DESKTOP GAS USER’S MANUAL

VERSION 4.0

COPYRIGHT NOTICE

The *DeskTop Gas* software and manual are copyrighted and licensed for use by one user per copy purchased. This manual and the software described in it are copyrighted with all rights reserved. Under the copyright laws, this manual or the software may not be copied, in whole or part without written consent of Techware Engineering Applications, Inc. Techware Engineering Applications, Inc. grants permission to the purchaser to make a limited number of copies of the add-in for backup purposes only, provided that the copies are not in use at the same time as the original. Additional reproduction of the software is a violation of copyright law. Violators will be prosecuted to the fullest extent of the law.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 OVERVIEW

DeskTop Gas is an interactive gas property calculator that provides thermodynamic and transport properties for mixtures of moist gases. The current library includes the following gases: nitrogen (N2), oxygen (O2), argon (Ar), carbon dioxide (CO2), and water vapor (H2O). The thermodynamic property functions are calculated for mixtures of all five gases using an accurate third order virial equation of state. See the theory and accuracy section for an explanation of how Techware developed the equation of state.

These five gases account for 99.997% of the volumetric composition of standard air and also account for better than 99.9% of most combustion gases.

The functions are valid over a temperature range from 180 °K, (-136 °F) to 2000 °K, (3140 °F) and at pressures up to 50 bar (725 psia).

DeskTop Gas can be used to calculate the thermodynamic and transport properties of moist air by using the composition of standard air. In some cases, when dealing with psychrometric properties of air such as relative humidity, wet bulb temperature or degree of saturation, it may be more convenient to use Techware's *DeskTop Air* add-in which includes properties to handle these parameters. The two packages use similar equations except that the *DeskTop Air* program mixes two gases (dry air plus moisture) while the *DeskTop Gas* product mixes five discrete gases. Nonetheless, the values returned by *DeskTop Gas* when using a mixture composition corresponding to standard dry air agree quite well with those returned by the *DeskTop Air*.

1.2 32-BIT AND 64-BIT VERSIONS

The *DeskTop Gas* package includes both 32-bit and 64-bit installation files. If you are running a 64-bit operating system, such as Windows 7, you should install the 64-bit version; otherwise you should install the 32-bit version. They are functionally identical.

2 USING DESKTOP GAS CALCULATOR

2.1 OVERVIEW

DeskTop Gas is a Windows application, which calculates the thermodynamic and transport properties of a mixture of moist gases. It can be used as an interactive replacement for gas property tables but does much more than that. It automatically calculates all unknown properties when a state point is defined by known properties. The program is flexible, and designed to minimize keystrokes for common calculations. *DeskTop Gas* allows you to enter any number of state points, label them and store the collection of points for later reference. You can print a table of stored points or copy them to the clipboard and paste them into your favorite spreadsheet or word processor.

Major features of this program include:

- validity over a wide range of pressures and temperatures
- flexible interactive design
- large choice of units for each property
- tools for heating, cooling, expansion and compression processes
- instant response time
- extensive help screens

If installed properly, DeskTop Gas is started by simply double clicking on its name/icon in the *DeskTop Gas* subgroup of the *TechwareEng* Group appearing on the Windows Start Menu.

2.2 BASIC OPERATION

The *DeskTop Gas* display is arranged in a tabular format that remains constant although the program window can be re-sized. You may sometimes find it convenient to make the program window smaller. Each of the rows in the top section is dedicated to one of the gas properties (pressure, temperature, specific volume, enthalpy, entropy, specific heat, dynamic viscosity, thermal conductivity and dew point temperature. Each of the rows in the “Gas Composition” section shows the fraction of one of the individual gasses as well as the humidity ratio and molecular weight of the mixture. There is a column that displays the property values for the active point and a column that displays data for one of the stored points.

The key properties that can be used to define the gas state point are: pressure, temperature, specific volume, enthalpy, entropy, and the gas composition. Theoretically, a state point can be uniquely identified by specifying the gas composition and any two of the other five properties. In most practical applications, pressure is usually one of the known variables. Most of the calculations require that the pressure be known. In the rare case when pressure is not known, it can be calculated from the equation of state if the dry bulb temperature and specific volume are known.

Each of the key properties has a check box associated with it. When checked, it signifies that this property is to be used in calculating the state point. In general, two thermodynamic properties and the gas composition must be selected before *DeskTop Gas* will allow a computation. If pressure and temperature are selected, *DeskTop Gas* can compute the gas properties in the state that is saturated with water vapor. In these cases, you will notice that the ‘Compute Saturated’ button is enabled. Once you select one property, *DeskTop Gas* will disable all the other check boxes whose properties are not allowed in combination with the first selected property. You may change your selections by un-checking one or all of the check boxes and selecting a new combination.

To compute a gas property state point, begin by entering the gas composition in the lower half of the calculator. If you wish to use the composition for standard dry air, press the button labeled “Set to Standard Dry Air”. Note the label in the units column next to each gas component. It indicates the basis of the gas composition. Initially, the label should indicate “Vol frac Dry”, which means that the gas composition is entered as a volume or mole fraction on a dry basis. Note that the value for water vapor is zero and the box is read only. This ensures that you can only enter water vapor as a humidity ratio. If you want to enter the composition on a wet basis, press the button labeled “Change to Wet Composition”. Now you will find that the humidity ratio is read only and water vapor box is enabled. If you want to enter the composition as mass fractions instead of mole fractions, press the button labeled “Change to Mass Fraction”. The other button in the gas composition section resets the gas composition to all zeros.

All mass-dependent properties (specific volume, enthalpy, entropy, specific heat and viscosity) can be expressed on either a dry or wet basis. The default for *DeskTop Gas* expresses the properties per mass of dry air. This is consistent with ASHRAE conventions and is quite useful when dealing with processes that involve evaporation or condensation of water vapor. If you want the mass-dependent properties to be expressed on a wet basis instead of a dry basis, press the button labeled “Change to per Wet Mass”.

Next, select the input properties by selecting the corresponding check boxes as described above. Enter values for those properties in the boxes to the right of the property names. (The next section describes various methods for entering data.) When you enter a value for any of the key properties, a red “X” appears next to the property value to indicate that a new value has been entered. This is a warning that the value being displayed is not consistent with the current state point. After a compute command is completed successfully, all property values are recalculated and the red “X’s” are cleared.

Be sure to enter the values in units consistent with the unit displayed to the right of the value box. If you wish to change units, select the desired units before entering the value. If you change units after the value is entered, the value entered will be converted to the new units.

Next, click the 'Compute' button to find all the unknown properties. If the ‘Compute’ button is grayed, you have not checked enough properties to define the state point. Fields without check boxes are output only. These include specific heat, viscosity and thermal conductivity and dew point. After recalculation, all fields contain property values for the gas mixture at a particular state point.

2.2.1 Reference Conditions

Enthalpy and entropy values are always expressed relative to particular reference conditions. Many people forget that the values of enthalpy and entropy that are found in published tables are not absolute values but instead, are relative to particular reference conditions. Engineering calculations always deal with enthalpy or entropy differences, typically between in-flowing and out-flowing streams. For this reason, it does not matter what you select as the reference conditions, as long as you use them consistently. *DeskTop Gas* allows you to select reference conditions consistent with ASHRAE or an alternate set of conditions based on absolute zero temperature.

In SI units, ASHRAE uses a reference condition of 0 °C and one atmosphere of pressure for dry air. For water vapor, ASHRAE used a reference condition of liquid water at the triple point temperature of 0.01 °C. In English units, however, ASHRAE uses a reference condition of 0 °F at one atmosphere of pressure for dry air properties while maintaining the convention of using the triple point as a reference temperature for water properties. *DeskTop Gas* allows you to set the reference temperature of 0 °F, 0 °C or 0 °K.

Please note that in all cases, the enthalpy and entropy of the water portion are set to zero for liquid water at the triple point. Some publications, which are based on perfect gas assumptions, assign the zero point for enthalpy and entropy to water in the vapor state at the triple point or some other specified temperature. We believe that setting the zero point for enthalpy and entropy to water in the liquid state rather than in the vapor state has two major advantages. First, the values are numerically equivalent to standard international steam tables (and Techware’s **WinSteam** product). This facilitates the handling of processes that include both moist gas and liquid water streams without worrying about reference temperatures. Second, It greatly simplifies analysis of processes in which water is either condensed from or evaporated to the gas stream.

All of *DeskTop Gas*’ reference conditions use the International Temperature Scale of 1990 (ITS-90) as the basis of temperature.

2.3 ENTERING DATA

Numeric data is entered in a specially designed edit box called an IO Box, which behaves like a standard Windows edit box but includes some additional features. To enter new data, double click the IO Box and all the data will be highlighted. As you enter new data, the old data will be replaced. To edit data, hold the left mouse button down and drag the mouse over the characters that you wish to replace, thereby highlighting them. Release the mouse button and type new characters to replace the highlighted ones.

The IO Box has two modes of operation, input and output. When new data is entered, the IO Box is placed in the input mode and a red X appears to the left of the box. After a new state point is computed, all IO Boxes are placed in the output mode and the red X's are removed.

The IO Box accepts either numerical values or arithmetic expressions that can be evaluated to a numeric value. A number can be entered in either decimal or scientific notation. The expression can be any valid arithmetic expression using the following operators:

+	add
-	subtract
*	multiply
/	divide
^	exponent
( )	parentheses

Arithmetic calculations can be nested to any level using parentheses. An example of a valid expression is:

((1004^2 + 997^2) / 2)^.5

which evaluates to 1000.506.

Expressions are evaluated whenever you tab to or click on another control or press the 'Enter' button. Only the resulting value is shown in the box. If you enter an incorrect expression, your computer will beep and the edit cursor will highlight the offending character. You must fix the error before *DeskTop Gas* will allow you to continue.

If the expression you are entering is too long to fit in the box, the box will temporarily increase in length so that you may view more of the expression. When you are finished editing, the box returns to its original length.

To recall the last expression used in an input box, use the 'Recall Expression' command on the 'Edit' menu. You'll then have the opportunity to edit the expression and let the IO Box re-evaluate it. Note that the box retains the last number or expression entered even after a compute command is issued. As a result, the value in the box will not reflect the value of the recalled expression if a compute command has altered the value.

You may use the 'Cut', 'Copy' and 'Paste' commands on the 'Edit' menu or the toolbar to exchange numeric data between *DeskTop Gas'* IO Boxes and any other application that supports the clipboard. If you start entering data in an IO Box and wish to go back to the original data you may use the 'Undo' command on the 'Edit' menu. However, once the IO Box loses the focus, the 'Undo' command is no longer available.

2.4 UNIT SELECTION

DeskTop Gas allows you to use any combination of units for input and output properties. The units for each property can be set independently by using its associated combo box. To change a unit, select its combo box and scroll through the list of available units using either the keyboard cursor arrows or the mouse. Whenever a new unit is selected, the program converts the values displayed for that property to the new units. Therefore, when entering data you should first select the units and then key in the input values. Otherwise, the values will be converted to the new units and you will have to re-enter them.

The first time the program is started, the properties will be displayed in SI units. You can change all of the units to either standard English or SI units by issuing the 'English Units' or 'SI Units' command from the 'Format' menu or pressing the ‘Eng’ or ‘SI’ toolbar button. When you change to English units in this manner, the reference temperature for the dry gas is changed to 0 °F. Similarly, when changing to SI units, the reference temperature is changed to 0 °C.

If you change the units one at a time, the reference temperature will not change, even if you change all of the units from English to SI units. You can force a change in the reference temperature by pressing the ‘Ref’ button on the toolbar or by selecting ‘Options’ from the ‘Tools’ menu and then choosing the ‘Reference Point’ tab. From either of the dialog boxes, you will be able to select the desired reference temperature.

You may choose any combination of available units for your personal default unit set. Simply select the units you desire for each property and issue the 'Make Current Settings Default' command from the 'Format' menu. The next time you start *DeskTop Gas*, your default unit set will be used.

If you change units and then save a file, those selected units will be restored whenever the file is opened. If you wish to change the units back to your default unit set, issue the command 'Restore Default Settings' from the 'Format' menu.

2.5 CALCULATING STATE POINTS

When you have finished entering values for the selected input variables, click the on-screen button labeled 'Compute' to calculate all of the state point properties. If the 'Compute' button is grayed, you have not checked enough properties to define the state point.

You may also compute the state point by pressing the 'Enter' key on your keyboard. Note that the 'Enter' key serves two purposes in *DeskTop Gas*. Pressing the 'Enter' key just after entering data in an IO Box, tells *DeskTop Gas* to evaluate the expression in the IO Box. Pressing the 'Enter' key a second time tells *DeskTop Gas* to compute the state point. If you move the focus to any other control after entering data in an IO Box, the expression is evaluated automatically and you only have to press the 'Enter' key only once to compute the state point. The ‘Enter’ key will not compute a state point if the ‘Compute’ button is grayed.

2.6 FORMATTING PROPERTY VALUES

DeskTop Gas normally displays all property values in fixed decimal notation. You may increase or decrease the number of decimal places in a selected property IO Box by selecting

‘Add Decimal Places’ or ‘Decrease Decimal Places’ from the ‘Format’ menu or by clicking either of the +.0 .00 .00 -.0 toolbar buttons, respectively.

If you wish to change the selected property to scientific notation, select the 'Scientific Notation' command from the ‘Format' menu or press the ‘EE’ toolbar button. The ‘Format’ menu many be used to change the number format to 'Fixed Decimal' or 'Percent' as well. Corresponding toolbar buttons are ‘Fix’ and ‘%’ respectively. Of course, the percent format only makes sense for the non-dimensional properties.

The formatting commands are only enabled when the focus is on an IO Box.

2.7 LABELING AND STORING STATE POINTS

DeskTop Gas gives you the option of labeling and storing any number of state points for future reference. After computing the state point, *DeskTop Gas* will automatically suggest a unique name for the new state point such as “Point 1” or “Point 2”, but you will probably want to enter something more descriptive. Just enter a new name in the Point Label box.

To store this point, press the 'Store Point' button. (The Store button will not be enabled if the displayed data is not a correctly calculated state point.) *DeskTop Gas* requires all stored points to have a unique label. If you try to store two points with the same label, *DeskTop Gas* will query whether you wish to replace the stored point, which has the same label, with the current point. If not, you should rename the point and try to store it again.

After storing the point, the state point values for the active point will be copied into a storage array and given the name you selected. The point will be displayed in the stored points column in same units as the active point. After a state point is stored, its name is added to the point name combo box in the upper right hand corner of the main window. You can view a stored point by pressing the arrow on the point name combo box and selecting a point from the drop down list.

If you wish to use a stored point with any of the special tools or as the basis for calculating a new point, you must recall the stored point to the active point. Begin by selecting the point from the point name combo box’s dropdown list. Next, press the ‘Recall Point’ button to copy the stored point to the active point. You may now use the active point for new calculations. If you change any input data and press 'Compute', the active point will be changed but the stored point from which you copied the values will remain intact.

You can delete a stored point by first selecting it from the Point Name combo box and then select 'Delete Point' from the 'Edit' menu.

This collection of state points can be saved as a *DeskTop Gas* file. In addition, you can copy state points to the clipboard, where they can be transferred to another application such as a spreadsheet program or word processor.

2.8 PRINTING

You can print a table consisting of all of the stored points by selecting the Print command from either the file menu or the toolbar. The tables will include a column for each of the stored points with each of its properties listed in a row. A label for each row includes the property name and the current units selected. The printing utility will attempt to fit as many points on a page as possible, based on the paper size and orientation that you specify using the 'Print Setup' command. You can preview the output by selecting the 'Print Preview' command from the 'File' menu.

2.9 SAVING AND OPENING DATA FILES

When you start *DeskTop Gas* or open a new file, it will be untitled. You may save a collection of stored state points along with your selections of units and formats to a *DeskTop Gas* file. Select 'Save' from the 'File' menu or click the disk icon on the toolbar, which will open the "Save As" dialog box. You should enter a name for the file; the file extension ".gas" will be added automatically. You may choose a folder in which to save the file or accept the default folder.

If you have saved the file at least one time during the session, you can save the work under a different filename by choosing the 'Save As' command from the 'File' menu.

To open a saved file, select 'Open' from the 'File' menu or click the open file icon on the toolbar. This will open a dialog box that lists all of your *DeskTop Gas* data files in the current folder. You may select a different folder to view other files. Select the file you want to open and press the 'Open' button to load the file.

To start a new file, select the 'New' button from the Toolbar. If you have stored any points and have not saved the file, you will be prompted to do so.

2.10 ADVANCED FEATURES

DeskTop Gas includes special tools that facilitate the calculation of some common gas processes. These tools include an Expansion/Compression tool and a Heating/Cooling tool.

2.10.1 Expansion/Compression Tool

The Expansion/Compression tool is used to evaluate performance of a gas turbine or an gas compressor. If you are predicting the performance and know the efficiency of the turbine or compressor, the tool can be used to calculate the state point conditions at the expansion or compression end point. If you are analyzing the performance of a turbine or compressor and know the conditions at the end point, the tool can be used to calculate the efficiency. The tool also computes the energy converted to shaft work generated by the turbine or used by the compressor.

To use the tool, first select the active state point representing the start of the expansion or compression path. Next, select 'Expand/Compress' from the 'Tools' menu or click the turbine icon on the toolbar, which will open the Expansion/Compression tool dialog box.

In the tool dialog box, select the conditions you will use to compute the end point from the combo box near the top of the screen. Select "Pressure & Efficiency" if you know the pressure and efficiency. If you are checking an actual machine you will need to know the exiting gas temperature or enthalpy. Check either the "Pressure, Enthalpy" or Pressure, Temperature" buttons as required. The two variables you have chosen will have their value fields enabled; all others will be grayed. Enter the appropriate values and click the 'Compute' button.

The "Gas Flow In" column displays the state point properties entering the equipment, which were copied from the active point. The "Total Flow Out" box has three columns that display the state point properties at the end of the expansion. The first column identifies the thermodynamic properties for the moist gas mixture and liquid water (if any) exiting the equipment. The second column displays the thermodynamic properties for the moist gas exiting and the third column shows the properties for the liquid water if any condensation occurs. The units displayed are those currently in use on *DeskTop Gas'* main window. If you wish to use different units, you should select those units on the main window before opening the expansion tool.

Below the state point properties, you will find the shaft power based on the entering gas flow rate that you entered. The units for these results will be consistent with your input units.

You may change any of the data and repeat the calculation as required. When you are satisfied with the result, you may copy that state point back to the active point on *DeskTop Gas'* main window by pressing the 'Close and Copy to Current Point' button. Note that the values of moist gas in the second column will be copied back to the active point. If no condensation has occurred, these values will be the same as in the first column labeled mixture. If condensation has occurred, then the values in the second column will be at saturated conditions.

If you do not wish to replace the current point on the main window with the expansion end point calculated, just press the 'Cancel' button.

2.10.2 Heating/Cooling Tool

The Heating/Cooling tool is used to analyze a gas stream in which heat is either added or removed. If you know the quantity of heat that is being added to or removed from the gas stream, you can use the tool to calculate the resulting state point temperature and other conditions. If you know the temperature or enthalpy of the gas leaving the heating or cooling device, you can use the tool to calculate the quantity of heat exchanged.

To use the tool, first make sure that the active state point represents the conditions of the gas entering the heating or cooling device. Next, select 'Heat/Cool' from the 'Tools' menu or click the flame icon on the toolbar, which will open the Heating/Cooling tool dialog box.

In the tool dialog box, select the conditions you will use to compute the end point from the combo box near the top of the screen. Select “Pressure, Heat Flow” if you know the pressure and heat added or removed. If you are measuring performance on an existing device you will need to know the exiting gas temperature or enthalpy. Check either of the “Pressure, Enthalpy” or “Pressure, Temperature” buttons as required. The two variables you have chosen will have their value fields enabled; all others will be grayed. Enter the appropriate values and click the 'Compute' button.

The “Gas Flow In” column displays the state point properties entering the equipment, which were copied from the Active Point in the main screen window. The “Total Flow Out” box has three columns that display the state point properties at the end of the expansion. The first column identifies the thermodynamic properties for the mixture of moist gas and liquid water exiting the equipment. The second column displays the thermodynamic properties for the moist gas exiting and the third column shows the properties for the liquid water if any condensation occurs. The units displayed are those currently in use on *DeskTop Gas’s* main window. If you wish to use different units, you should select those units on the main window before opening the Heating/Cooling tool.

Below the state point properties, you will find the heat added based on the entering gas flow rate that you entered. The units for these results will be consistent with your input units.

You may change any of the data and repeat the calculation as required. When you are satisfied with the result, you may copy that state point back to the Active Point on *DeskTop Gas’* main window by pressing the 'Close and Copy to Current Point' button. Note that the values for moist gas in the second column will be copied back to the active point. If no condensation has occurred, these values will be the same as in the first column labeled mixture. If condensation has occurred, then the values in the second column will be at saturated conditions.

If you do not wish to replace the Active Point on the main window with the heating/cooling state point calculated, just press the 'Cancel' button.

2.10.3 Exchanging Data with Other Programs

DeskTop Gas includes two ways to share data with other applications running on your PC such as Excel. Both methods use the Windows clipboard.

In the first data sharing method, *DeskTop Gas'* 'Edit / Copy' command copies whatever text is highlighted in an IO Box (e.g., a number or part of a number) to the Windows clipboard. From there, that text can be pasted into other applications running on your PC. This is typically done using those applications’ 'Edit / Paste' command).

The second data sharing method also places text on the clipboard but uses an extended format that is especially useful for calculations involving gas properties. This method is accessed using the 'Copy Point' command on the 'Edit' menu. Regardless of whether any text is selected, this command copies a *table* of text values to the clipboard using either the Active Point or all of the stored points. The table includes one column for each point. You can optionally direct *DeskTop Gas* to also include property and unit labels in which case they appear as the first column in the table. The table includes one row for each property in the same order as they are displayed on *DeskTop Gas'* main window. All values are copied to the clipboard using the same format displayed on the screen. So, if you need more accuracy in your Excel calculations, set the *DeskTop Gas* display accuracy accordingly, before issuing the 'Copy Point' command.

2.11 GETTING HELP

The Help menu offers extensive on-line help for *DeskTop Gas*. The 'About' item in the Help menu presents the version and serial numbers of your copy of **@Gas**. If the program is running in its Demo mode, the number of days remaining on the Demo are displayed instead of a serial number.

2.12 ERROR MESSAGES

When input values are out of range or any other errors occur, a message box is displayed describing the error. The calculated fields will not be updated until the error condition is resolved.

2.13 EXITING DESKTOP GAS

You may exit *DeskTop Gas* by using any of the standard methods for closing Windows applications. These include the following:

- Click the upper left corner of its program window and select close from the menu.
- Select Exit from the File menu.
- Press Alt + F4 keys.
- Click the "X" button in the upper right corner of the program window.

3 THEORETICAL BASIS OF @GAS FUNCTIONS

It is commonly accepted that virial equations of state work well for gases. In @Gas, the P-V-T behavior of a gas mixture is described by a third order virial equation of state:

$$\frac{pv}{RT} = 1 + \frac{B_m}{v} + \frac{C_m}{v^2} + \cdots$$

where,

p = Total pressure

T = Absolute Thermodynamic Temperature

v = Total volume of gas

R = Universal Gas Constant

B_m = second order virial coefficient of the mixture

C_m = third order virial coefficient of the mixture

For the ranges of pressure and temperature used in these functions, coefficients higher than third order can be ignored. It is important to note that B_m and C_m are functions only of temperature.

Over the range of temperatures and pressures covered by these functions, all of the gases except water exist only in the gaseous state. (Actually, CO_2 can exist in a liquid state at the high end of the pressure range and the low end of the temperature range but this state is not considered because it would only occur in a mixture that is almost pure CO_2.) At temperatures where the saturation pressure of pure water is greater than the total gas pressure, the mole fraction of water vapor can range from 0 to 1. That is, there is no limit to the percentage of water vapor in the gas mixture in that situation. Elsewhere, the mole fraction of water vapor can range from 0 to a limiting, saturated, value x_{eq}, which is reached when the condensed phase of water is in thermodynamic equilibrium with the gas solution. This equilibrium fraction is equivalent to the solubility of the condensed water in the solvent gas mixture. In order to facilitate calculation of x_{eq} it is convenient to group the virial coefficients of the non-water gases so that the mixture can be treated as a binary mixture between the non-water gases and water vapor.

The virial coefficients of the gas mixture can be expressed as:

$$B_m = x_g^2 B_{gg} + 2 x_g x_w B_{gw} + x_w^2 B_{ww}$$

and

$$C_m = x_g^3 C_{ggg} + 3x_g^2 x_w C_{ggw} + 3x_g x_w^2 C_{gww} + x_w^3 C_{www}$$

where,

x_g = mole fraction of the non-water gases in mixture

x_w = mole fraction of water vapor in the mixture

B_{gg}, C_{ggg} = virial coefficients of the non-water gases

B_{ww}, C_{www} = virial coefficients of water vapor

B_{gw}, C_{ggw}, C_{gww} = cross virial coefficients

Since the sum of the mole fractions of the mixture must equal 1, the value x_g is equal to 1 - x_w. The second virial coefficient of the non-water gases can be expressed as:

$$B_{gg} = \left[\begin{array}{l} B_{NN} x_N^2 + B_{OO} x_O^2 + B_{AA} x_A^2 + B_{CC} x_C^2 + \\ 2\left(\begin{array}{l} B_{NO} x_N x_O + B_{NA} x_N x_A + B_{NC} x_N x_C + \\ B_{OA} x_O x_A + B_{OC} x_O x_C + B_{AC} x_A x_C \end{array} \right) \end{array} \right] / (1 - x_W)^2$$

and the second cross virial coefficient of the mixture can be expressed as:

$$B_{gw} = \left[B_{NW} x_N + B_{OW} x_O + B_{AW} x_A + B_{CW} x_C \right] / \left(1 - x_W \right)$$

Similarly, the third virial coefficients can be expressed as:

$$C_{ggg} = \left[\begin{array}{l} C_{NNN} x_N^3 + C_{OOO} x_O^3 + C_{AAA} x_A^3 + C_{CCC} x_C^3 + \\ 3\left(\begin{array}{l} (C_{NNO} x_O + C_{NNA} x_A + C_{NNC} x_C) x_N^2 + \\ (C_{OON} x_N + C_{OOA} x_A + C_{OOC} x_C) x_O^2 + \\ (C_{CCN} x_N + C_{CCO} x_O + C_{CCA} x_C) x_C^2 + \\ (C_{AAN} x_N + C_{AAO} x_O + C_{AAC} x_C) x_A^2 \\ 2\left(\begin{array}{l} C_{NOA} x_N x_O x_A + C_{NOC} x_N x_O x_C + \\ C_{NAC} x_N x_A x_C + C_{OAC} x_O x_A x_C \end{array} \right) \end{array} \right) \end{array} \right] / (1 - x_W)^3$$

and

$$C_{ggw} = \left[\begin{array}{l} C_{NNW} x_N^2 + C_{OOW} x_O^2 + C_{AAW} x_A^2 + C_{CCW} x_C^2 + \\ 2\left(\begin{array}{l} C_{NOW} x_N x_O + C_{NAW} x_N x_A + C_{NCW} x_N x_C + \\ C_{OAW} x_O x_A + C_{OCW} x_O x_C + C_{ACW} x_A x_C \end{array} \right) \end{array} \right] / \left(1 - x_W \right)^2$$

and

$$C_{gww} = \left[C_{NWW} x_N + C_{OWW} x_O + C_{AWW} x_A + C_{CWW} x_C \right] / \left(1 - x_W \right)$$

where the subscripts N, O, A and C refer to N_2, O_2, Ar and CO_2 respectively.

Assuming that the condensed phase is pure water, the value of x_{eq} can be found by equating the chemical potential of pure condensed water with the chemical potential of its vapor in the gas solution. Since the equations describing chemical potentials are non-linear and difficult to analyze, phase equilibrium is often described in terms of a thermodynamic function called fugacity. The equality of chemical potentials can be replaced by equating the logarithms of the fugacity of pure condensed water with that of its vapor in the gas mixture solution. The equation of solubility based on this concept is derived by Rabinovich [3] and can be expressed as follows:

$$\ln \frac{x_{eq} p}{p_{ws}} = \ln \frac{z\left(p, T, x_{eq}\right)}{z_w\left(p_{ws}, T\right)} + \frac{1}{RT} \int_{p_{ws}}^{p} v_{wcond}\, dp + \frac{2B_{ww}}{v_w''} + \frac{3C_{www}}{2\left(v_2''\right)^2} -$$
$$\frac{2}{v}\left(B_{gw} + \left(B_{ww} - B_{gw} \right) x_{eq}^2 \right) - \frac{3}{2v^2} \left(\begin{matrix} C_{ggw} + 2\left(C_{gww} - C_{ggw} \right) x_{eq} + \\ \left(C_{ggw} - 2C_{gww} + C_{www} \right) x_{eq}^2 \end{matrix} \right)$$

where,

$z = 1 + \frac{B}{v} + \frac{C}{v^2}$, the compressibility of the gas mixture or the water vapor as required.

$p_{ws} =$ saturation pressure of water vapor at temperature T.

$v_{wcond} =$ the volume of the condensed water.

The solubility equation can be solved for x_{eq} by iteration. For an ideal solution, $x_{eqideal}$ is equal to the ratio of the vapor pressure of the pure water, to the total pressure of the mixture. The ratio of x_{eq} / $x_{eqideal}$ is called the enhancement factor or excess solubility and has a value greater than 1. The value of x_{eq} is used to find the dew point temperature of a gas mixture, to determine the amount of condensation that occurs in a cooling process and to verify that the value of x input by the user does not exceed x_{eq}.

The thermodynamic properties (enthalpy, entropy and specific heat at constant pressure) can be determined from knowledge of the properties in the ideal gas state and the virial coefficients.

The molar enthalpy of a moist gas mixture, h_m, can be described by the equation:

$$h_m = x_N\left(h_N^o + h_N^{'}\right) + x_O\left(h_O^o + h_O^{'}\right) + x_A\left(h_A^o + h_A^{'}\right) + x_C\left(h_C^o + h_C^{'}\right) +$$

$$x_W\left(h_W^0 + h_W^{'}\right) + \frac{RT}{v}\left[\left(B_m - T\frac{\partial B_m}{\partial T}\right) + \left(C_m - \frac{1}{2}T\frac{\partial C_m}{\partial T}\right)\frac{1}{v}\right]$$

where,

h_i^o = ideal gas molar enthalpy for gas i

$h_i^{'}$ = constant to adjust reference state for gas i

The molar entropy of the moist gas mixture s_m can be described by the equation:

$$s_m = x_N\left(s_N^o + s_N^{'}\right) + x_O\left(s_O^o + s_O^{'}\right) + x_A\left(s_A^o + s_A^{'}\right) + x_C\left(s_C^o + s_C^{'}\right)x_W + \left(s_W^o + s_W^{'}\right) - R\ln p + x_N R\ln\left(\frac{pv}{x_N RT}\right) +$$

$$x_O R\ln\left(\frac{pv}{x_O RT}\right) + x_C R\ln\left(\frac{pv}{x_C RT}\right) + x_W R\ln\left(\frac{P\bar{v}}{x_W RT}\right) - \frac{R}{v}\left(B_m - T\frac{\partial B_m}{\partial T}\right) - \frac{R}{2v^2}\left(C_m - T\frac{\partial C_m}{\partial T}\right)$$

where,

s_i^o = ideal gas molar entropy for gas i

$s_i^{'}$ = constant to adjust reference state for gas i

The molar specific heat at constant pressure of a moist gas mixture, c_m, can be described by the equation:

$$c_m = c_N^o x_N + c_O^o x_O + c_A^o x_A + c_C^o x_C + c_W^o x_W - R - \frac{RT}{v}\left(2\frac{\partial B_m}{\partial T} + T\frac{\partial^2 B_m}{\partial T^2}\right) - \frac{RT}{2v^2}\left(2\frac{\partial C_m}{\partial T} + T\frac{\partial^2 C_m}{\partial T^2}\right) +$$

$$\frac{R\left(1 + \frac{B_m}{v} + \frac{C_m}{v^2} + \frac{T}{v}\frac{\partial B_m}{\partial T} + \frac{T}{v}\frac{\partial C_m}{\partial T}\right)}{1 + \frac{2B_m}{v} + \frac{3C_m}{v^2}}$$

where,

c_i^o = ideal gas molar specific heat at constant pressure for gas i.

3.1 GAS PROPERTY DATABASE

In order to use the equations presented in the previous section to calculate the thermodynamic properties, it is necessary to know the *B* and *C* virial coefficients of each of the pure gas components and the mixed virial coefficients for all mixture combinations. In addition, the ideal gas enthalpies, entropies and specific heats are required for each gas component. Tables of compressibility data for the pure gases and the ideal gas enthalpies, entropies and specific heats are provided in reference [1]. *B* and *C* virial coefficients for the pure gases were obtained by using a least square fit of the compressibility function to isotherms at 10 degree increments from 180 ºK to 800 ºK and at 50 degree increments from 800 ºK to 2000 ºK.

Mixed virial coefficients were calculated from molecular theory using the Leonard-Jones (6-12) potential model. The following equations were used to calculate the virial coefficients based on the model:

$$B_{ij}(T) = (2\pi N_A / 3)\sigma_{ij}^3 B_{LJ}^*(T^*)$$

$$C_{iij}(T) = (2\pi N_A / 3)^2 \sigma_{iij}^6 C_{LJ}^*(T^*)$$

$$C_{ijj}(T) = (2\pi N_A / 3)^2 \sigma_{ijj}^6 C_{LJ}^*(T^*)$$

where $N_A = 6.02205E^{23}$ per mole (Avogadro's number)

$T^* = kT / \varepsilon_{ij}$ or $T^* = kT / \varepsilon_{iij}$ or $T^* = kT / \varepsilon_{ijj}$

$k = 1.3807E^{-23}$ J/K (Boltzmann constant)

The equations and constants for calculating B_{Lj}^* and C_{Lj}^* are found in Hirshfelder, Curtis and Bird [4]. Values of potential parameters σ and ε/k for the pure gases were obtained by minimizing the errors in predicting the compressibility factors of the pure gases using the Leonard-Jones (6-12) potential. Mixed potential parameters were obtained by means of the following semi-empirical mixing rules:

$$\sigma_{12} = 0.5(\sigma_{11} + \sigma_{22})\xi^{-1/6}$$

$$(\varepsilon / k)_{12} = \sqrt{(\varepsilon / k)_{11}(\varepsilon / k)_{22}} / \xi^2$$

$$\sigma_{112} = \sqrt[3]{\sigma_{11}\sigma_{12}^2}$$

$$\sigma_{122} = \sqrt[3]{\sigma_{22}\sigma_{12}^2}$$

$$(\varepsilon / k)_{112} = \sqrt[3]{(\varepsilon / k)_{11}(\varepsilon / k)_{12}^2}$$

$$(\varepsilon / k)_{122} = \sqrt[3]{(\varepsilon / k)_{22}(\varepsilon / k)_{12}^2}$$

where

$\xi = 1 + 0.892\left(3a_{11}t_{22}^{*}\sqrt{\varepsilon_{11}/\varepsilon_{22}}/2\pi N_A\sigma_{11}^{3}\right)$ when gas 1 is non-water and gas 2 is water

or

$\xi = 1.0$ when both gases are non-water

and

a_{11} = polarizability of the apolar molecules

$t^{*} = 8^{-0.5}\mu/\varepsilon\sigma^{3}$

$\mu =$ dipole moment of the molecule

Some of the mixed potential parameters between N_2, Ar and CO_2 with water were determined by Rabinovich [3] based on experimental data on the equilibrium fractional content of water vapor in the solvent gas. Where available, these mixed potential parameters were used instead of the ones derived from the mixing rules.

Based on the methods described, a database was developed containing all of the pure gas and mixed virial coefficients for the five gases at 10 degree increments from 180 °K to 800 °K and at 50 degree increments between 800 °K and 2000 °K. A similar database was developed for the ideal gas enthalpies, entropies and specific heats.

3.2 COMPUTATIONAL MODEL

With most of the functions, the mixture's pressure and temperature are known. Since the virial coefficients are functions only of temperature, the database is used to calculate mixed coefficients B_{gg}, B_{gw}, B_{ww}, C_{ggg}, C_{ggw}, C_{gww} and C_{www} based on the formulas identified above at four temperatures surrounding the desired temperature. Four point non-linear interpolation is used to calculate the mixed coefficients and their derivatives at the desired temperature.

Since most of the properties require knowledge of the specific volume of the mixture, the virial equation of state is used iteratively to calculate the specific volume. In cases where the temperature of the mixture is not known, iterative procedures are used to determine the temperature as well.

3.3 TRANSPORT PROPERTIES

Values for viscosity and thermal conductivity of individual gases at atmospheric pressure can be found in many references although there does not appear to be any definitive standard of accepted values as there are for steam and water. We found the most complete coverage by Vasserman, Kazavchinskii, and Rabinovich [2] who have surveyed the available literature and presented tables of values over a range of temperatures and pressures. We have used their tabular values of viscosity and thermal conductivity as the basis of our database for Nitrogen, Oxygen, Argon and Carbon Dioxide.

We have used the equations recommended by ASME [6] to compute the viscosity and thermal conductivity properties for water vapor. These are the same equations used in our WinSteam product.

There is little information available regarding the viscosity and conductivity of moist gases. In most practical cases, the relatively small quantity of water vapor in gas mixtures has a small effect on the overall transport properties, unlike the thermodynamic properties, which are greatly affected by moisture. Nonetheless, we have selected a method to account for the effects of moisture on viscosity based on kinetic theory as presented by Hirshfelder, Curtis and Bird [4].

3.3.1 Viscosity

We treat the gas as a binary mixture between the non-polar gases (N_2, O_2, Ar and CO_2) and water vapor. For the non-polar gases, the viscosity of the mixture can be calculated as follows:

$$\eta_g = \frac{\begin{vmatrix} H_{11} & H_{12} & H_{13} & H_{14} & x_1 \\ H_{12} & H_{22} & H_{23} & H_{24} & x_2 \\ H_{13} & H_{23} & H_{33} & H_{34} & x_3 \\ H_{14} & H_{24} & H_{34} & H_{44} & x_4 \\ x_1 & x_2 & x_3 & x_4 & 0 \end{vmatrix}}{\begin{vmatrix} H_{11} & H_{12} & H_{13} & H_{14} \\ H_{12} & H_{22} & H_{23} & H_{24} \\ H_{13} & H_{23} & H_{33} & H_{34} \\ H_{14} & H_{24} & H_{34} & H_{44} \end{vmatrix}}$$ where

$$H_{ii} = \frac{x_i^2}{\eta_i} + \sum_{\substack{k=1 \\ k \neq i}}^{4} \frac{2x_i x_k}{\eta_{ik}} \frac{M_i M_k}{(M_i + M_k)^2} \left[\frac{5}{3A_{ik}^*} \frac{M_k}{M_i} \right]$$ and

$$H_{ij} = -\frac{2x_i x_j}{\eta_{ij}} \frac{M_i M_j}{(M_i + M_j)^2} \left[\frac{5}{3A_{ij}^*} - 1 \right]$$

where,

$\eta_i =$ coefficient of viscosity of pure gas component i

$$\eta_{ij} = 266.93 * 10^{-7} \frac{\sqrt{2 M_i M_j T / (M_i + M_j)}}{\sigma_{ij}^2 \Omega_{ij}^{(2,2)*} (T_{ij}^*)}$$

$T_{ij}^* = kT / \varepsilon_{ij}$ reduced temperature

$\sigma_{ij}, \varepsilon_{ij} / T =$ parameters in the potential function characteristic of 1-2 interaction

$x_i =$ mole fraction of component i

$M_i =$ molecular weight of component i

$A^* = \Omega^{(2,2)*} / \Omega^{(1,1)*}$

$\Omega^{(i,i)*} =$ integrals for calculating the transport coefficients for the Leonard-Jones (6-12) potential

Once we have the viscosity of the non-polar gas mixture, we can use the equations for a polar/non-polar mixture. The equation for viscosity of a binary mixture is as follows:

$$1/\eta = \frac{X_\eta + Y_\eta}{1 + Z_\eta}$$

where

$\eta =$ viscosity of the mixture

$$X_\eta = \frac{x_g^2}{\eta_g} + \frac{2 x_g x_w}{\eta_{gw}} + \frac{x_w^2}{\eta_w}$$

$$Y_\eta = \tfrac{3}{5} A_{12}^* \left[\frac{x_g^2}{\eta_g} \left(\frac{M_g}{M_w} \right) + \frac{2 x_g x_w}{\eta_g} \left(\frac{(M_g + M_w)^2}{4 M_g M_w} \right) \left(\frac{\eta_{gw}^2}{\eta_g \eta_w} \right) + \frac{x_w^2}{\eta_w} \left(\frac{M_w}{M_g} \right) \right]$$

$$Z_\eta = \tfrac{3}{5} A_{12}^* \left[x_g^2 \left(\frac{M_g}{M_w} \right) + 2 x_g x_w \left[\left(\frac{(M_g + M_w)^2}{4 M_g M_w} \right) \left(\frac{\eta_{gw}}{\eta_g} + \frac{\eta_{gw}}{\eta_w} - 1 \right) \right] + x_w^2 \left(\frac{M_w}{M_g} \right) \right]$$

$\eta_g =$ viscosity of dry gas mixture at the specified temperature

$\eta_w =$ viscosity of water vapor at the specified temperature

$$\eta_{gw} = C_1 \frac{\sqrt{2M_g M_w T / (M_g + M_w)}}{\sigma_{gw}^2 \Omega_{12}^{(2,2)*} (T_{gw}^*)}$$ and C1 = 266.93E-7

σ_{gw}= potential function parameter for mixture adjusted for one polar molecule

$M_g =$ weighted average molecular mass of the dry gas mixture

To correct for pressure, we use the method of Chung et al. as described in Reid, Prausnitz and Poling [9]

3.3.2 Thermal Conductivity

In a similar manner, to calculate thermal conductivity we treat the gas as a binary mixture of the non-polar gases and water vapor.

For the non-polar gas mixture, we use the Wassiljewa equation with the Mason and Saxena modification described by Reid, Prausnitz and Poling [9].

$$\lambda_g = \sum_{i=1}^{4} \frac{x_i \lambda_i}{\sum_{j=1}^{4} x_j A_{ij}}$$ where

$\lambda_g =$ thermal conductivity of the gas mixture

$\lambda_i =$ thermal conductivity of component i

$x_i, x_j =$ mole fraction of components i and j

$A_{ii} = 1.0$

$$A_{ij} = \frac{\varepsilon\left[1 + (\lambda_{tri} / \lambda_{trj})^{1/2} (M_i / M_j)^{1/4}\right]^2}{\left[8(1 + M_i / M_j)\right]^{1/2}}$$

$\varepsilon =$ value that varies from 0.9 to 1.05 as a function of temperature

$$\lambda_{tri} / \lambda_{trj} = \frac{\Gamma_j \left[\exp(0.0464 T_{ri}) - \exp(-0.2412 T_{ri})\right]}{\Gamma_i \left[\exp(0.0464 T_{rj}) - \exp(-.2412 T_{rj})\right]}$$

$$\Gamma = 210 \left(\frac{T_c M^3}{P_c^4} \right)^{1/6}$$

$T_c, P_c =$ critical temperature and pressure

The equation for thermal conductivity of the moist gases is as follows:

$$1/\lambda = \frac{X_\lambda + Y_\lambda}{1 + Z_\lambda}$$

where,

$\lambda =$ thermal conductivity of the mixture

$$X_\lambda = \frac{x_g^2}{\lambda_g} + \frac{2x_g x_w}{\lambda_{gw}} + \frac{x_w^2}{\lambda_w}$$

$$Y_\lambda = \frac{x_g^2}{\lambda_g} U^{(1)} + \frac{2x_g x_w}{\lambda_{gw}} U^{(Y)} + \frac{x_w^2}{\lambda_w} U^{(2)}$$

$$Z_\lambda = x_g^2 U^{(1)} + 2x_g x_w U^{(Y)} + x_w^2 U^{(2)}$$

$$U^{(1)} = \frac{4}{15} A_{12}^* - \frac{1}{12}\left(\frac{12}{5} B_{12}^* + 1\right)\frac{M_g}{M_w} + \frac{1}{2}\frac{\left(M_g - M_w\right)^2}{M_g M_w}$$

$$U^{(2)} = \frac{4}{15} A_{12}^* - \frac{1}{12}\left(\frac{12}{5} B_{12}^* + 1\right)\frac{M_w}{M_g} + \frac{1}{2}\frac{\left(M_w - M_g\right)^2}{M_g M_w}$$

$$U^{(Y)} = \frac{4}{15} A_{12}^* \left(\frac{\left(M_g + M_w\right)^2}{4 M_g M_w}\right)\frac{\lambda_{gw}^2}{\lambda_g \lambda_w} - \frac{1}{12}\left(\frac{12}{5} B_{12}^* + 1\right) - \frac{5}{32 A_{12}^*}\left(\frac{12}{5} B_{12}^* - 5\right)\frac{\left(M_g - M_w\right)^2}{M_g M_w}$$

$$U^{(Z)} = \frac{4}{15} A_{12}^* \left[\left(\frac{\left(M_g + M_w\right)^2}{4 M_g M_w}\right)\left(\frac{\lambda_{gw}}{\lambda_g} + \frac{\lambda_{gw}}{\lambda_w}\right) - 1\right] - \frac{1}{12}\left(\frac{12}{5} B_{12}^* + 1\right)$$

$\lambda_g =$ Thermal conductivity of dry gas mixture at the specified temperature

$\lambda_w =$ Thermal conductivity of water vapor at the specified temperature

$\lambda_{gw} = C_2 \dfrac{\sqrt{T\left(M_g + M_w\right)/2 M_g M_w}}{\sigma_{gw}^2 \Omega_{12}^{(2,2)*}\left(T_{gw}^*\right)}$ and C_2 = 1989.1E-7

B_{12}^* = function of reduced temperature

To correct for pressure, we use the Stiel and Thodos modification as described in Reid, Prausnitz and Poling [9].

4 ACCURACY

4.1 ACCURACY OF CALCULATIONS

Thermodynamic properties for the pure gases calculated by *DeskTop Gas* have been checked against the values published by NBS [1] and ASME [6] for water vapor. As shown on Tables 1 through 20, the calculated values show excellent agreement with the source data throughout most of the valid range. Some small differences can be observed at low temperatures and high pressures. This is due to the limitations of using a third order virial equation of state.

There is little published data on the properties of mixed gases. One method to illustrate the accuracy of the mixing equations is to compare the results of *DeskTop Gas* to data for dry air, which is a mixture of Nitrogen, Oxygen, Argon and a small amount of Carbon Dioxide. Tables 21 through 24 show the comparison with air for the thermodynamic properties.

As with the pure components, small errors can be observed at low temperatures and high pressures due to the limitations of the model. The tables show some differences in enthalpy, entropy and specific heat occurring at 850 °K and growing with temperature. This initially, was thought to be attributed to dissociation, but this was dismissed for two reasons. First, dissociation effects were not included below 1500 °K in reference 1. Second, the error is much greater than what can be attributed to dissociation above 1500 °K.

Further examination of the data tables suggests that the tables in reference 1 are in error. One would expect the thermodynamic properties to approach the ideal gas properties as the pressure is reduced to zero. While this is the case for temperatures up to 800 °K, it is not the case above 800 °K. Curiously, at 800 °K, the tables in reference 1 change from a temperature increment of 10 °K to 50 °K at the point where the error begins. Perhaps this change of temperature increment was not handled properly.

Comparison of data from Vasserman et al [2] in the temperature range from 850 °K to 1300 °K supports the conclusion that the tables from NBS [1] are in error. Unfortunately, the tables from Vasserman et al [2] do not contain data for temperatures above 1300 °K.

Thermodynamic properties for moist air are presented by ASHRAE [10] at atmospheric pressure for temperatures up to 200 deg C. The ASHRAE data is based on work done by Hyland and Wexler [8], who provide tables of calculated data at pressures up to 50 bar. Comparisons with this data are shown on Tables 29 through 40.

Data for Viscosity and Thermal Conductivity is taken from Vasserman et al [2] for the pure gases except for water vapor which is taken from ASME [6]. Tables 41 and 42 show excellent agreement with this data. As with the thermodynamic properties, the accuracy of the mixing equations for the transport properties are illustrated by comparison with dry air. These comparisons are shown in Table 43. The mixing equations for the transport properties are not as precise as those for the thermodynamic properties; however, in most cases the errors are less than 1%.

Some of the table data was generated using the **@Gas** functions for convenience. They use the exact same function library as used in *DeskTop Gas*.

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 1 - COMPRESSIBILITY OF NITROGEN

Temperature Range		Pressure							
From	To	0.01 atm		1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.000%	0.000%	0.001%	0.006%	0.006%	0.022%	0.056%	0.101%
260	300	0.000%	0.001%	0.001%	0.001%	0.005%	0.006%	0.011%	0.019%
310	350	0.000%	0.000%	0.000%	0.001%	0.004%	0.006%	0.016%	0.020%
360	400	0.000%	0.000%	0.000%	0.000%	0.001%	0.003%	0.005%	0.009%
410	500	0.000%	0.000%	0.000%	0.001%	0.001%	0.002%	0.005%	0.009%
510	600	0.000%	0.000%	0.000%	0.001%	0.001%	0.002%	0.007%	0.009%
610	700	0.000%	0.000%	0.000%	0.000%	0.001%	0.001%	0.003%	0.005%
710	800	0.000%	0.000%	0.000%	0.000%	0.001%	0.002%	0.002%	0.003%
850	1450	0.000%	0.000%	0.000%	0.001%	0.003%	0.006%	0.007%	0.012%
1500	2000	0.000%	0.000%	0.000%	0.000%	0.001%	0.002%	0.003%	0.006%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 2 - COMPRESSIBILITY OF OXYGEN

Temperature Range		Pressure							
From	To	0.01 atm		1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.000%	0.000%	0.004%	0.012%	0.008%	0.034%	0.112%	0.199%
260	300	0.000%	0.000%	0.001%	0.001%	0.007%	0.008%	0.009%	0.021%
310	350	0.000%	0.000%	0.000%	0.000%	0.005%	0.006%	0.009%	0.010%
360	400	0.000%	0.000%	0.000%	0.000%	0.001%	0.002%	0.004%	0.006%
410	500	0.000%	0.000%	0.000%	0.001%	0.001%	0.002%	0.004%	0.006%
510	600	0.000%	0.000%	0.000%	0.001%	0.002%	0.002%	0.005%	0.006%
610	700	0.000%	0.000%	0.000%	0.001%	0.001%	0.001%	0.001%	0.003%
710	800	0.000%	0.000%	0.000%	0.000%	0.000%	0.001%	0.002%	0.004%
850	1450	0.000%	0.000%	0.000%	0.001%	0.001%	0.002%	0.006%	0.008%
1500	2000	0.000%	0.000%	0.000%	0.001%	0.001%	0.002%	0.002%	0.005%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 3 - COMPRESSIBILITY OF ARGON

Temperature Range		Pressure							
From	To	0.01 atm		1 atm		10 atm		40 atm	
deg K	Deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.000%	0.001%	0.001%	0.002%	0.004%	0.007%	0.071%	0.213%
260	300	0.000%	0.000%	0.001%	0.001%	0.006%	0.007%	0.020%	0.030%
310	350	0.000%	0.001%	0.001%	0.001%	0.003%	0.005%	0.014%	0.020%
360	400	0.000%	0.000%	0.000%	0.001%	0.001%	0.002%	0.004%	0.012%
410	500	0.000%	0.000%	0.000%	0.000%	0.001%	0.003%	0.008%	0.012%
510	600	0.000%	0.000%	0.000%	0.001%	0.002%	0.002%	0.008%	0.013%
610	700	0.000%	0.000%	0.000%	0.001%	0.001%	0.002%	0.005%	0.010%
710	800	0.000%	0.000%	0.000%	0.001%	0.000%	0.001%	0.004%	0.007%
850	1450	0.000%	0.000%	0.000%	0.001%	0.001%	0.002%	0.006%	0.011%
1500	2000	0.000%	0.000%	0.000%	0.000%	0.001%	0.002%	0.002%	0.006%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 4 - COMPRESSIBILITY OF CARBON DIOXIDE

Temperature Range		Pressure							
From	To	0.01 atm		1 atm		10 atm		40 atm	
deg K	Deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
200	250	0.001%	0.001%	NA	NA	NA	NA	NA	NA
260	300	0.000%	0.001%	0.004%	0.005%	NA	NA	NA	NA
310	350	0.000%	0.001%	0.003%	0.003%	NA	NA	NA	NA
360	400	0.000%	0.001%	0.001%	0.002%	NA	NA	NA	NA
410	500	0.000%	0.001%	0.001%	0.001%	NA	NA	NA	NA
510	600	0.001%	0.001%	0.001%	0.001%	NA	NA	NA	NA
610	700	0.001%	0.001%	0.001%	0.001%	NA	NA	NA	NA
710	800	0.000%	0.000%	0.000%	0.001%	NA	NA	NA	NA

850	1450	0.000%	0.000%	0.005%	0.008%	NA	NA	NA	NA
1500	2000	0.000%	0.000%	0.005%	0.006%	0.011%	0.028%	NA	NA

*NA indicates that CO_2 is not in vapor state in this range.

COMPARISON OF RESULTS WITH ASME [6] DATA
TABLE 5 - COMPRESSIBILITY OF WATER VAPOR

Temperature Range		Pressure							
From	To	0.01 atm		1 atm		10 atm		40 atm	
deg K	Deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
290	350	0.001%	0.002%	NA	NA	NA	NA	NA	NA
360	400	0.002%	0.002%	NA	NA	NA	NA	NA	NA
410	500	0.002%	0.002%	0.002%	0.003%	NA	NA	NA	NA
510	600	0.002%	0.002%	0.003%	0.003%	0.003%	0.003%	NA	NA
610	700	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%	0.005%
710	800	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%
850	1450	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%	0.004%
1500	2000	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%	0.002%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 6 - ENTHALPY OF NITROGEN

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.005%	0.022%	0.054%	0.221%	0.287%	1.235%
260	300	0.001%	0.002%	0.004%	0.009%	0.031%	0.074%
310	350	0.001%	0.001%	0.005%	0.006%	0.017%	0.024%
360	400	0.001%	0.001%	0.006%	0.006%	0.022%	0.025%
410	500	0.001%	0.001%	0.003%	0.005%	0.011%	0.019%

510	600	0.000%	0.001%	0.001%	0.005%	0.004%	0.007%
610	700	0.001%	0.001%	0.002%	0.005%	0.009%	0.009%
710	800	0.000%	0.001%	0.002%	0.002%	0.009%	0.010%
810	1450	0.000%	0.000%	0.001%	0.001%	0.004%	0.006%
1500	2000	0.000%	0.000%	0.002%	0.002%	0.008%	0.009%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 7 - ENTHALPY OF OXYGEN

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.005%	0.015%	0.041%	0.174%	0.287%	1.102%
260	300	0.002%	0.002%	0.005%	0.010%	0.028%	0.062%
310	350	0.001%	0.002%	0.009%	0.010%	0.018%	0.028%
360	400	0.001%	0.002%	0.006%	0.007%	0.025%	0.026%
410	500	0.001%	0.001%	0.003%	0.006%	0.010%	0.019%
510	600	0.000%	0.001%	0.001%	0.002%	0.006%	0.011%
610	700	0.000%	0.001%	0.002%	0.002%	0.007%	0.010%
710	800	0.000%	0.001%	0.002%	0.002%	0.006%	0.010%
810	1450	0.000%	0.001%	0.001%	0.001%	0.004%	0.007%
1500	2000	0.000%	0.000%	0.002%	0.002%	0.008%	0.009%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 8 - ENTHALPY OF ARGON

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.049%	0.376%	0.082%	0.529%	0.075%	0.199%
260	300	0.001%	0.002%	0.004%	0.007%	0.015%	0.032%
310	350	0.002%	0.002%	0.008%	0.011%	0.038%	0.056%
360	400	0.001%	0.002%	0.007%	0.010%	0.015%	0.033%
410	500	0.001%	0.001%	0.002%	0.005%	0.012%	0.027%
510	600	0.001%	0.001%	0.002%	0.003%	0.007%	0.015%
610	700	0.000%	0.001%	0.003%	0.003%	0.013%	0.022%
710	800	0.000%	0.001%	0.002%	0.003%	0.010%	0.018%
810	1450	0.000%	0.000%	0.002%	0.004%	0.004%	0.007%
1500	2000	0.000%	0.001%	0.002%	0.003%	0.012%	0.014%

COMPARISON OF RESULTS WITH NBS [1] DATA

TABLE 9 - ENTHALPY OF CARBON DIOXIDE

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	NA	NA	NA	NA	NA	NA
260	300	0.019%	0.030%	0.023%	0.057%	NA	NA
310	350	0.014%	0.021%	0.049%	0.064%	0.389%	0.864%
360	400	0.008%	0.011%	0.034%	0.041%	0.307%	0.436%
410	500	0.008%	0.011%	0.019%	0.027%	0.099%	0.153%
510	600	0.005%	0.009%	0.005%	0.010%	0.024%	0.064%
610	700	0.006%	0.011%	0.007%	0.012%	0.025%	0.035%
710	800	0.002%	0.003%	0.006%	0.012%	0.033%	0.037%
810	1450	0.002%	0.004%	0.003%	0.007%	0.012%	0.028%
1500	2000	**	**	**	**	**	**

**** NBS data not available**

COMPARISON OF RESULTS WITH ASME [6] DATA

TABLE 10 - ENTHALPY OF WATER VAPOR

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	290	NA	NA	NA	NA	NA	NA
290	370	NA	NA	NA	NA	NA	NA
380	450	0.013%	0.015%	NA	NA	NA	NA
460	530	0.017%	0.018%	0.013%	0.024%	NA	NA
540	600	0.021%	0.021%	0.026%	0.030%	0.006%	0.012%
610	700	0.022%	0.023%	0.022%	0.023%	0.021%	0.024%
710	800	0.026%	0.028%	0.026%	0.028%	0.026%	0.028%
850	1450	0.047%	0.064%	0.047%	0.064%	0.048%	0.064%
1500	2000	0.082%	0.093%	0.082%	0.093%	0.082	0.093%

COMPARISON OF RESULTS WITH NBS [1] DATA

TABLE 11 - ENTROPY OF NITROGEN

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.001%	0.003%	0.009%	0.037%	0.049%	0.208%
260	300	0.000%	0.000%	0.001%	0.002%	0.006%	0.011%
310	350	0.000%	0.000%	0.001%	0.001%	0.002%	0.003%
360	400	0.000%	0.000%	0.001%	0.001%	0.003%	0.004%
410	500	0.000%	0.000%	0.001%	0.001%	0.002%	0.003%
510	600	0.000%	0.000%	0.000%	0.000%	0.001%	0.001%
610	700	0.000%	0.000%	0.001%	0.001%	0.001%	0.002%
710	800	0.000%	0.000%	0.000%	0.001%	0.001%	0.002%
810	1450	0.000%	0.000%	0.000%	0.001%	0.001%	0.001%
1500	2000	0.000%	0.000%	0.000%	0.000%	0.001%	0.001%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 12 - ENTROPY OF OXYGEN

Temperature Range		Pressure					
From	To	1	Atm	10	Atm	40	Atm
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.005%	0.015%	0.041%	0.174%	0.287%	0.102%
260	300	0.002%	0.002%	0.005%	0.010%	0.028%	0.062%
310	350	0.001%	0.002%	0.009%	0.010%	0.018%	0.028%
360	400	0.001%	0.002%	0.006%	0.007%	0.025%	0.026%
410	500	0.001%	0.001%	0.003%	0.006%	0.010%	0.019%
510	600	0.000%	0.001%	0.001%	0.002%	0.006%	0.011%
610	700	0.000%	0.001%	0.002%	0.002%	0.007%	0.010%
710	800	0.000%	0.001%	0.002%	0.002%	0.006%	0.010%
810	1450	0.000%	0.001%	0.001%	0.001%	0.004%	0.007%
1500	2000	0.000%	0.000%	0.002%	0.002%	0.003%	0.009%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 13 - ENTROPY OF ARGON

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.000%	0.001%	0.006%	0.022%	0.129%	1.102%
260	300	0.000%	0.000%	0.000%	0.001%	0.005%	0.062%
310	350	0.000%	0.000%	0.001%	0.001%	0.006%	0.028%
360	400	0.000%	0.000%	0.001%	0.001%	0.004%	0.026%
410	500	0.000%	0.000%	0.000%	0.001%	0.001%	0.019%
510	600	0.000%	0.000%	0.000%	0.001%	0.001%	0.011%
610	700	0.000%	0.001%	0.001%	0.001%	0.002%	0.010%
710	800	0.000%	0.000%	0.001%	0.001%	**	**
810	1450	0.000%	0.000%	0.000%	0.001%	**	**
1500	2000	0.000%	0.000%	0.000%	0.000%	**	**

**** NBS data not available**

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 14 - ENTROPY OF CARBON DIOXIDE

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	NA	NA	NA	NA	NA	NA
260	300	0.002%	0.003%	0.006%	0.014%	NA	NA
310	350	0.001%	0.003%	0.003%	0.005%	0.033%	0.086%
360	400	0.002%	0.006%	0.006%	0.007%	0.038%	0.050%
410	500	0.003%	0.004%	0.004%	0.006%	0.020%	0.025%
510	600	0.003%	0.002%	0.002%	0.004%	0.010%	0.016%
610	700	0.003%	0.001%	0.001%	0.003%	0.003%	0.006%
710	800	0.003%	0.001%	0.001%	0.003%	0.001%	0.002%
810	1450	0.002%	0.002%	0.002%	0.004%	0.003%	0.006%
1500	2000	**	**	**	**	**	**

COMPARISON OF RESULTS WITH ASME [6] DATA
TABLE 15 – ENTROPY OF WATER VAPOR

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	290	NA	NA	NA	NA	NA	NA
290	370	NA	NA	NA	NA	NA	NA
380	450	0.017%	0.020%	NA	NA	NA	NA
460	530	0.019%	0.020%	0.019%	0.030%	NA	NA
540	600	0.021%	0.022%	0.028%	0.030%	0.013%	0.020%
610	700	0.022%	0.022%	0.025%	0.025%	0.026%	0.028%
710	800	0.023%	0.024%	0.026%	0.027%	0.029%	0.030%
850	1450	0.033%	0.041%	0.037%	0.045%	0.040%	0.048%
1500	2000	0.048%	0.052%	0.053%	0.058%	0.056	0.061%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 16 – SPECIFIC HEAT OF NITROGEN

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.062%	0.182%	0.758%	2.899%	2.923%	9.543%
260	300	0.004%	0.005%	0.050%	0.057%	0.325%	0.368%
310	350	0.002%	0.003%	0.014%	0.029%	0.123%	0.206%
360	400	0.001%	0.002%	0.016%	0.022%	0.028%	0.053%
410	500	0.002%	0.003%	0.026%	0.027%	0.076%	0.084%
510	600	0.001%	0.003%	0.021%	0.024%	0.061%	0.076%
610	700	0.001%	0.002%	0.014%	0.017%	0.029%	0.041%
710	800	0.001%	0.001%	0.009%	0.011%	0.008%	0.015%
810	1450	0.001%	0.002%	0.004%	0.007%	0.013%	0.022%
1500	2000	0.001%	0.004%	0.006%	0.007%	0.005%	0.010%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 17 – SPECIFIC HEAT OF OXYGEN

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.043%	0.122%	0.466%	1.381%	2.495%	8.550%
260	300	0.001%	0.002%	0.047%	0.055%	0.326%	0.386%
310	350	0.001%	0.002%	0.011%	0.025%	0.111%	0.192%
360	400	0.002%	0.004%	0.014%	0.020%	0.023%	0.042%
410	500	0.002%	0.004%	0.020%	0.022%	0.062%	0.065%
510	600	0.001%	0.002%	0.012%	0.017%	0.044%	0.059%
610	700	0.001%	0.004%	0.004%	0.008%	0.015%	0.026%
710	800	0.001%	0.001%	0.001%	0.003%	0.004%	0.009%
810	1450	0.001%	0.001%	0.005%	0.008%	0.017%	0.029%
1500	2000	0.000%	0.001%	0.003%	0.004%	0.011%	0.016%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 18 – SPECIFIC HEAT OF ARGON

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.031%	0.093%	0.517%	1.643%	1.574%	4.829%
260	300	0.005%	0.007%	0.073%	0.096%	0.307%	0.575%
310	350	0.001%	0.003%	0.014%	0.029%	0.259%	0.437%
360	400	0.003%	0.004%	0.020%	0.026%	0.158%	0.355%
410	500	0.003%	0.005%	0.026%	0.028%	0.095%	0.261%
510	600	0.001%	0.003%	0.017%	0.022%	0.049%	0.068%
610	700	0.001%	0.002%	0.007%	0.012%	0.023%	0.047%
710	800	0.001%	0.002%	0.004%	0.008%	0.015%	0.022%
810	1450	0.001%	0.002%	0.008%	0.014%	0.043%	0.066%
1500	2000	0.001%	0.001%	0.001%	0.003%	0.023%	0.039%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 19 – SPECIFIC HEAT OF CARBON DIOXIDE

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	NA	NA	NA	NA	NA	NA
260	300	0.040%	0.052%	1.336%	4.255%	NA	NA
310	350	0.029%	0.097%	0.167%	0.229%	4.022%	9.111%
360	400	0.006%	0.008%	0.030%	0.052%	0.359%	0.849%
410	500	0.004%	0.007%	0.065%	0.078%	0.184%	0.286%
510	600	0.003%	0.007%	0.039%	0.051%	0.247%	0.328%
610	700	0.004%	0.007%	0.013%	0.023%	0.114%	0.178%
710	800	0.003%	0.007%	0.005%	0.017%	0.021%	0.043%
810	1450	0.006%	0.013%	0.009%	0.016%	0.072%	0.206%
1500	2000	**	**	**	**	**	**

**** NBS data not available**

COMPARISON OF RESULTS WITH ASME [6] DATA
TABLE 20 – SPECIFIC HEAT OF WATER VAPOR

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	290	NA	NA	NA	NA	NA	NA
290	370	NA	NA	NA	NA	NA	NA
380	450	0.102%	0.310%	NA	NA	NA	NA
460	530	0.080%	0.155%	0.334%	0.778%	NA	NA
540	600	0.065%	0.319%	0.414%	2.008%	0.731%	2.673%
610	700	0.065%	0.080%	0.045%	0.075%	0.146%	0.302%
710	800	0.093%	0.106%	0.093%	0.119%	0.087%	0.154%
850	1450	0.148%	0.197%	0.146%	0.276%	0.190%	0.693%
1500	2000	0.190%	0.218%	0.`90%	0.217%	0.189%	0.216%

COMPARISON OF RESULTS WITH NBS [1] DATA

TABLE 21 - COMPRESSIBILITY OF DRY AIR

Temperature Range		Pressure							
From	To	0.01 atm		1 atm		10 atm		40 atm	
Deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.001%	0.001%	0.001%	0.002%	0.018%	0.027%	0.124%	0.278%
260	300	0.001%	0.001%	0.000%	0.001%	0.004%	0.007%	0.010%	0.014%
310	350	0.001%	0.001%	0.000%	0.000%	0.002%	0.002%	0.010%	0.014%
360	400	0.001%	0.001%	0.000%	0.001%	0.002%	0.003%	0.002%	0.003%
410	500	0.001%	0.001%	0.000%	0.001%	0.002%	0.003%	0.009%	0.012%
510	600	0.001%	0.001%	0.001%	0.001%	0.001%	0.002%	0.011%	0.012%
610	700	0.001%	0.001%	0.001%	0.001%	0.000%	0.001%	0.007%	0.009%
710	800	0.001%	0.001%	0.001%	0.002%	0.001%	0.002%	0.003%	0.005%
810	1450	0.001%	0.001%	0.001%	0.002%	0.002%	0.003%	0.003%	0.005%
1500	2000	0.0038	0.167%	0.005%	0.017%	0.005%	0.007%	0.004%	0.011%

COMPARISON OF RESULTS WITH NBS [1] DATA
TABLE 22 - ENTHALPY OF DRY AIR

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.004%	0.016%	0.031%	0.119%	0.125%	0.262%
260	300	0.001%	0.002%	0.004%	0.009%	0.037%	0.070%
310	350	0.001%	0.003%	0.005%	0.008%	0.007%	0.011%
360	400	0.002%	0.005%	0.008%	0.009%	0.006%	0.009%
410	500	0.001%	0.002%	0.005%	0.007%	0.005%	0.011%
510	600	0.001%	0.002%	0.001%	0.003%	0.005%	0.007%
610	700	0.001%	0.002%	0.001%	0.001%	0.007%	0.008%
710	800	0.001%	0.004%	0.002%	0.004%	0.007%	0.010%
810	1450	* 0.03%	* 0.10%	* 0.03%	* 0.09%	* 0.03%	* 0.10%
1500	2000	**	**	**	**	**	**

COMPARISON OF RESULTS WITH NBS [1] DATA

TABLE 23 - ENTROPY OF DRY AIR

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.002%	0.003%	0.006%	0.022%	0.020%	0.052%
260	300	0.001%	0.002%	0.001%	0.002%	0.005%	0.006%
310	350	0.003%	0.004%	0.001%	0.002%	0.006%	0.008%
360	400	0.002%	0.004%	0.002%	0.004%	0.004%	0.007%
410	500	0.001%	0.004%	0.001%	0.003%	0.003%	0.005%
510	600	0.002%	0.004%	0.002%	0.004%	0.001%	0.003%
610	700	0.002%	0.003%	0.002%	0.004%	0.001%	0.002%
710	800	0.001%	0.003%	0.001%	0.003%	0.002%	0.003%
850	1450	0.005%	0.014%	0.003%	0.005%	0.005%	0.009%
1500	2000	**	**	**	**	**	**

COMPARISON OF RESULTS WITH NBS [1] DATA

TABLE 24 - SPECIFIC HEAT OF DRY AIR

Temperature Range		Pressure					
From	To	1 atm		10 atm		40 atm	
deg K	deg K	Avg Error	Max Error	Avg Error	Max Error	Avg Error	Max Error
180	250	0.036%	0.098%	0.352%	1.026%	1.046%	3.162%
260	300	0.004%	0.005%	0.049%	0.061%	0.294%	0.382%
310	350	0.005%	0.007%	0.020%	0.034%	0.096%	0.170%
360	400	0.001%	0.002%	0.004%	0.007%	0.016%	0.033%
410	500	0.001%	0.003%	0.009%	0.012%	0.044%	0.056%
510	600	0.002%	0.003%	0.005%	0.010%	0.028%	0.038%
610	700	0.001%	0.003%	0.003%	0.007%	0.008%	0.022%
710	800	0.001%	0.002%	0.005%	0.024%	0.012%	0.038%
850	1450	* 0.47%	* 1.40%	* 0.48%	* 1.38%	* 0.50%	* 1.40%
1500	2000	**	**	**	**	**	**

Notes: *, ** - Questionable reference data

COMPARISON OF RESULTS WITH HYLAND & WEXLER [8]
SATURATED HUMIDITY RATIO OF MOIST AIR
(kg of Water Vapor/kg of Dry Air)

TABLE 2 - Pressure = 1 bar

Temp deg C	Hyland & Wexler	@Air	@Gas
0	0.00384	.00834	.00834
90	1.4833	1.4835	1.4833

TABLE 26 - Pressure = 5 bar

Temp deg C	Hyland & Wexler	@Air	@Gas
0	0.000775	0.000777	0.000777
90	0.10368	0.10375	0.10374
100	0.16201	0.16207	0.16205
150	13.041	12.989	12.989

TABLE 27 - Pressure = 10 bar

Temp deg C	Hyland & Wexler	@Air	@Gas
0	0.000394	0.000396	0.000396
90	0.04838	0.04844	0.04840
100	0.07251	0.07258	0.07257
150	0.5974	0.5069	0.5970
160	1.0718	1.0708	1.0709
170	2.5434	2.5400	2.5403

TABLE 28 - Pressure = 50 bar

Temp deg C	Hyland & Wexler	@Air	@Gas
0	9.09E-5	9.25E-5	9.27E-5
90	0.00985	0.00988	0.00989
100	0.01430	0.01434	0.01435
150	0.0736	0.0732	0.0733
160	0.0993	0.0986	0.0987
170	0.1336	0.1324	0.1325
180	0.1796	0.1778	0.1779
200	0.3306	0.3263	0.3263

COMPARISON OF RESULTS WITH HYLAND & WEXLER [8]
SPECIFIC VOLUME OF SATURATED MOIST AIR
(m^3/kg of Dry Air)

TABLE 29 - Pressure = 1 bar

Temp	Hyland & Wexler		@Air		@Gas	
Deg C	Value	Uncert	Value	Error	Value	Error
0	0.78846	0.00010	0.78847	0.00001	0.78846	0.00000
90	3.4974	0.00029	3.4973	-0.0001	3.4976	0.0002

TABLE 30 - Pressure = 5 bar

Temp	Hyland & Wexler		@Air		@Gas	
Deg C	Value	Uncert	Value	Error	Value	Error
0	0.15657	0.00011	0.15657	0.00000	0.15657	0.00000
90	0.24273	0.00015	0.24270	-0.00003	0.24271	-0.00002
100	0.26904	0.00020	0.26902	-0.00002	0.26902	-0.00002
150	5.115	0.0063	5.117	0.002	5.116	0.001

TABLE 31 - Pressure = 10 bar

Temp	Hyland & Wexler		@Air		@Gas	
Deg C	Value	Uncert	Value	Error	Value	Error
0	0.078022	0.00015	0.078023	0.000001	0.078022	0.000000
90	0.11226	0.00017	0.11225	-0.00001	0.11225	-0.00001
100	0.11942	0.00022	0.11940	-0.00002	0.11940	-0.00002
150	0.23281	0.00165	0.23289	0.00008	0.23288	0.00007
160	0.32711	0.00120	0.32732	0.00021	0.32729	0.00018
170	0.61489	0.00152	0.61553	0.00064	0.61547	0.00058

TABLE 32 - Pressure = 50 bar

Temp	Hyland & Wexler		@Air		@Gas	
deg C	Value	Uncert	Value	Error	Value	Error
0	0.015331	0.00077	0.015324	-0.000007	0.015324	-0.000007
90	0.021310	0.00050	0.021302	-0.000008	0.021301	-0.000009
100	0.022073	0.00053	0.022066	-0.000007	0.022065	-0.000008
150	0.02727	0.00186	0.02729	0.00002	0.02729	0.00002
160	0.02885	0.00256	0.02888	0.00003	0.02888	0.00003
170	0.03077	0.00346	0.03082	0.00005	0.03081	0.00004
180	0.03315	0.00459	0.03323	0.00008	0.03323	0.00008
200	0.0402	0.0076	0.0404	0.0012	0.0404	0.0002

The differences in saturated humidity ratios between @Air or @Gas and Hyland & Wexler can be attributed mostly to the equations used to calculate the pressure of saturated vapor over liquid water. @Air and @Gas use the latest equations provided by IAPWS [7].

In the following comparisons, the properties calculated by @Air and @Gas use the saturated humidity ratio as calculated by Hyland & Wexler in order to show a comparison based on the same composition.

5 REFERENCES

1. Tables of Thermal Properties of Gases, NBS Circular 564, 1955
2. Vasserman, A. A., Kazavchinskii, Ya Z., and Rabinovich, V. A., *Thermophysical Properties of Air and Air Components,* Nauka Press, Moscow, 1966; English translation by Israel Program for Scientific Translations, Ltd., available from NTIS, Springfield, Va., 1971,as TT70-50095.
3. Rabinovich, V. A., Beketov, V. G., *Moist Gases: Thermodynamic Properties,* Begell House, Inc., New York, 1995.
4. Hirschfelder, J. O., Curtiss, C. F., and Bird, R. B., *Molecular Theory of Liquids and Gases,* John Wiley and Sons, 1954.
5. Mangum, B. W., and Furukawa, G. T., *Guidelines for Realizing the International Temperature Scale of 1990 (ITS-90),* NIST Technical Note 1265, 1990.
6. *Thermodynamic and Transport Properties of Steam,* ASME, New York, NY, 1993.
7. *The IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use,* International Association for the Properties of Water and Steam, Paris France, September 1995
8. R. W. Hyland, A. Wexler, 1983, "Formulations for the Thermodynamic Properties of Dry Air from 173.15 K to 473.15 K, and of Saturated Moist Air from 173.25 K to 372.15 K, at Pressures to 5 MPa", ASHRAE *Transactions* 89(2A):520-35
9. Robert C. Reid, John M. Prausnitz, Bruce E. Poling, *The Properties of Gases and Liquids, Fourth Edition,*McGraw Hill, Inc.
10. American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) – Fundamentals 1993