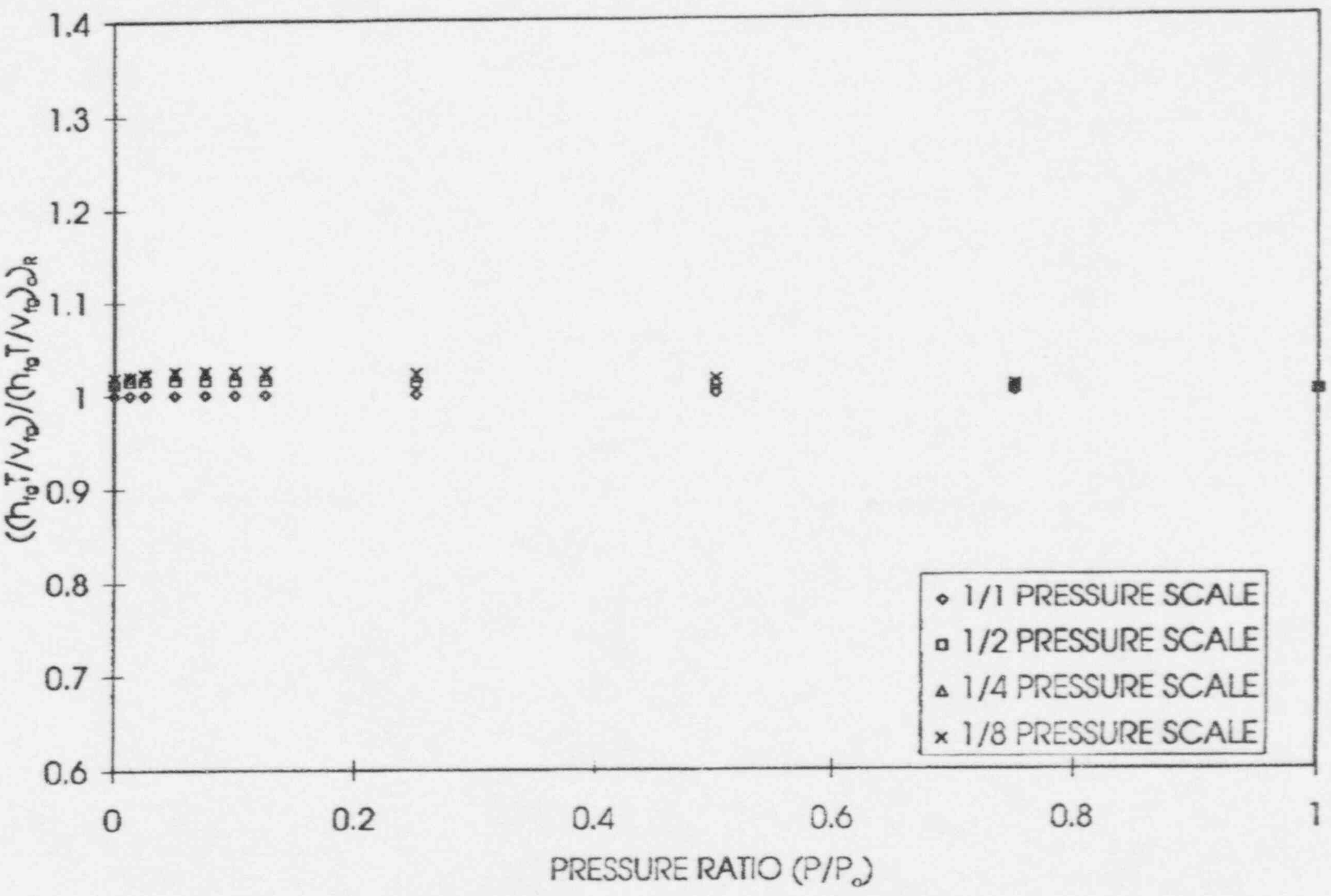

□ WATER
◇ NITROGEN
△ OXYGEN
○ R-11
✕ R-50C
■ R-12
+ R-113
$(\psi - \psi_t)$
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$\theta\ ((T - T_t)/(T_c - T_t))$

Figure 7-9


1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
$((h_{fg}'T/v_{fg})/(h_{fg}T/v_{fg})_o)_R$
0
0.2
0.4
0.6
0.8
1
PRESSURE RATIO (P/P_o)
◇ 1/1 PRESSURE SCALE
□ 1/2 PRESSURE SCALE
△ 1/4 PRESSURE SCALE
× 1/8 PRESSURE SCALE