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General P-T Fit Construction for He, N_2, Ar, H_2 and Ne VPT used at Fermilab

Michael Geynisman, Jerry Makara

Abstract Polynomial fits are constructed for Fermilab Tevatron vapor pressure thermometers (VPT) for use with ACNET database /1/. Fit coefficients and P-T graphs are included. Fits cover the VPT saturation region and the gas region. The thermodynamic analysis of VPT bulb is used to define transition points for each cryogenic VPT with given geometry and "charge" conditions. The methodology is described to repeat fit construction calculations for any geometry and "charge" conditions if required.

I. Objective The gas used in the VPT is determined by the temperature range to be measured. Fermilab Tevatron control system uses the following types of VPT for temperature measurements: He VPT for TI11, TI12; H_2 VPT for TI7, TI9; N_2 VPT for TI4, TI5, TI6; Ne VPT for TI8. Temperature measurements with VPTs, including Argon VPTs, are also used in CDF, D0, MTF and other cryogenic systems in Fermilab. These measurements are needed for control and database, and considered to be basic information sources for operation personnel to evaluate refrigerator performance. At the same time, convenience in using these devices is impaired by the absence of a direct translation of pressure readings into the corresponding temperature values. This translation is normally performed manually by personnel with look-up tables or graphs. This is a time consuming process with very loose approximation, but it can be automated with readily available ACNET Common Units Transform feature /1/. This approach has already been utilized at CDF for the following devices: BBTI3,5,7,8,11,30 and SC. The 6 term linear polynomial transformation is used to translate He, N_2, Ar and H_2 VPT pressure readings into corresponding temperature values and display them as common units.

At the same time, it is necessary to prove that any designed polynomial fit shows a good correlation with NBS properties data and works for the entire VPT range, especially at the bottom (cold) end of the saturation range. Also, it is very important to identify the points on the curves where VPT can no longer be considered as a saturation vapor pressure device, but converts itself into a superheated vapor pressure bulb. This is especially important for those VPTs which use cryogens with "critical" pressure below VPT "charge" pressure, such as He VPTs. Thus, we consider that it would be useful to canonize the method of fits construction to approximate VPT curves within the entire pressure-temperature region and use those fits for pressure-to-temperature conversion in ACNET.

In our analysis of this problem we will consider the simplified general case of a cryogenic VPT, determine the VPT-to-gas bulb thermometer transition point for a given VPT geometry, determine the low temperature limit for a VPT of a given geometry, derive the general strategy for fit construction, discuss valid temperature ranges and include fits coefficients and comparative graphs for He, N_2, Ne, H_2 and Ar VPTs used in the Tevatron control system.

II. Discussion The vapor pressure thermometer commonly used (regardless of substance) is comprised of 2 volumes of gas connected by a fine capillary. They consist of a warm volume V_w and a cold volume V_c. The cold volume is the vapor pressure bulb located in the cold temperature region, and the warm volume consists of a gauge system and a ballast volume located at the warm region. We will not discuss the methods of VPT sizing and charging, though this is extremely important for proper system performance and response. We will assume that V_w, V_c, "charge" pressure P_{ch} and "charge" temperature T_{ch} are known values, and capillary volume $V_{cap} << V_w$ or V_c. In the case of the Fermilab Tevatron control system these values are the standard design parameters: $V_w = 25$ cc, $V_c = 0.31$ cc, $P_{ch} = 100$ psig, $T_{ch} = 300$ deg.K. Also, we will assume that the temperature of the warm region T_w is constant and equal to the "charge" temperature T_{ch}. These assumptions will necessarily affect the accuracy of our calculations, thus each calculated value should be allowed to float within certain limits.

Equation (1) is used to describe the VPT in its "gas thermometer" region. In this equation and later subscript "v" will mean vapor phase, subscript "l" will mean liquid phase, superscript "sat" will mean saturation conditions.

$$m_{tot}=\rho_{ch}*(V_c+V_w)=\rho_c V_c+\rho_w V_w=const \qquad (1)$$

where:

$\rho_{ch}=\rho_v[P_{ch}, T_{ch}]$ *density of the vapor at warm "charge" conditions*

$\rho_c=\rho_v[P_v, T_v]_{bulb}$ *density of the vapor at cold "bulb" conditions*

$\rho_w=\rho_v[P_v, T_v=300K]$ *density of the vapor at warm conditions*

Thus, the characteristic curve for this region can be expressed as:

$$T=T[P_v, \rho_v=\frac{m_{tot}-\rho_w V_w}{V_c}] \qquad (2)$$

We define the point at which the VPT-to-gas bulb thermometer transition occurs as a point at which gas in the VPT gets to the saturation conditions, but no liquid yet exists. The temperature of the saturated vapor T_v^{sat} is uniquely defined by P_v^{sat}, and the P_v^{sat} value should satisfy the conditions of equation (3):

$$m_{tot} = V_w \rho_w [P_v^{sat}, T_{ch}] + V_c \rho_c [P_v^{sat}, T_v^{sat}] = const \quad (3)$$

The values of $[P_v, T_v]^{sat}_{trans}$ for each particular fluid can be defined through an iteration process if the fluid properties computer program /2/ is available. It is not, though, the case for He VPT since the equation (3), which is written with the assumption that the liquid phase does not exist, can not be satisfied below T_v^{crit}=5.1953°K and P_v^{crit}=18.296 psig. Thus, the VPT-to-gas bulb thermometer transition occurs for He at critical point with liquid phase volume, which can be calculated at this point with equation (6) shown below. Table 1 shows these values for He, N_2, Ar and H_2.

Table 1. VPT Upper Temperature Limits

	Helium	Nitrogen	Argon	Hydrogen
P_v^{sat}, psig	18.296	96.5	97.2	82.3
T_v^{sat}, deg.K	5.172	99.81	112.3	28.76
% liquid in volume	54.8	0	0	0

Below the point $[P_v, T_v]^{sat}_{trans}$ which is defined with equation (3) the saturation curve is described as a one-to-one correspondence between P_v^{sat} and T_v^{sat} accordingly computed with NBS fluid properties computer program. Numerical data can be easily fitted with any available engineering software package (in our case it is "Mathematica") and the coefficients of the polynomial fits can be used in ACNET Common Units Transformation.

To determine the low temperature limit of VPT we will describe the VPT mass balance with equation (4):

$$m_{tot} = V_w \rho_w [P_v^{sat}, T_v = 300K] + V_v \rho_v [P_v^{sat}, T_v^{sat}] + V_l \rho_l [P_v^{sat}, T_l^{sat}] = const \quad (4)$$

Since $V_c = V_v + V_l$, and if we denote $(V_w/V_c) = K$ we can express equation (4) in the form of equation (5) or (6):

$$\frac{m_{tot}}{V_c} = (\rho_v^{sat} + K\rho_w^{sat}) + (\rho_l^{sat} - \rho_v^{sat}) * (\frac{V_l}{V_c}) = const \quad (5)$$

$$V_l = \frac{m_{tot} - V_c * (\rho_v^{sat} + K\rho_w^{sat})}{\rho_l^{sat} - \rho_v^{sat}} \qquad (6)$$

It is easy to notice that when the temperature T_v^{sat} decreases the densities of the vapor phases decrease, but the density of the liquid phase increases. Thus the first term in equation (5) will decrease in value, and therefore the second term in equation (5) will necessarily increase in value. But since the density difference shown in the second term also increases in value, then an increase in volume of the liquid phase V_l is questionable, depends on the K value and should be investigated for each particular VPT geometry. Thus, the series of calculations made for equation (6) at decreasing T_v^{sat} values and known value of K will show the direction in the V_l change. If V_l increases, then the low temperature limit will be defined as a point when the bulb will be filled with liquid ($V_l = V_c$), and equation (6) will degrade into equation (7):

$$m_{tot} = V_w \rho_w^{sat} + V_c \rho_l^{sat} \qquad (7)$$

The $[P_v, T_v]^{sat}_{L.limit}$, which satisfy the conditions of equation (7), define the low temperature limit of the VPT. If equation (7) does not have a solution at saturation conditions, then there is no low temperature limit for the VPT of this geometry. Thus, VPT can be successfully used down to the triple point temperature. The analysis made for Fermilab Tevatron VPTs shows that coefficient K defines an increase in liquid phase volume when the VPT bulb temperature decreases, but VPTs never get full and there is no low temperature limit for He, N_2, Ar or H_2 VPTs. Unfortunately we do not have a computer routine for Ne properties to define VPT-to-gas bulb thermometer transition point and to check the low temperature limit, but in order to cover all types of VPTs we will nevertheless include the constructed fit for Ne for available tabulated data.

III. Fit Construction Shown below are 6 term polynomial fits and their graphs for He, N2, Ar, H_2 and Ne VPTs. For each cryogen two fits are constructed: the first fit is an approximation of the NBS computer routine generated data and covers the saturation region, the second fit is an approximation of the data calculated according to equation (2) with NBS computer routine and it covers the gas bulb thermometer region[1]. Two fits mate with each other at the transition points indicated in Table 1. Since all devices are calibrated as: 0-100 psig corresponds to 0-5 volt, then all fit variables are expressed in volts (1v=20psig). For better representation and comprehensibility all graphs are shown in P(psig) and T(deg.K) axes. The following designations are used:

[1]For cryogens with relatively low critical temperature, such as He and H_2, the gas region considered for fit construction is reduced and capped somewhat below "charge" conditions to keep dT/dP below reasonable limit.

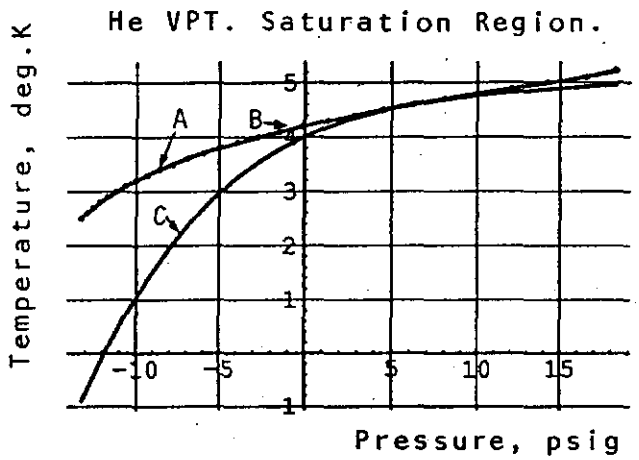
A - NBS routine generated data for saturation region /2/
B - Fit constructed for saturation region
C - Fit used in CDF ACNET database
D - NBS routine generated data as per equation (2) for gas region
E - Fit constructed for gas region.

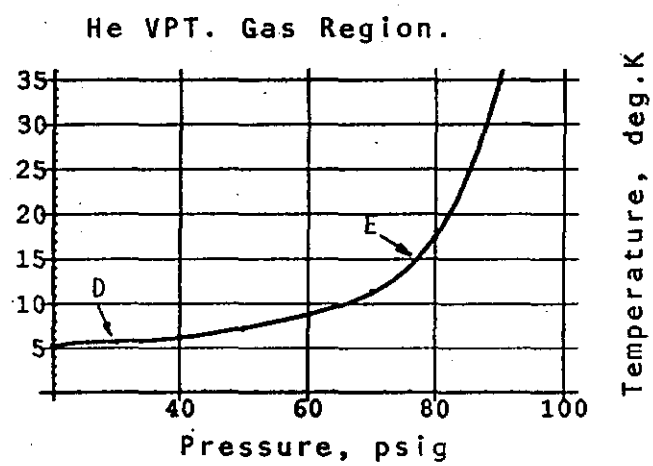
III.a. Helium:

B: $T,deg.K = 4.2+1.443V-0.40755V^2+0.3005V^3-1.5166V^4+1.3716V^5$, $-0.66v<V<0.9148v$

C: $T,deg.K = 4.01+2.89V-4.11V^2+3.27V^3-1.26V^4+.202V^5$

E: $T,deg.K = -15.89+54.49V-53.181V^2+24.887V^3-5.5417V^4+0.4806V^5$, $0.9148v<V<4.5v$





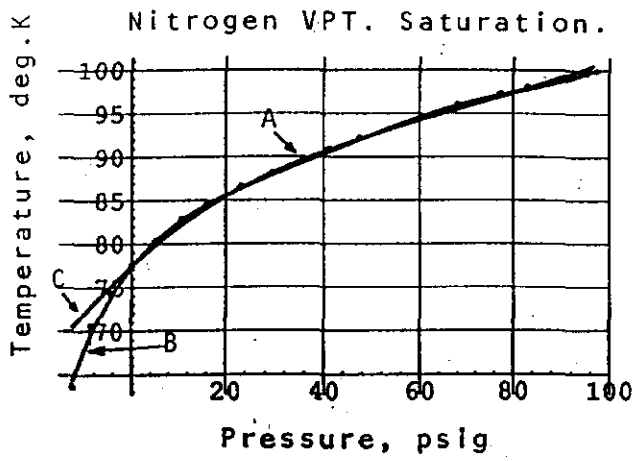
As seen from the graphs, fit C does not work below ~4.2 deg.K, but constructed fits B and E cover the temperature range from 2.5 deg.K to 35 deg.K.

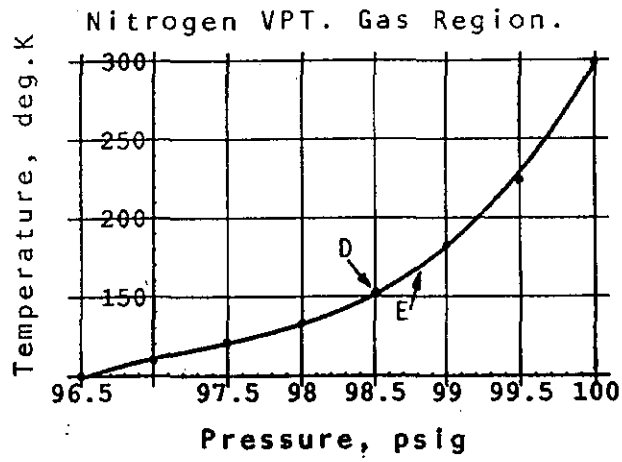
III.b. Nitrogen:

B: $T,deg.K = 77.4+13.463V-8.2465V^2+3.6896V^3-0.7824V^4+0.0608V^5$, $-0.64v<V<4.825v$

C: $T,deg.K = 77.47+9.68V-1.94V^2+0.191V^3$

E: $T,deg.K = -0.5983-470.133V-230817V^2+142462V^3-29295V^4+2008V^5$, $4.825v<V<5v$





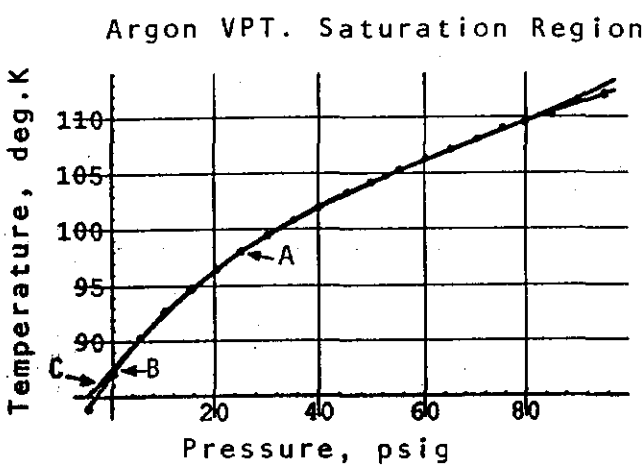
As seen from the graphs, fit C does not work below ~77 deg.K, but constructed fits B and E cover the entire temperature range from 65 deg.K to 300 deg.K.

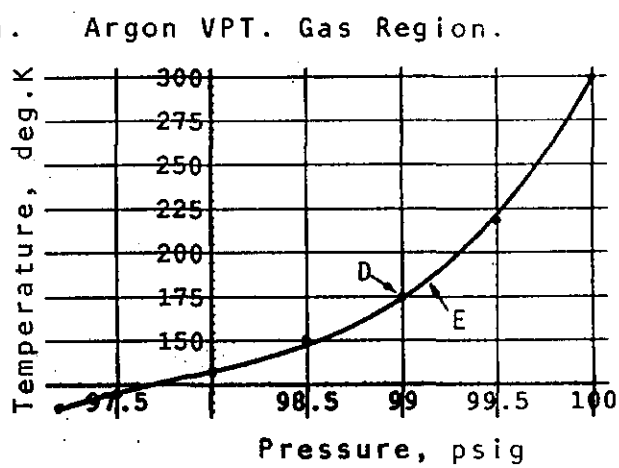
III.c. Argon:

B: $T,deg.K = 87.179+12.755V-4.908V^2+1.5631V^3-0.2689V^4+0.01834V^5$, $-0.235v<V<4.86v$

C: $T,deg.K = 87.58+10.53V-2.06V^2+0.202V^3$

E: $T,deg.K = -1.122-885.05V-436133V^2+267663V^3-54729V^4+3729.9V^5$, $4.86v<V<5v$





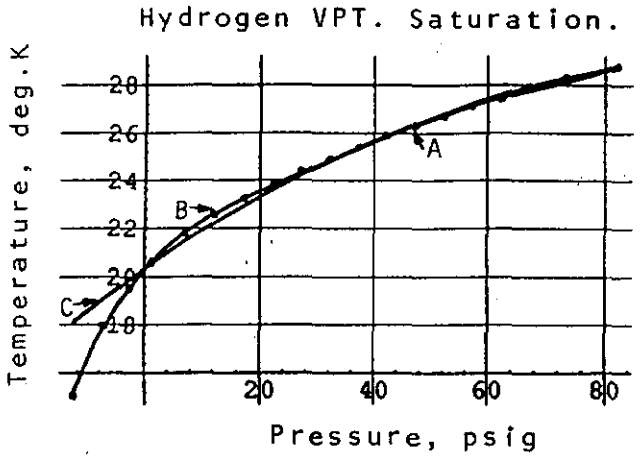
As seen from the graphs, both fits C and B work within saturation region from 84 deg.K to 112.3 deg.K, but constructed fit E additionally covers the temperature range from 112.3 deg.K to 300 deg.K.

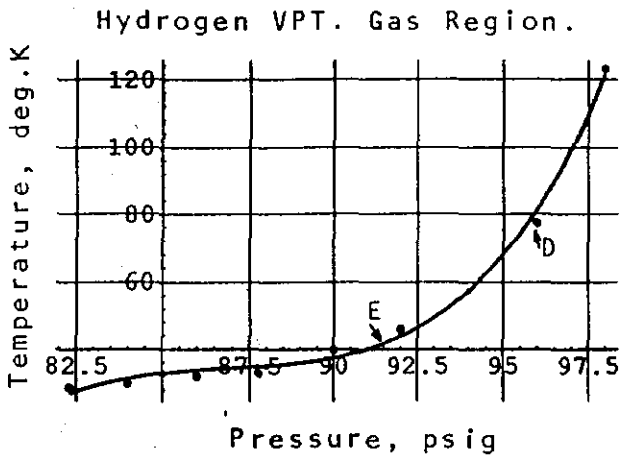
III.d. Hydrogen:

B: $T,deg.K = 20.312+5.18V-3.2428V^2+1.679V^3-0.4212V^4+0.03887V^5$, $-0.68v<V<4.115v$

C: T,deg.K = $20.33+3.28V-0.303V^2$

E: T,deg.K = $-0.005-3.7435V-1682.5V^2+1162.4V^3-267.18V^4+20.46V^5$, $4.115v<V<4.9v$



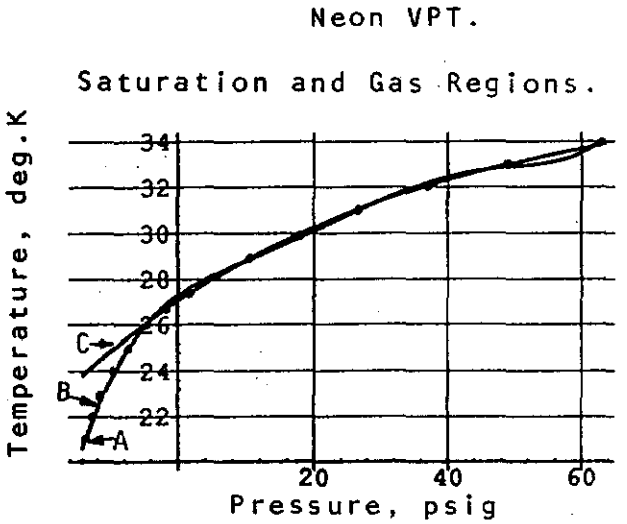


As seen from the graphs, fit C does not work below ~20.5 deg.K, but constructed fits B and E cover the temperature range from 14 deg.K to 120 deg.K.

III.e. Neon:

B: T,deg.K = $27.304+4.17V-3.836V^2+3.8395V^3-1.6151V^4+0.2278V^5$, $-0.71v<V<3.15v$

C: T,deg.K = $27.05+3.95V-0.81099V^2+0.0769V^3$, $-0.71v<V<3.15v$



As it's seen from the graphics fit C does not work below ~26 deg.K, but constructed fit B covers the temperature range from 20 deg.K to 34 deg.K.[2]

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[2]This fit is based on tabulated data /R.Ferry, Basic Refrigeration Course, AD-Cryogenics, 1989/.

IV. Summary

Fermilab Tevatron VPTs' characteristics have been analyzed for a given geometry and "charge" pressure. Low and upper temperature limits have been defined. The 6 term polynomial fits have been constructed to cover the entire temperature ranges of He, N_2, Ar, H_2 and Ne VPTs. These fits can be readily used with ACNET to translate pressure readings into temperature values and display them as engineering units in degrees Kelvin while primary units will still be displayed in volts. This will simplify the system analysis for cryogenic personnel and eliminate the errors of presently used manual translation.

V. References:

1. User's Guide To ACNET Console Systems. Software Documentation Memo No. 62.3. Fermilab. June 1985.

2. GASPAK. Software Package for IBM PC. Version 2.22. CRYODATA INC. 1990.