

AGA Report No. 10

Speed of Sound in Natural Gas and Other Related Hydrocarbon Gases

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Prepared by
Transmission Measurement Committee

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FOREWORD

This report outlines a method for the calculation of the speed of sound in natural gas and the individual components that make up natural gas. It also calculates the entropy, enthalpy and C^* coefficient for sonic nozzles. This information is based on research that was developed and managed by the Gas Technology Institute (formerly the Gas Research Institute). The research indicates that the calculation is highly accurate and is consistent with the equation-of-state used in AGA Report No. 8, *Compressibility Factors of Natural Gas and Other Related Hydrocarbon Gases*. The original work for AGA Report No. 8 was developed under the auspices of the Gas Research Institute's Basic Fluid Properties Research Program, the AGA Transmission Measurement Committee, the Gas European de Researchers Group (GERG), members of the American Petroleum Institute (API) and the International Standards Organization (ISO).

The purpose of this report is to provide the natural gas industry with a method for solving problems involving thermodynamics. Industry's incentive for establishing these methods was spurred by the advent of ultrasonic gas meters. However, the value of these methods is apparent for other applications of natural gas thermodynamics, such as compression.

The audience of the report is gas measurement engineers, especially those supporting ultrasonic meters, as well as those who intend to apply the principles of thermodynamics to gas production, transmission or distribution.

The intended benefits to users of this report are:

- clear traceability to recognized scientific sources
- extensive testing and validation
- an implementation example upon which to build

The report is based on scientific data collected for pure gases and natural gas mixtures. As such, the range of application is focused on the single-phase natural gas mixtures common to industry. The performance of the methods is intended to meet the needs of the gas industry. Caution is advised to users applying this technology to other purposes and other fluids.

It may become necessary to make revisions to this document in the future. Whenever any revisions are advisable, recommendations should be forwarded to the **American Gas Association**, 400 N. Capitol Street, NW, 4th Floor, Washington, DC 20001, USA. A form has been included at the end of this report for that purpose.

ACKNOWLEDGEMENTS

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Those who deserve special recognition and appreciation for their help, suggestions and guidance in finalizing this report are — Dr. Eric Lemmon, National Institute of Standards and Technology; Paul J. LaNasa, CPL & Associates; Dr. Kenneth Starling, Starling Associates, Inc.; and Dr. Jeff Savidge, Consultant.

This report was originally initiated under the chairmanship of late Ron Rich, Natural Gas Pipeline, who could not complete it because of his untimely death. He is respectfully remembered and recognized for his contributions in initiating this document.

Others who participated during the development of this report, reviewed the final draft or provided comments and should also be acknowledged are:

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1. Introduction

1.1. Scope

This document contains information for computation of sound speed in natural gas and other related hydrocarbon gases. Procedures are included for computation of several related gas properties, including heat capacity, enthalpy, entropy and the critical flow coefficient, C^* .

The methods in this document are extensions to *Compressibility Factors for Natural Gas and Other Hydrocarbon Gases*, AGA Transmission Measurement Committee Report No. 8, Second Edition, Second Printing (1994). This document contains excerpts from Report No. 8, but intentionally does not reproduce the full report.

Similarly, the methods for computing the critical flow coefficient, C^* , are based on the information in appendix E of *ASME/ANSI MFC-7M-1987*. Users are referred to this source for background and pertinent references.

Procedures for computing other natural gas properties, such as volumetric heating value and relative density, fall outside of the scope of this report and are not included.

1.2. Background

This is the first AGA document on speed of sound. It is based on a large database of high-accuracy basic physical property research data obtained through research sponsored by the Gas Research Institute in cooperation with the AGA, API and GERG.

The methods presented in this AGA document utilize high-accuracy calculation procedures and related equations-of-state already implemented by AGA, API and ISO.

For continuity and ease of application, the original AGA Report No. 8 solution methods have been carried forward with little change. Computer code development for Report No. 10 will be modest and incremental to most existing AGA Report No. 8 implementations.

1.3. Field of Application

High-accuracy sound speed information is needed in a variety of gas flow measurement applications, such as ultrasonic meters and critical flow nozzles, as well as analytical applications such as transducers and densitometers.

This report provides the information needed to compute the speed of sound in natural gas and other related hydrocarbon gases. The equations utilized are consistent with AGA Report No. 8, API MPMS Chapter 14.2 and ISO Standard 12213 Part 2.

1.4. Types of Properties

The methods in this document may be used to compute a number of gas properties including speed of sound, enthalpy, entropy, heat capacity and critical flow coefficient.

In conjunction with the methods in AGA Report No. 8, procedures can be developed to support a variety of applications including sonic nozzles, compressor efficiency and heat exchanger calculations.

1.5. Types of Gases

This report is intended for natural gases and other related hydrocarbon gases. Table 1 identifies the ranges of gas characteristics for which this report can be used. The normal range column gives the range of gas characteristics for which the average expected uncertainty corresponds to the uncertainties identified in Figure 1. The expanded range of gas characteristics has an uncertainty, which is expected to be higher, especially outside of region 1 of Figure 1. The use of this report for computations of the physical properties of gases with component mole percentages outside the ranges given in Table 1 is not recommended.

An accepted database for water, heavy hydrocarbons and hydrogen sulfide in natural gases currently is not available for determinations of uncertainties of calculated gas properties. Therefore, as a practical matter, the only limitation is that the calculation is for the gas phase. Thus, the limits are the water dew point for mole percent water, the hydrocarbon dew point for mole percent heavy hydrocarbons, and pure hydrogen sulfide. The presentation of methods for calculations using the various heavy hydrocarbon fraction characterization methods used in the hydrocarbon industry is beyond the scope of this report.

Quantity	Normal Range	Expanded Range
Relative Density *	0.554 to 0.87	0.07 to 1.52
Gross Heating Value **	477 to 1150 Btu/scf	0 to 1800 Btu/scf
Gross Heating Value ***	18.7 to 45.1 MJ/m ³	0 to 66 MJ/m ³
Mole Percent Methane	45.0 to 100.0	0 to 100.0
Mole Percent Nitrogen	0 to 50.0	0 to 100.0
Mole Percent Carbon Dioxide	0 to 30.0	0 to 100.0
Mole Percent Ethane	0 to 10.0	0 to 100.0
Mole Percent Propane	0 to 4.0	0 to 12.0
Mole Percent Total Butanes	0 to 1.0	0 to 6.0
Mole Percent Total Pentanes	0 to 0.3	0 to 4.0
Mole Percent Hexanes Plus	0 to 0.2	0 to Dew Point
Mole Percent Helium	0 to 0.2	0 to 3.0
Mole Percent Hydrogen	0 to 10.0	0 to 100.0
Mole Percent Carbon Monoxide	0 to 3.0	0 to 3.0
Mole Percent Argon	#	0 to 1.0
Mole Percent Oxygen	#	0 to 21.0
Mole Percent Water	0 to 0.05	0 to Dew Point
Mole Percent Hydrogen Sulfide	0 to 0.02	0 to 100.0

* Reference Conditions: Relative Density at 60° F, 14.73 psia.

** Reference Conditions: Combustion at 60° F, 14.73 psia; density at 60° F, 14.73 psia.

*** Reference Conditions: Combustion at 25° C, 0.101325 MPa; density at 0° C, 0.101325 MPa.

The normal range is considered to be zero for these compounds.

Table 1: Range of Gas Mixture Characteristics Consistent with this Report

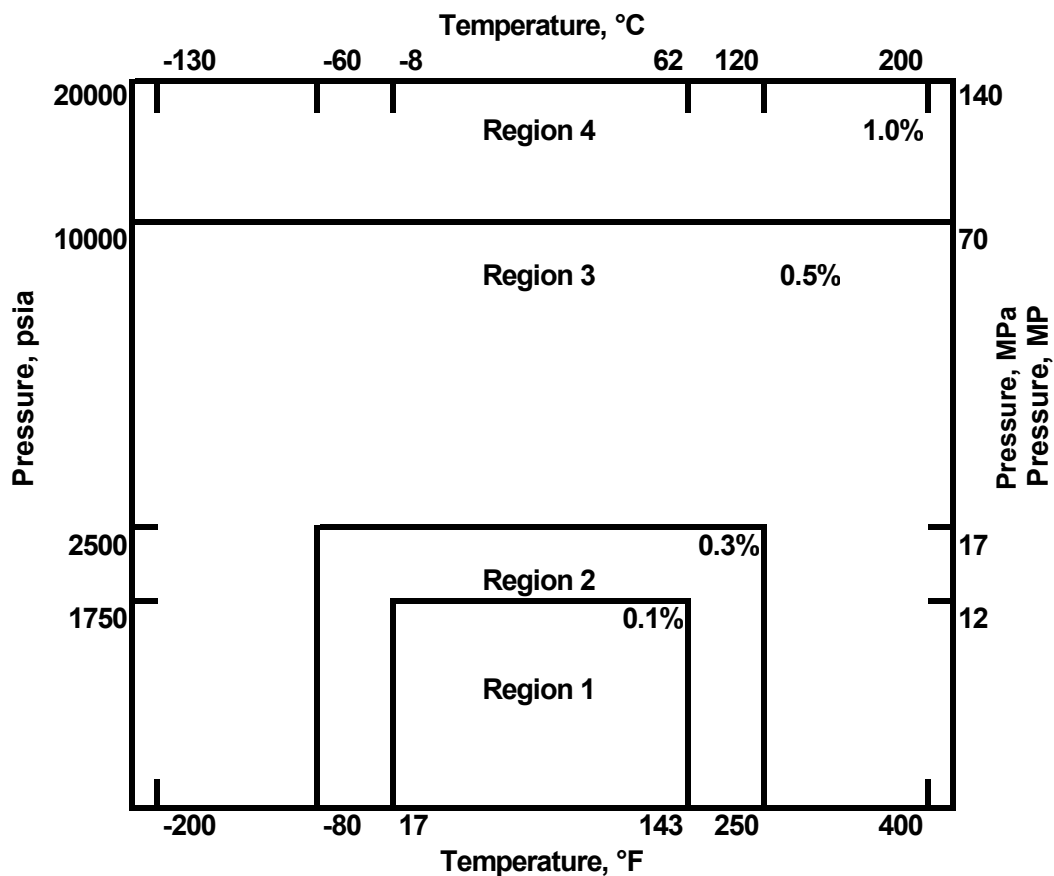


Figure 1: Targeted Uncertainty for Natural Gas Speed of Sound
Using the AGA Report No. 10 Method

1.6. Types of Conditions

This report is for the gas phase only. The methods can be applied for temperatures from -130°C to 200°C (-200°F to 400°F) at pressures up to 138 MPa (20,000 psia). Application at extreme conditions should be verified by other means (e.g., experimental verification). Use of the calculation method is not recommended within the vicinity of the critical point. For pipeline-quality gas, this is usually not a constraint because operating conditions near the critical point generally are not encountered.

2. Uncertainty

The uncertainty of calculated speed of sound depends on natural gas temperature, pressure and composition. The uncertainties of speed of sound methods were evaluated by comparing calculated values to experimentally measured speed of sound from NIST Monograph 178 [7].

Calculations were compared with experimental measured values for 17 gravimetrically prepared natural gas mixtures, listed in Table 2, over the range of 250° K to 350° K (-10° F to 165° F) and pressures up to 17 MPa (2500 psia). Some of the gas mixtures included in the uncertainty analysis are outside of the range of Table 1.

The measurements conducted demonstrate that the uncertainty in the speed of sound is within 0.1% for Gulf Coast, Amarillo and Ekofisk gases for pressures up to 12 MPa (1750 psia) and temperatures between 250 K and 350 K (-10° F and 165° F).

The uncertainty in the speed of sound is also within 0.1% for other gas mixtures whose characteristics fall within the normal range of Table 1. Higher levels of uncertainty are indicated for gases outside of the normal range of Table 1.

Statistical analyses of the differences between calculated and experimental values were performed to evaluate the uncertainties in the calculated speed of sound values. Statistics were calculated using the following equations where N is the number of data points:

$$W_{diff} = \frac{W_{calc} - W_{exp}}{W_{exp}} \times 100 \quad (2.1)$$

$$BIAS = \frac{1}{N} \sum_{i=1}^N W_{diff,i} \quad (2.2)$$

$$AAD = \frac{1}{N} \sum_{i=1}^N \left[(W_{diff,i})^2 \right]^{\frac{1}{2}} \quad (2.3)$$

$$Std.Dev. = \left[\frac{1}{N-1} \sum_{i=1}^N (W_{diff,i} - BIAS)^2 \right]^{\frac{1}{2}} \quad (2.4)$$

where:

W_{diff} = relative percentage difference between calculated and experimental speed of sound

$W_{diff,i}$ = W_{diff} for i th data point

W_{calc} = calculated speed of sound

W_{exp} = experimental speed of sound

AAD = average absolute deviation

BIAS = bias

Std.Dev. = standard deviation

Gas No.	Methane	Nitrogen	Carbon Dioxide	Ethane	Propane	Isobutane	Normal Butane	Isopentane	Normal Pentane	Normal Hexane
2	0.94985	0	0	0.05015	0	0	0	0	0	0
3	0.84992	0	0	0.15008	0	0	0	0	0	0
4	0.68526	0	0	0.31474	0	0	0	0	0	0
5	0.50217	0	0	0.49783	0	0	0	0	0	0
6	0.34524	0	0	0.65476	0	0	0	0	0	0
7	0.90016	0	0	0	0.09984	0	0	0	0	0
8	0.95114	0.04886	0	0	0	0	0	0	0	0
9	0.8513	0.1487	0	0	0	0	0	0	0	0
10	0.71373	0.28627	0	0	0	0	0	0	0	0
11	0.94979	0	0.05021	0	0	0	0	0	0	0
12	0.85026	0	0.14974	0	0	0	0	0	0	0
13	0.69944	0	0.30056	0	0	0	0	0	0	0
14	0	0.49593	0.50407	0	0	0	0	0	0	0
15	0.96561	0.00262	0.00597	0.01829	0.0041	0.00098	0.00098	0.00046	0.00032	0.00067
16	0.90708	0.03113	0.005	0.04491	0.00815	0.00106	0.00141	0.00065	0.00027	0.00034
17	0.8398	0.00718	0.00756	0.13475	0.00943	0.0004	0.00067	0.00013	0.00008	0
18	0.74348	0.00537	0.01028	0.12005	0.08251	0	0.03026	0	0.00575	0.0023

Table 2: Gas Mixture Characteristics Included in Statistical Analysis

Gas No.	No. Points	AAD %	Bias %	Std. Dev. %
2	80	0.021	-0.026	0.026
3	67	0.079	0.016	0.133
4	95	0.600	0.317	1.094
5	78	0.418	0.103	0.803
6	72	0.086	-0.011	0.127
7	76	0.327	0.144	0.721
8	81	0.021	-0.037	0.026
9	87	0.024	-0.036	0.029
10	97	0.025	-0.023	0.033
11	80	0.026	-0.053	0.038
12	71	0.024	-0.041	0.039
13	90	0.096	-0.009	0.184
14	65	0.148	0.230	0.205
15	83	0.030	-0.045	0.040
16	82	0.031	-0.026	0.051
17	91	0.094	0.001	0.153
18	44	0.148	0.068	0.224

Table 3: Statistical Analysis of the Differences between Calculated and Experimental Speed of Sound Values for 17 Natural Gas Mixtures

3. Calculations

3.1. Symbols

$\partial B / \partial T$	First partial derivative of B wrt T
$\partial^2 B / \partial T^2$	Second partial derivative of B wrt T
$\partial Z / \partial T$	First partial derivative of Z wrt T
$\partial^2 Z / \partial T^2$	Second partial derivative of Z wrt T
$\partial Z / \partial \rho$	First partial derivative of Z wrt ρ
ρ	Molar density
κ	Isentropic exponent
B	Second virial coefficient
c_p	Constant pressure heat capacity (real gas)
c_p°	Constant pressure heat capacity (ideal gas)
c_v	Constant volume heat capacity (real gas)
c_v°	Constant volume heat capacity (ideal gas)
H	Enthalpy (real gas)
H°	Enthalpy (ideal gas)
M_r	Molar mass
P	Absolute pressure
R	Universal gas constant
S	Entropy (real gas)
S°	Entropy (ideal gas)
T	Temperature
W	Speed of sound
X_i	Mole fraction of ith component
Z	Compressibility Factor

3.2. Overview of Calculation Method and Sequence

The speed of sound is related to the compressibility of a gas and can be computed from its fundamental physical property relationships. The information contained in this report and in AGA Report No. 8 is needed to implement the AGA speed of sound calculation.

The method used in this report utilizes a detail characterization of the gas composition (i.e., a representative gas analysis). As such, implementation is limited to methods provided in the AGA Report No. 8, "Detail Characterization Method."

The reliability of calculation results is dependent on the reliability of the gas composition data, temperature data and, to a lesser extent, pressure data.

Except where noted, all computations are performed in metric units. For conversions to other unit systems, users are referred to applicable documents by NIST[10] and the Canadian Standards Association[11].

Pure fluid ideal gas heat capacities, enthalpies and entropies are computed from equations given by Aly and Lee[3], with the additions given by McFall[2]. The originally published constants and units of measure have been preserved for this set of equations, necessitating conversion from thermochemical calories to joules. In this document, all references to the Btu refer to the International Table Btu (Btu_{IT}).

In the appendix to this report, real gas heat capacity, enthalpy and entropy are solved through numerical integration, applying gaussian quadrature. Alternative solution methods are feasible but users are advised to carefully evaluate the potential impact on accuracy and robustness.

Several partial derivatives are solved during computation. Three of these ($\partial Z/\partial T$, $\partial^2 Z/\partial T^2$, $\partial Z/\partial \rho$) are solved using the approach given in AGA Report No. 8 for subroutine “ZDETAIL.” Two other derivatives, $\partial B/\partial T$ and $\partial^2 B/\partial T^2$ are solved as minor additions to subroutine “B,” also given in AGA Report No. 8.

The general procedure for computing speed of sound at the flowing or operating condition of interest is:

1. Input the operating temperature (T), operating pressure (P) and gas analysis.
2. Calculate the molar mass of the mixture.
3. Calculate the compressibility and density of the fluid at the conditions of interest.
4. Calculate the ideal gas constant pressure heat capacity at the operating temperature.
5. Calculate the real gas constant volume heat capacity at the operating conditions.
6. Calculate the real gas constant pressure heat capacity at the operating conditions.
7. Calculate the ratio of heat capacities, c_p/c_v , at the operating conditions.
8. Calculate the speed of sound, based on the results of the preceding steps.
9. Calculate the isentropic exponent, κ .

3.3. Compliance

To be compliant with this AGA Report, a computational solution by this or any other method must demonstrate agreement within 50 parts per million of the sound speeds given in Section 8.2, Table 6a (English units) or Table 6b (Metric units).

Other tables of computed values are given in Section 8 for computational checks but a compliance level is not specified.

3.4. Equations for Speed of Sound

The speed of sound is derived from thermodynamic relationships[1-9]. The relationships include the compressibility factor, density, ratio of specific heats, molar mass and the partial derivative of the compressibility factor with respect to the density at a constant temperature.

The basic speed of sound relation can be expressed as:

$$W = \left[\left(\frac{c_p}{c_v} \right) \left(\frac{RT}{M_r} \right) \left(Z + \rho \left(\frac{\partial Z}{\partial \rho} \right)_T \right) \right]^{0.5} \quad (3.1)$$

The isentropic exponent may be expressed in terms of its relationship to the speed of sound:

$$\kappa = W^2 \frac{M_r}{ZRT} \quad (3.2)$$

The quantities c_v and c_p are the constant volume and constant pressure heat capacities of the gas.

$$c_v = c_p^o - R \left\{ 1 + T \int_0^{\rho} \left[\frac{T}{\rho} \left(\frac{\partial^2 Z}{\partial T^2} \right)_{\rho} + \frac{2}{\rho} \left(\frac{\partial Z}{\partial T} \right)_{\rho} \right] d\rho \right\} \quad (3.3)$$

$$c_p = c_v + \left(\frac{T}{\rho^2} \right) \frac{\left[\left(\frac{\partial P}{\partial T} \right)_{\rho} \right]^2}{\left[\left(\frac{\partial P}{\partial \rho} \right)_T \right]} \quad (3.4a)$$

or, expressed in terms of compressibility:

$$c_p = c_v + R \frac{\left[Z + T \left(\frac{\partial Z}{\partial T} \right)_{\rho} \right]^2}{\left[Z + \rho \left(\frac{\partial Z}{\partial \rho} \right)_T \right]} \quad (3.4b)$$

Note that the ideal gas specific heat ratio, $\frac{c_p^o}{c_v^o}$, real gas specific heat ratio, $\frac{c_p}{c_v}$, and the isentropic

exponent, κ , are related but separate quantities. In certain gas industry applications, the ratio of ideal gas specific heats is assumed to be synonymous with the isentropic exponent.

The pure fluid constant pressure ideal gas heat capacity is computed as:

$$c_p^o = B + C \left[\frac{D/T}{\sinh(D/T)} \right]^2 + E \left[\frac{F/T}{\cosh(F/T)} \right]^2 + G \left[\frac{H/T}{\sinh(H/T)} \right]^2 + I \left[\frac{J/T}{\cosh(J/T)} \right]^2 \quad (3.5)$$

The pure fluid ideal gas enthalpy is computed as:

$$H^o = A + BT + CD \coth(D/T) - EF \tanh(F/T) + GH \coth(H/T) - IJ \tanh(J/T) \quad (3.6)$$

The real gas enthalpy is computed as:

$$H = H^o + RT \left[(Z-1) - \int_0^{\rho} \frac{T}{\rho} \left(\frac{\partial Z}{\partial T} \right) \partial \rho \right] \quad (3.7)$$

The pure fluid ideal gas entropy is computed as:

$$\begin{aligned} S^o = & K + B \ln(T) + C \left[(D/T) \coth(D/T) - \ln(\sinh(D/T)) \right] \\ & - E \left[(F/T) \tanh(F/T) - \ln(\cosh(F/T)) \right] \\ & + G \left[(H/T) \coth(H/T) - \ln(\sinh(H/T)) \right] \\ & - I \left[(J/T) \tanh(J/T) - \ln(\cosh(J/T)) \right] \end{aligned} \quad (3.8)$$

The entropy of mixing is computed as:

$$S_{\text{mixing}} = -R \sum_{i=1}^N X_i \ln(X_i) \quad (3.9)$$

The real gas entropy is computed as:

$$S = S^o + S_{\text{mixing}} - R \ln\left(\frac{P}{ZP^o}\right) - R \int_0^{\rho} \left(\frac{(Z-1)}{\rho} + \frac{T}{\rho} \left(\frac{\partial Z}{\partial T} \right) \right) \partial \rho \quad (3.10)$$

where $P^o = 0.101325 \text{ MPa}$

The coefficients for computing the ideal gas constant pressure heat capacity, enthalpy and entropy are given in Table 4. In this table, the unit of measure for energy is the thermochemical calorie ($1 \text{ cal}_{(\text{th})} = 4.184 \text{ J}$).

The basic equation for the compressibility factor, from AGA Report No. 8, is:

$$Z = 1 + \frac{DB}{K^3} - D \sum_{n=13}^{18} C_n^* T^{-u_n} + \sum_{n=13}^{58} C_n^* T^{-u_n} (b_n - c_n k_n D^{k_n}) D^{b_n} \exp(-c_n D^{k_n}) \quad (3.11)$$

where

$$B = \sum_{n=1}^{18} a_n T^{-u_n} \sum_{i=1}^N \sum_{j=1}^N x_i x_j E_{ij}^{u_n} (K_i K_j)^{\frac{3}{2}} B_{nij}^* \quad (3.12)$$

Component	A (cal/mol)	B (cal/mol-K)	C (cal/mol-K)	D (K)	E (cal/mol-K)	F (K)	G (cal/mol-K)	H (K)	I (cal/mol-K)	J (K)	K (cal/mol-K)
Methane	-29776.4	7.95454	43.9417	1037.09	1.56373	813.205	-24.9027	1019.98	-10.1601	1070.14	-20.0615
Nitrogen	-3495.34	6.95587	0.272892	662.738	-0.291318	-680.562	1.78980	1740.06	0	100	4.49823
Carbon Dioxide	20.7307	6.96237	2.68645	500.371	-2.56429	-530.443	3.91921	500.198	2.13290	2197.22	5.81381
Ethane	-37524.4	7.98139	24.3668	752.320	3.53990	272.846	8.44724	1020.13	-13.2732	869.510	-22.4010
Propane	-56072.1	8.14319	37.0629	735.402	9.38159	247.190	13.4556	1454.78	-11.7342	984.518	-24.0426
Water	-13773.1	7.97183	6.27078	2572.63	2.05010	1156.72	0	100	0	100	-3.24989
Hydrogen Sulfide	-10085.4	7.94680	-0.0838	433.801	2.85539	843.792	6.31595	1481.43	-2.88457	1102.23	-0.51551
Hydrogen	-5565.6	6.66789	2.33458	2584.98	0.749019	559.656	0	100	0	100	-7.94821
Carbon Monoxide	-2753.49	6.95854	2.02441	1541.22	0.096774	3674.81	0	100	0	100	6.23387
Oxygen	-3497.45	6.96302	2.40013	2522.05	2.21752	1154.15	0	100	0	100	9.19749
Isobutane	-72387	17.8143	58.2062	1787.39	40.7621	808.645	0	100	0	100	-44.1341
Normal Butane	-72674.8	18.6383	57.4178	1792.73	38.6599	814.151	0	100	0	100	-46.1938
Isopentane	-91505.5	21.3861	74.3410	1701.58	47.0587	775.899	0	100	0	100	-60.2474
Normal Pentane	-83845.2	22.5012	69.5789	1719.58	46.2164	802.174	0	100	0	100	-62.2197
Normal Hexane	-94982.5	26.6225	80.3819	1718.49	55.6598	802.069	0	100	0	100	-77.5366
Normal Heptane	-103353	30.4029	90.6941	1669.32	63.2028	786.001	0	100	0	100	-92.0164
Normal Octane	-109674	34.0847	100.253	1611.55	69.7675	768.847	0	100	0	100	-106.149
Normal Nonane	-122599	38.5014	111.446	1646.48	80.5015	781.588	0	100	0	100	-122.444
Normal Decane	-133564	42.7143	122.173	1654.85	90.2255	785.564	0	100	0	100	-138.006
Helium	0.0	4.968	0	100	0	100	0	100	0	100	1.8198
Argon	0.0	4.968	0	100	0	100	0	100	0	100	8.6776

Table 4: Calculation Coefficients for Heat Capacity, Enthalpy and Entropy

The first partial derivative of Z with respect to T is:

$$\left(\frac{\partial Z}{\partial T}\right)_d = \frac{D}{K^3} \left(\frac{\partial B}{\partial T}\right)_d + D \sum_{n=13}^{18} u_n C_n^* T^{-(u_n+1)} - \sum_{n=13}^{58} u_n C_n^* T^{-(u_n+1)} (b_n - c_n k_n D^{k_n}) D^{b_n} \exp(-c_n D^{k_n}) \quad (3.13)$$

where

$$\left(\frac{\partial B}{\partial T}\right)_d = - \sum_{n=1}^{18} u_n a_n T^{-(u_n+1)} \sum_{i=1}^N \sum_{j=1}^N x_i x_j E_{ij}^{u_n} (K_i K_j)^{\frac{3}{2}} B_{nij}^* \quad (3.14)$$

The second partial derivative of Z with respect to T is:

$$\left(\frac{\partial^2 Z}{\partial T^2}\right)_d = \frac{D}{K^3} \left(\frac{\partial^2 B}{\partial T^2}\right)_d - D \sum_{n=13}^{18} u_n (u_n + 1) C_n^* T^{-(u_n+2)} + \sum_{n=13}^{58} u_n (u_n + 1) C_n^* T^{-(u_n+2)} (b_n - c_n k_n D^{k_n}) D^{b_n} \exp(-c_n D^{k_n}) \quad (3.15)$$

where

$$\left(\frac{\partial^2 B}{\partial T^2}\right)_d = \sum_{n=1}^{18} u_n (u_n + 1) a_n T^{-(u_n+2)} \sum_{i=1}^N \sum_{j=1}^N x_i x_j E_{ij}^{u_n} (K_i K_j)^{\frac{3}{2}} B_{nij}^* \quad (3.16)$$

The first partial derivative of Z with respect to ρ is:

$$\left(\frac{\partial Z}{\partial \rho}\right)_T = K^3 \left\{ \left[\frac{B}{K^3} - \sum_{n=13}^{18} C_n^* T^{-u_n} \right] + \sum_{n=13}^{58} C_n^* T^{-u_n} (-c_n k_n^2 D^{(k_n-1)}) D^{b_n} \exp(-c_n D^{k_n}) + \sum_{n=13}^{58} C_n^* T^{-u_n} (b_n - c_n k_n D^{k_n}) b_n D^{(b_n-1)} \exp(-c_n D^{k_n}) - \sum_{n=13}^{58} C_n^* T^{-u_n} (b_n - c_n k_n D^{k_n}) D^{b_n} (c_n k_n D^{(k_n-1)}) \exp(-c_n D^{k_n}) \right\} \quad (3.17)$$

4. Critical Flow Factor Determination

The critical flow factor can be determined from an iterative procedure whereby the energy and entropy balances are solved around a converging nozzle with a throat velocity that is sonic.

Applying procedures listed in the appendix of ASME standard MFC-7M [5], thermodynamic changes are predicted for the acceleration of gas from the plenum to the throat of a critical flow nozzle. An assumption is made of one-dimensional flow, isentropic and adiabatic. The method may be implemented to account for non-zero gas velocity in the plenum.

5. Characteristics of Typical Gases

This section contains graphical representations (Figures 2 through 5) of thermodynamic properties relevant to this document. The graphs are intended as an aid to familiarity with concepts, not as a substitute for the equations given elsewhere in this report. Five different gas mixtures are explored in terms of speed of sound, critical flow coefficient and isentropic exponent. Each characteristic is mapped, as a function of pressure and/or temperature.

The gas mixtures in Table 5 match the examples given in AGA Report No. 8, Second Edition. The Amarillo, Gulf Coast, Ekofisk, High N₂ and High CO₂ mixtures represent a range of commercial quality natural gases found throughout the industry.

Component	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
Methane	96.5222	90.6724	85.9063	81.4410	81.2110
Nitrogen	0.2595	3.1284	1.0068	13.4650	5.7020
Carbon Dioxide	0.5956	0.4676	1.4954	0.9850	7.5850
Ethane	1.8186	4.5279	8.4919	3.3000	4.3030
Propane	0.4596	0.8280	2.3015	0.6050	0.8950
Isobutane	0.0977	0.1037	0.3486	0.1000	0.1510
Normal Butane	0.1007	0.1563	0.3506	0.1040	0.1520
Isopentane	0.0473	0.0321	0.0509	0.0000	0.0000
Normal Pentane	0.0324	0.0443	0.0480	0.0000	0.0000
Normal Hexane	0.0664	0.0393	0.000	0.0000	0.0000

Table 5: Composition of Typical Gases

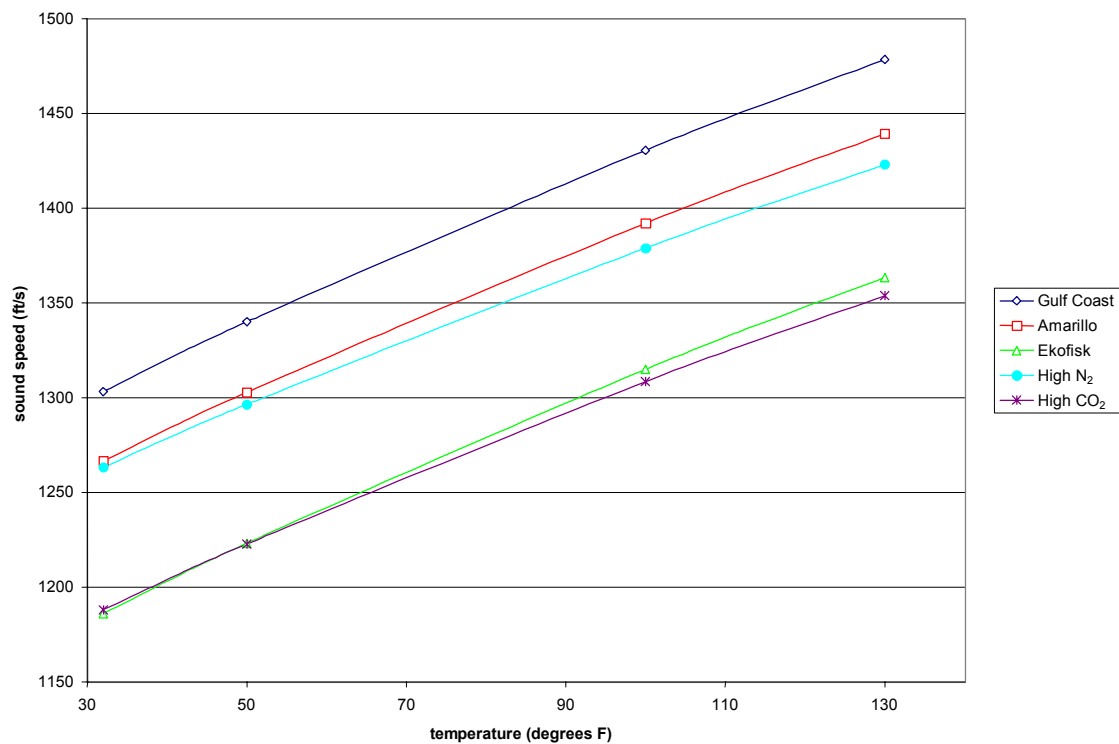


Figure 2a: Sound Speed at 1200 psia as a Function of Temperature

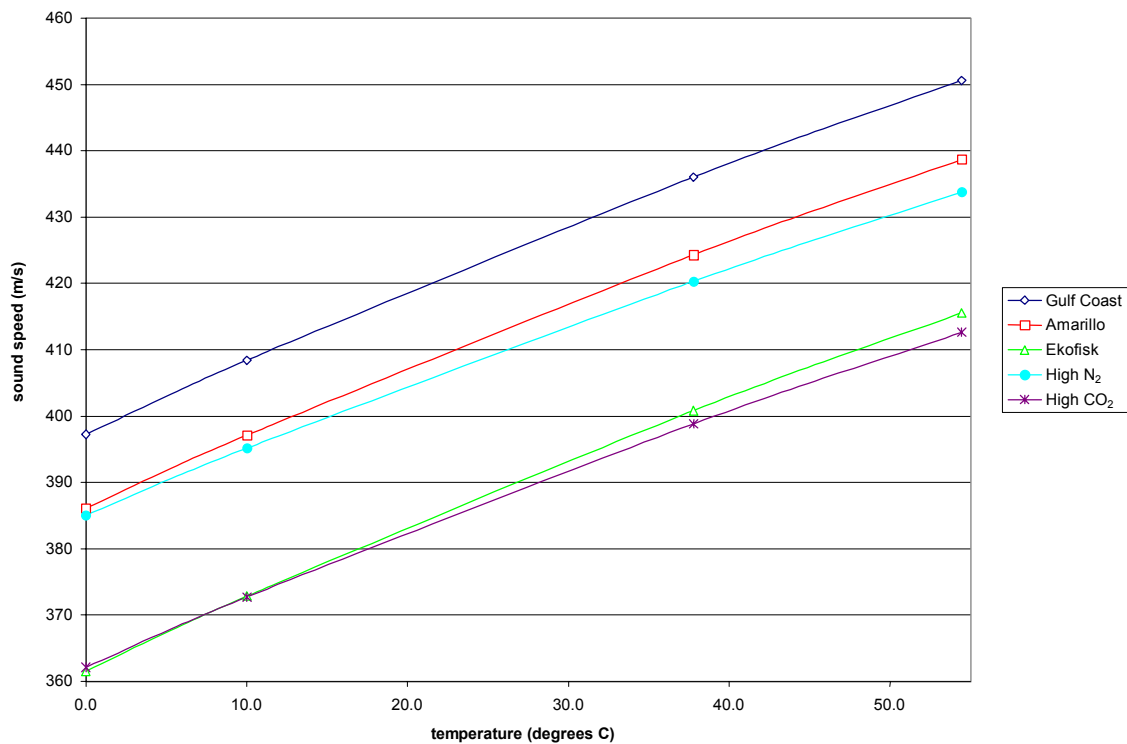


Figure 2b: Sound Speed at 8.27 MPa as a Function of Temperature

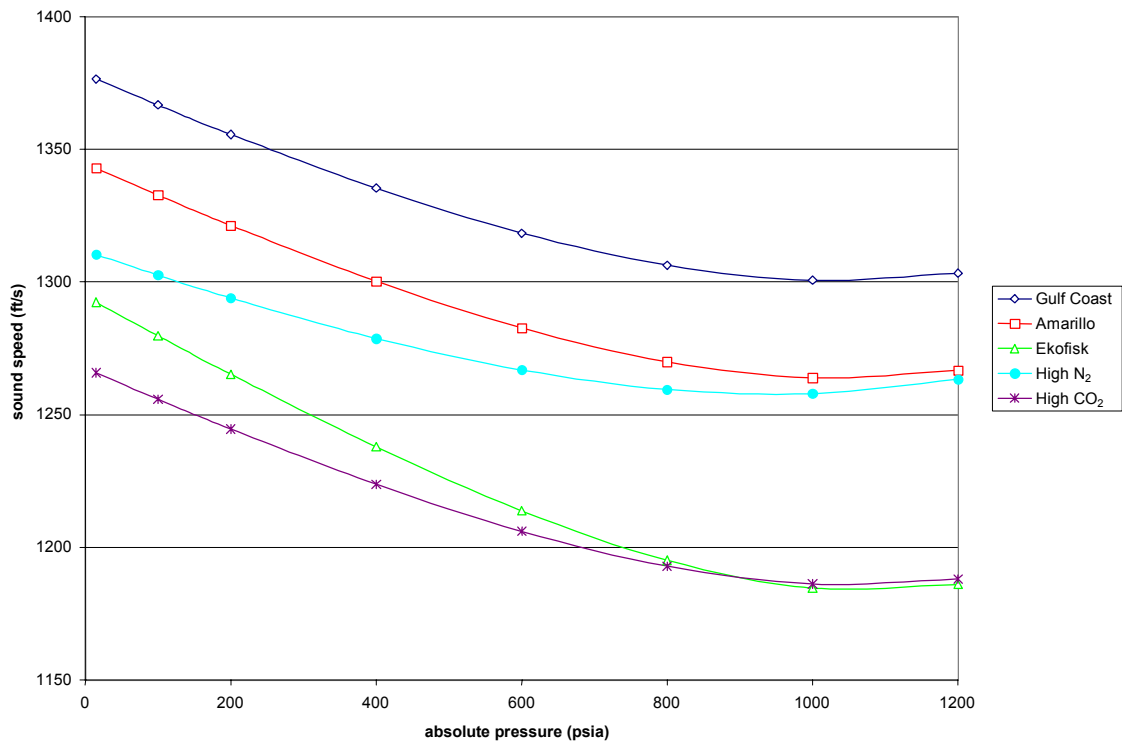


Figure 3a: Sound Speed at 32° F as a Function of Pressure

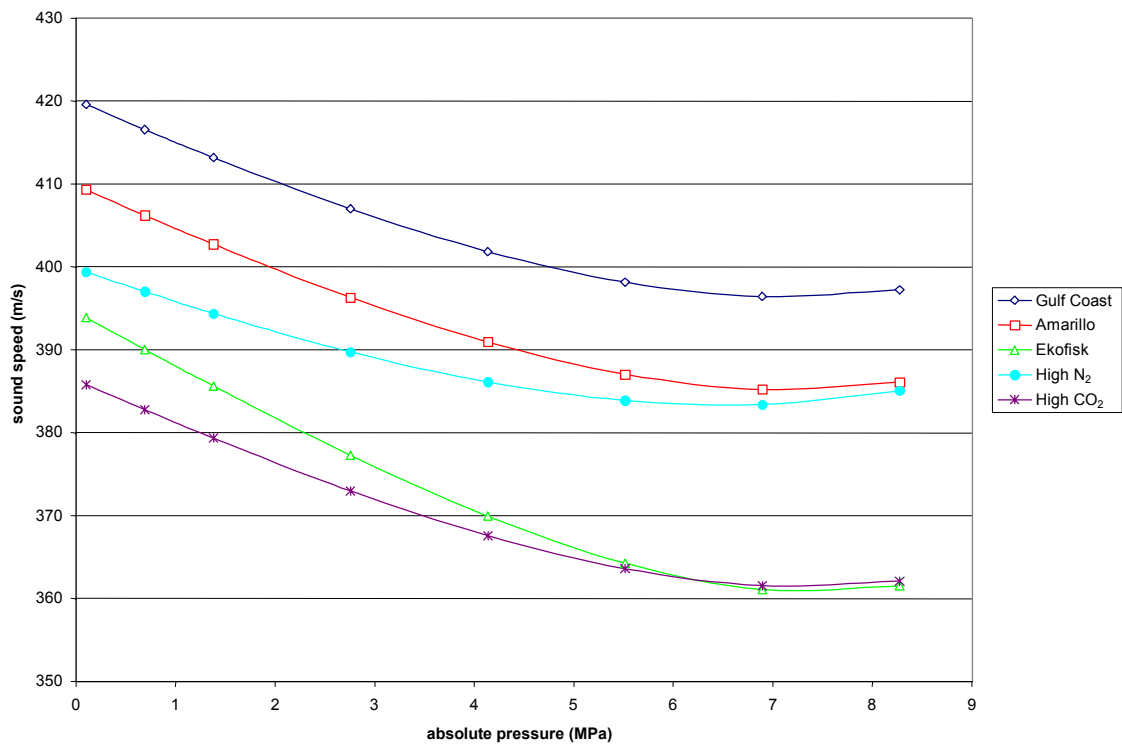


Figure 3b: Sound Speed at 0° C as a Function of Pressure

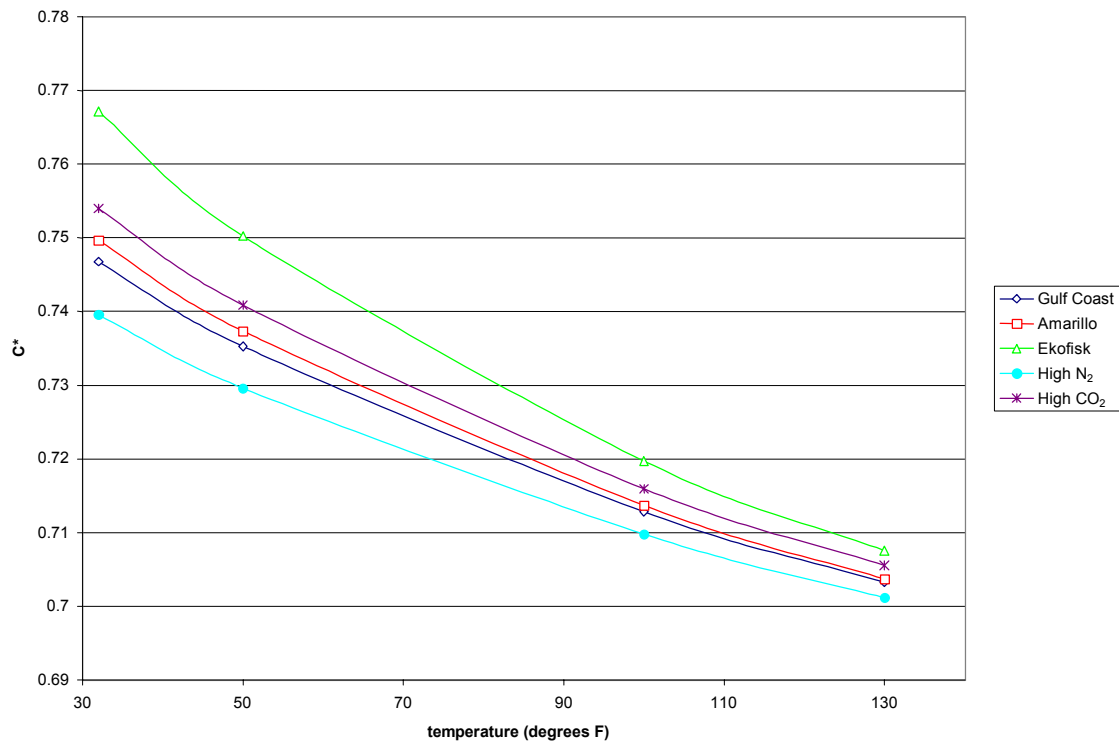


Figure 4a: Critical Flow Coefficient, C^* , at 1000 psia as a Function of Stagnation Temperature

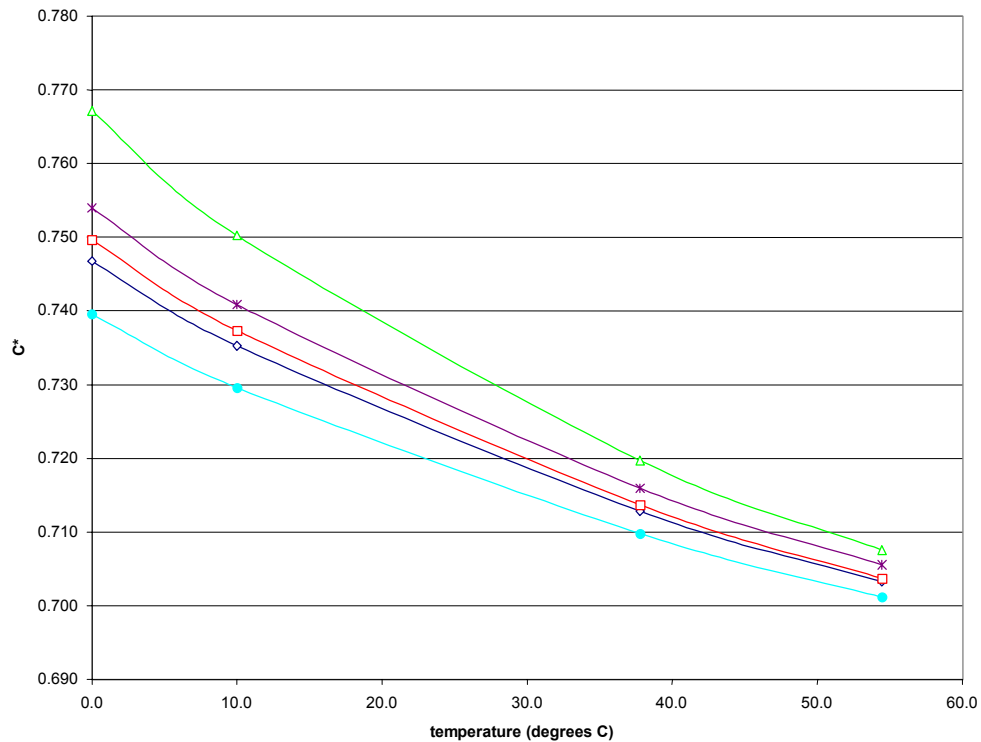


Figure 4b: Critical Flow Coefficient, C^* , at 6.9 MPa as a Function of Stagnation Temperature

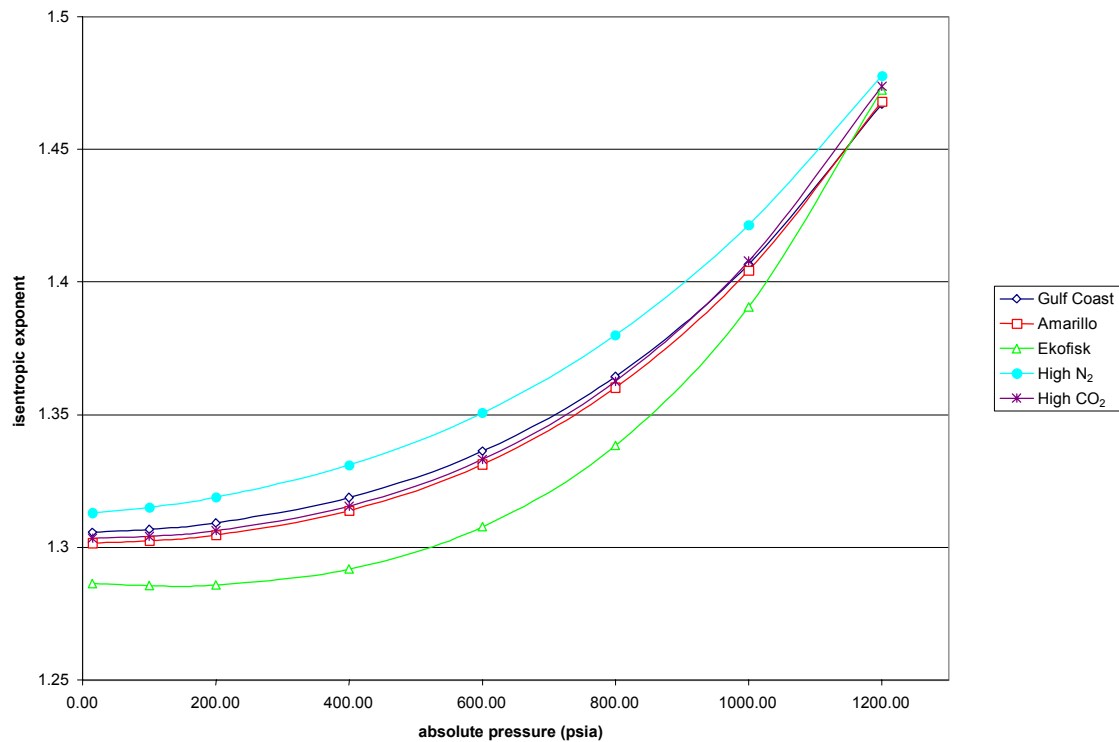


Figure 5a: Isentropic Exponent at 32° F as a Function of Pressure

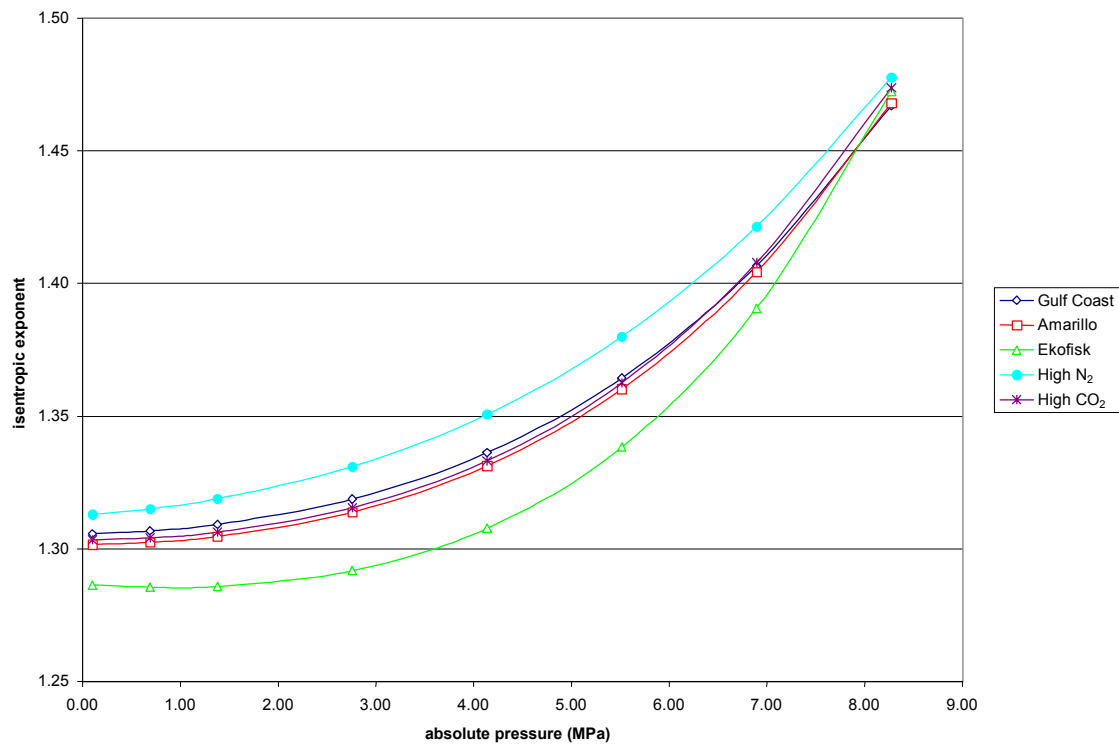


Figure 5b: Isentropic Exponent at 0° C as a Function of Pressure

6. References

- [1] K.E. Starling and J.L. Savidge, *Compressibility Factors of Natural Gas and Other Related Hydrocarbon Gases*, AGA Transmission Measurement Committee Report No. 8, Second Edition, Second Printing, July, 1994.
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- [10] B.N. Taylor, *Guide for the Use of the International System of Units (SI)*, NIST Special Publication No. 811, (Supersedes 1991 Edition), National Institute of Standards and Technology (NIST) (1995).
- [11] Canadian Standards Association, *Canadian Standards Association Metric Practice Guide, 2000: Z234.1-00*.

7. Computation Flow Charts

Extending the calculation process of AGA Report No. 8, the method for calculating speed of sound, enthalpy and entropy can be summarized as shown in Figure 6.

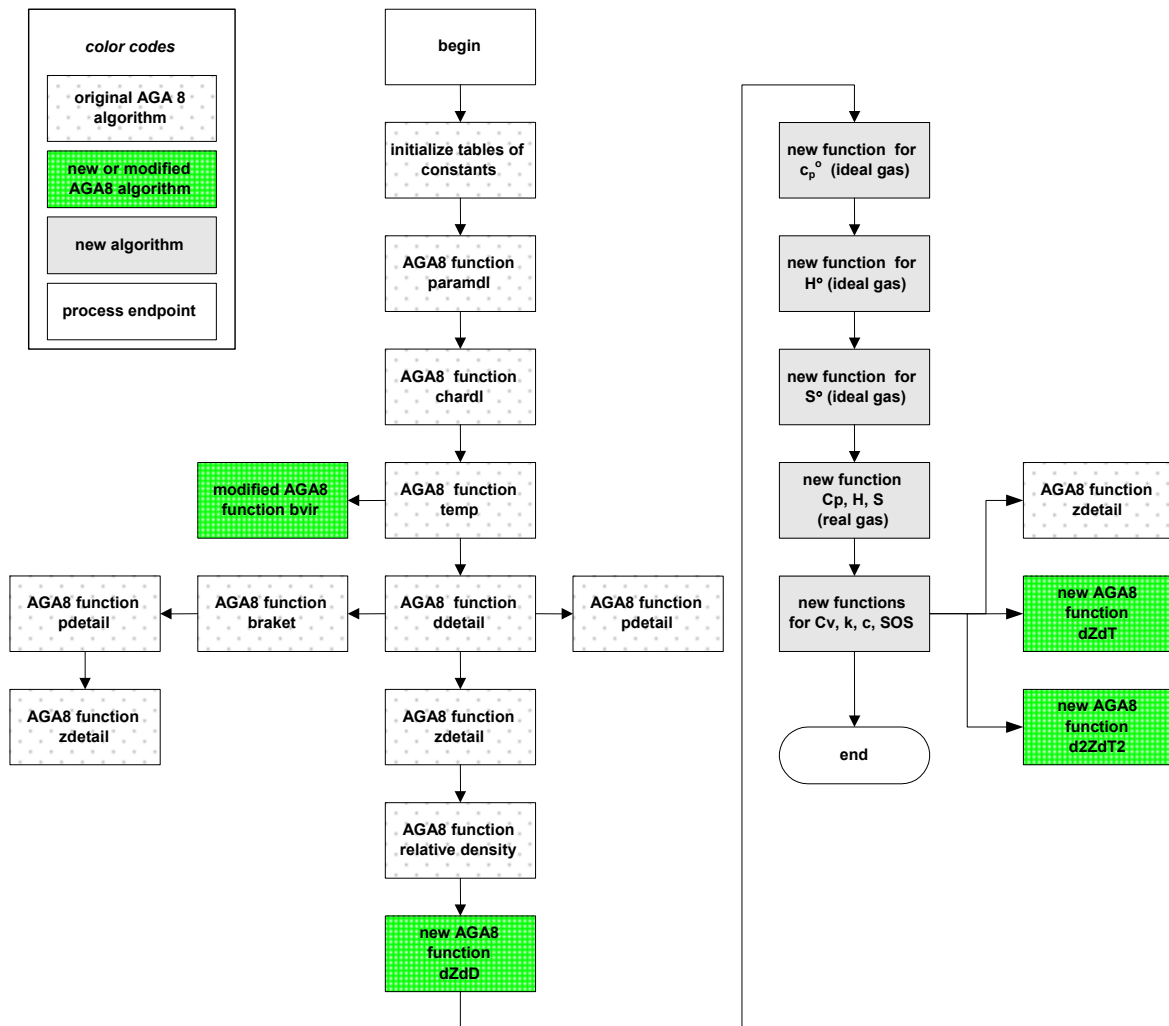


Figure 6: Flowchart of Sound Speed Calculation Procedure

The calculation sequence for the critical flow function, C^* , is an extension of the algorithms for sound speed, enthalpy and entropy, as shown in Figure 7.

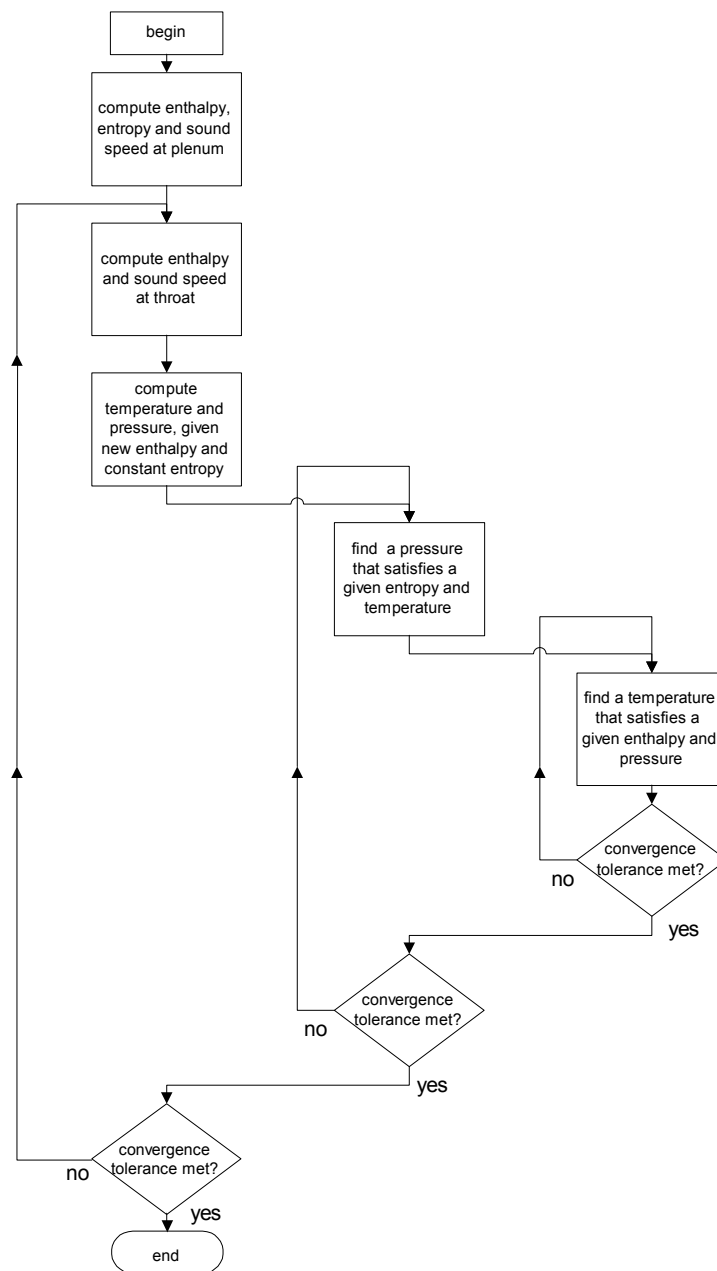


Figure 7: Diagram of Critical Flow Function Calculation

8. Calculation Output for Program Verification

8.1. Detailed Output Results for Program Development

The following three calculation scenarios provide detailed intermediate and output data for specific sets of input conditions. The purpose of this data set is to facilitate computer program development.

8.1.1. Detailed Output — Result #1

Input

Composition	:	Pure Methane
Pressure	:	8.000 MPa (1160.3019 psia)
Temperature	:	20.0° C (68.0° F)

Output

Molar Density	:	3.79174963 moles/dm ³
Molar Mass	:	16.0430000 kg/kg-mol
Compressibility Factor	:	0.865613011
$\partial Z / \partial T$	:	0.001370797803
$\partial^2 Z / \partial T^2$	:	-1.08884683127e-005
$\partial Z / \partial p$	:	-0.02602812374
$\partial B / \partial T$	:	0.000396764069
$\partial^2 B / \partial T^2$	:	-3.34719916156e-006
c_p^o (ideal gas)	:	2.21437395 kJ/kg-K
c_p (real gas)	:	2.86910318 kJ/kg-K
c_v (real gas)	:	1.78350108 kJ/kg-K
Isentropic exponent	:	1.42527799
Sound Speed	:	432.944437 m/s
Specific Enthalpy	:	528.977205 kJ/kg
Specific Entropy	:	9.09475139 kJ/kg-K
C*	:	0.732987437

8.1.2. Detailed Output — Result #2

Input

Composition	:	Amarillo
Pressure	:	4.000 MPa (580.15095 psia)
Temperature	:	10.0° C (50° F)

Output

Molar Density	:	1.87396178 moles/dm ³
Molar Mass	:	17.5955109 kg/kg-mol
Compressibility Factor	:	0.90666330
$\partial Z / \partial T$	:	0.00084934112
$\partial^2 Z / \partial T^2$	:	-7.3766250161e-6
$\partial Z / \partial p$	:	-0.0442939010
$\partial B / \partial T$	:	0.00047962844
$\partial^2 B / \partial T^2$	:	-4.2808097391e-006
c_p^0 (ideal gas)	:	2.06018714 kJ/kg-K
c_p (real gas)	:	2.40008811 kJ/kg-K
c_v (real gas)	:	1.64511520 kJ/kg-K
Isentropic exponent	:	1.32535394
Sound Speed	:	400.972536 m/s
Specific Enthalpy	:	499.296977 kJ/kg
Specific Entropy	:	9.02299618 kJ/kg-K
C*	:	0.704302274

8.1.3. Detailed Output — Result #3

Input

Composition: Hypothetical 21 Component Mixture

Methane	86.29
Nitrogen	2.0
Carbon Dioxide	0.50
Ethane	5.0
Propane	3.0
Water	0.01
Hydrogen Sulfide	0.1
Hydrogen	0.01
Carbon Monoxide	0.01
Oxygen	0.02
i-Butane	1.10
n-Butane	0.90
i-Pentane	0.35
n-Pentane	0.25
n-Hexane	0.20
n-Heptane	0.10
n-Octane	0.05
n-Nonane	0.02
n-Decane	0.01
Helium	0.04
Argon	0.04

Pressure : 6.000 MPa (870.2264 psia)
Temperature : 40.0° C (104.0° F)

Output

Molar Density : 2.62533592 moles/dm³
Molar Mass : 19.4780144 kg/kg-mol
Compressibility Factor : 0.877763047
 $\partial Z / \partial T$: 0.00110251388
 $\partial^2 Z / \partial T^2$: -8.7236464045e-006
 $\partial Z / \partial p$: -0.0375423163
 $\partial B / \partial T$: 0.0004594320
 $\partial^2 B / \partial T^2$: -3.776948019e-006
c_p^o (ideal gas) : 2.08298699 kJ/kg-K
c_p (real gas) : 2.55641833 kJ/kg-K
c_v (real gas) : 1.73699984 kJ/kg-K
Isentropic exponent : 1.30648621
Sound Speed : 391.528389 m/s
Specific Enthalpy : 508.00420 kJ/kg
Specific Entropy : 8.51434681 kJ/kg-K
C* : 0.710708883

8.2. Tabled Results for Compliance Checking and Program Development

The following tables (Tables 6a and 6b through Tables 12a and 12b) were generated with the algorithms described in this report. The numerical resolution provided is suitable for compliance checking but does not reflect the uncertainties inherent in the solution method itself.

The compliance criteria given in Section 3.2 of this document refer only to the results given in Tables 6a and 6b.

Temperature	Pressure	Speed of Sound (ft/s)				
°F	psia	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
32	14.73	1376.597	1342.938	1292.325	1310.350	1265.813
32	100	1366.745	1332.778	1279.700	1302.556	1255.856
32	200	1355.642	1321.304	1265.215	1293.922	1244.570
32	400	1335.321	1300.228	1237.817	1278.667	1223.691
32	600	1318.413	1282.605	1213.748	1266.847	1205.990
32	800	1306.276	1269.889	1195.063	1259.523	1192.885
32	1000	1300.594	1263.899	1184.617	1257.912	1186.169
32	1200	1303.310	1266.743	1186.056	1263.309	1187.957
50	14.73	1399.778	1365.493	1313.880	1332.486	1287.058
50	100	1391.213	1356.638	1302.733	1325.815	1278.371
50	200	1381.650	1346.728	1290.049	1318.509	1268.612
50	400	1364.443	1328.825	1266.410	1305.883	1250.851
50	600	1350.531	1314.261	1246.097	1296.509	1236.186
50	800	1340.972	1304.165	1230.700	1291.207	1225.721
50	1000	1337.006	1299.870	1222.250	1290.879	1220.765
50	1200	1339.995	1302.842	1223.155	1296.448	1222.771
100	14.73	1460.830	1424.940	1370.746	1390.875	1343.132
100	100	1455.126	1418.987	1362.902	1386.697	1337.269
100	200	1448.935	1412.505	1354.172	1382.301	1330.855
100	400	1438.390	1401.389	1338.541	1375.317	1319.748
100	600	1430.716	1393.186	1325.949	1371.076	1311.372
100	800	1426.462	1388.482	1317.221	1369.996	1306.299
100	1000	1426.212	1387.900	1313.273	1372.500	1305.135
100	1200	1430.551	1392.061	1315.055	1378.986	1308.491
130	14.73	1495.370	1458.605	1403.004	1423.961	1374.940
130	100	1490.996	1454.003	1396.704	1420.941	1370.392
130	200	1486.351	1449.093	1389.791	1417.877	1365.511
130	400	1478.794	1441.021	1377.738	1413.428	1357.384
130	600	1473.848	1435.600	1368.490	1411.448	1351.750
130	800	1471.893	1433.233	1362.617	1412.219	1349.001
130	1000	1473.315	1434.333	1360.724	1416.016	1349.538
130	1200	1478.487	1439.294	1363.406	1423.092	1353.747

Table 6a: Speed of Sound (W); English Units

Temperature	Pressure	Speed of Sound (m/s)				
° C	MPa	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
0	0.101560	419.5867	409.3274	393.9008	399.3948	385.8198
0	0.689476	416.5839	406.2307	390.0524	397.0190	382.7850
0	1.378951	413.1998	402.7334	385.6374	394.3874	379.3451
0	2.757903	407.0058	396.3094	377.2867	389.7378	372.9809
0	4.136854	401.8523	390.9379	369.9503	386.1351	367.5856
0	5.515806	398.1531	387.0622	364.2551	383.9027	363.5914
0	6.894757	396.4209	385.2363	361.0712	383.4116	361.5444
0	8.273709	397.2489	386.1033	361.5100	385.0567	362.0892
10	0.101560	426.6523	416.2024	400.4707	406.1417	392.2953
10	0.689476	424.0418	413.5034	397.0729	404.1083	389.6475
10	1.378951	421.1270	410.4828	393.2070	401.8816	386.6731
10	2.757903	415.8822	405.0260	386.0018	398.0332	381.2593
10	4.136854	411.6419	400.5867	379.8104	395.1759	376.7896
10	5.515806	408.7283	397.5095	375.1172	393.5599	373.5999
10	6.894757	407.5195	396.2005	372.5418	393.4601	372.0890
10	8.273709	408.4305	397.1062	372.8175	395.1572	372.7007
37.77778	0.101560	445.2610	434.3217	417.8034	423.9387	409.3866
37.77778	0.689476	443.5224	432.5074	415.4124	422.6653	407.5996
37.77778	1.378951	441.6354	430.5315	412.7517	421.3253	405.6445
37.77778	2.757903	438.4214	427.1435	407.9873	419.1965	402.2592
37.77778	4.136854	436.0821	424.6432	404.1493	417.9039	399.7063
37.77778	5.515806	434.7855	423.2094	401.4891	417.5749	398.1599
37.77778	6.894757	434.7095	423.0320	400.2857	418.3379	397.8052
37.77778	8.273709	436.0321	424.3002	400.8288	420.3148	398.8279
54.44444	0.101560	455.7889	444.5827	427.6358	434.0233	419.0817
54.44444	0.689476	454.4556	443.1802	425.7152	433.1027	417.6954
54.44444	1.378951	453.0398	441.6836	423.6082	432.1689	416.2077
54.44444	2.757903	450.7364	439.2233	419.9346	430.8128	413.7308
54.44444	4.136854	449.2290	437.5708	417.1157	430.2093	412.0134
54.44444	5.515806	448.6331	436.8495	415.3258	430.4443	411.1754
54.44444	6.894757	449.0665	437.1847	414.7486	431.6017	411.3391
54.44444	8.273709	450.6429	438.6969	415.5661	433.7584	412.6220

Table 6b: Speed of Sound (W); Metric Units

Temperature	Pressure	C*				
° F	psia	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
32	14.73	0.670417	0.669863	0.667375	0.671600	0.670255
32	100	0.675541	0.675065	0.673485	0.676352	0.675744
32	200	0.681844	0.681589	0.681097	0.682164	0.682419
32	400	0.695500	0.695774	0.697897	0.694621	0.697193
32	600	0.710734	0.711681	0.717468	0.708285	0.713849
32	800	0.727755	0.729555	0.740770	0.723243	0.732690
32	1000	0.746747	0.749611	0.767156	0.739544	0.753948
32	1200	0.767596	0.771751	0.798146	0.756775	0.777601
50	14.73	0.669873	0.669189	0.666598	0.670993	0.669556
50	100	0.674358	0.673917	0.672034	0.675235	0.674450
50	200	0.679953	0.679608	0.678754	0.680394	0.680355
50	400	0.691938	0.692034	0.693445	0.691341	0.693279
50	600	0.705083	0.705721	0.709959	0.703174	0.707576
50	800	0.719491	0.720788	0.729277	0.715923	0.723392
50	1000	0.735236	0.737325	0.750218	0.729588	0.740840
50	1200	0.751996	0.755020	0.774151	0.743905	0.759633
100	14.73	0.667905	0.667144	0.663869	0.669223	0.667476
100	100	0.671300	0.670641	0.668316	0.672365	0.671094
100	200	0.675397	0.674866	0.673183	0.676043	0.675470
100	400	0.683874	0.683630	0.683511	0.683878	0.684666
100	600	0.692961	0.693044	0.694685	0.692103	0.694475
100	800	0.702570	0.703021	0.706747	0.700698	0.704905
100	1000	0.712829	0.713688	0.719707	0.709787	0.715930
100	1200	0.723242	0.724557	0.733378	0.718835	0.727355
130	14.73	0.666606	0.665350	0.662451	0.667998	0.665680
130	100	0.669465	0.668756	0.665798	0.670639	0.669192
130	200	0.672895	0.672289	0.670296	0.673795	0.672851
130	400	0.680003	0.679624	0.678807	0.680297	0.680458
130	600	0.687336	0.687314	0.687851	0.686925	0.688452
130	800	0.695076	0.695346	0.697432	0.693870	0.696821
130	1000	0.703241	0.703692	0.707531	0.701146	0.705538
130	1200	0.711526	0.712298	0.718088	0.708427	0.714547

Table 7a: Critical Flow Coefficient (C*); English Units

Temperature	Pressure	C*				
° C	MPa	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
0	0.101560	0.670417	0.669863	0.667375	0.671600	0.670255
0	0.689476	0.675541	0.675065	0.673485	0.676352	0.675744
0	1.378951	0.681844	0.681589	0.681097	0.682164	0.682419
0	2.757903	0.695500	0.695774	0.697897	0.694621	0.697193
0	4.136854	0.710734	0.711681	0.717468	0.708285	0.713849
0	5.515806	0.727755	0.729555	0.740770	0.723243	0.732690
0	6.894757	0.746747	0.749611	0.767156	0.739544	0.753948
0	8.273709	0.767596	0.771751	0.798146	0.756775	0.777601
10	0.101560	0.669873	0.669189	0.666598	0.670993	0.669556
10	0.689476	0.674358	0.673917	0.672034	0.675235	0.674450
10	1.378951	0.679953	0.679608	0.678754	0.680394	0.680355
10	2.757903	0.691938	0.692034	0.693445	0.691341	0.693279
10	4.136854	0.705083	0.705721	0.709959	0.703174	0.707576
10	5.515806	0.719491	0.720788	0.729277	0.715923	0.723392
10	6.894757	0.735236	0.737325	0.750218	0.729588	0.740840
10	8.273709	0.751996	0.755020	0.774151	0.743905	0.759633
37.77778	0.101560	0.667905	0.667144	0.663869	0.669223	0.667476
37.77778	0.689476	0.671300	0.670641	0.668316	0.672365	0.671094
37.77778	1.378951	0.675397	0.674866	0.673183	0.676043	0.675470
37.77778	2.757903	0.683874	0.683630	0.683511	0.683878	0.684666
37.77778	4.136854	0.692961	0.693044	0.694685	0.692103	0.694475
37.77778	5.515806	0.702570	0.703021	0.706747	0.700698	0.704905
37.77778	6.894757	0.712829	0.713688	0.719707	0.709787	0.715930
37.77778	8.273709	0.723242	0.724557	0.733378	0.718835	0.727355
54.44444	0.101560	0.666606	0.665350	0.662451	0.667998	0.665680
54.44444	0.689476	0.669465	0.668756	0.665798	0.670639	0.669192
54.44444	1.378951	0.672895	0.672289	0.670296	0.673795	0.672851
54.44444	2.757903	0.680003	0.679624	0.678807	0.680297	0.680458
54.44444	4.136854	0.687336	0.687314	0.687851	0.686925	0.688452
54.44444	5.515806	0.695076	0.695346	0.697432	0.693870	0.696821
54.44444	6.894757	0.703241	0.703692	0.707531	0.701146	0.705538
54.44444	8.273709	0.711526	0.712298	0.718088	0.708427	0.714547

Table 7b: Critical Flow Coefficient (C*); Metric Units

Temperature	Pressure	Isentropic Exponent				
° F	psia	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
32	14.73	1.305655	1.301604	1.286355	1.312895	1.303308
32	100	1.306753	1.302437	1.285530	1.315093	1.304100
32	200	1.309207	1.304616	1.285824	1.318859	1.306240
32	400	1.318742	1.313783	1.291748	1.330968	1.315401
32	600	1.336248	1.331335	1.307683	1.350659	1.333142
32	800	1.364448	1.360274	1.338425	1.380034	1.362646
32	1000	1.406731	1.404366	1.390576	1.421522	1.407936
32	1200	1.467046	1.468004	1.472470	1.477732	1.473756
50	14.73	1.301927	1.297762	1.282196	1.309313	1.299415
50	100	1.303386	1.298975	1.281857	1.311802	1.300595
50	200	1.306168	1.301500	1.282621	1.315805	1.303089
50	400	1.315861	1.310837	1.288893	1.327887	1.312423
50	600	1.332420	1.327375	1.303641	1.346517	1.329108
50	800	1.357804	1.353264	1.330207	1.373215	1.355410
50	1000	1.394331	1.391058	1.372867	1.409667	1.394037
50	1200	1.444570	1.443593	1.436681	1.457613	1.448015
100	14.73	1.290446	1.286086	1.269898	1.298338	1.287777
100	100	1.292600	1.288045	1.270578	1.301364	1.289724
100	200	1.295972	1.291213	1.272307	1.305760	1.292886
100	400	1.305799	1.300745	1.279297	1.317578	1.302444
100	600	1.320395	1.315252	1.292024	1.333960	1.317060
100	800	1.340624	1.335680	1.311904	1.355575	1.337718
100	1000	1.367416	1.363040	1.340524	1.383107	1.365478
100	1200	1.401707	1.398353	1.379548	1.417209	1.401410
130	14.73	1.283014	1.278619	1.262233	1.291253	1.280429
130	100	1.285431	1.280867	1.263345	1.294468	1.282679
130	200	1.289002	1.284263	1.265466	1.298971	1.286084
130	400	1.298767	1.293772	1.272716	1.310547	1.295641
130	600	1.312465	1.307379	1.284661	1.325890	1.309355
130	800	1.330650	1.325687	1.302202	1.345425	1.327855
130	1000	1.353891	1.349315	1.326299	1.369567	1.351784
130	1200	1.382745	1.378866	1.357915	1.398701	1.381773

Table 8a: Isentropic Exponent (K); English Units

Temperature	Pressure	Isentropic Exponent				
° C	MPa	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
0	0.101560	1.305655	1.301604	1.286355	1.312895	1.303308
0	0.689476	1.306753	1.302437	1.285530	1.315093	1.304100
0	1.378951	1.309207	1.304616	1.285824	1.318859	1.306240
0	2.757903	1.318742	1.313783	1.291748	1.330968	1.315401
0	4.136854	1.336248	1.331335	1.307683	1.350659	1.333142
0	5.515806	1.364448	1.360274	1.338425	1.380034	1.362646
0	6.894757	1.406731	1.404366	1.390576	1.421522	1.407936
0	8.273709	1.467046	1.468004	1.472470	1.477732	1.473756
10	0.101560	1.301927	1.297762	1.282196	1.309313	1.299415
10	0.689476	1.303386	1.298975	1.281857	1.311802	1.300595
10	1.378951	1.306168	1.301500	1.282621	1.315805	1.303089
10	2.757903	1.315861	1.310837	1.288893	1.327887	1.312423
10	4.136854	1.332420	1.327375	1.303641	1.346517	1.329108
10	5.515806	1.357804	1.353264	1.330207	1.373215	1.355410
10	6.894757	1.394331	1.391058	1.372867	1.409667	1.394037
10	8.273709	1.444570	1.443593	1.436681	1.457613	1.448015
37.77778	0.101560	1.290446	1.286086	1.269898	1.298338	1.287777
37.77778	0.689476	1.292600	1.288045	1.270578	1.301364	1.289724
37.77778	1.378951	1.295972	1.291213	1.272307	1.305760	1.292886
37.77778	2.757903	1.305799	1.300745	1.279297	1.317578	1.302444
37.77778	4.136854	1.320395	1.315252	1.292024	1.333960	1.317060
37.77778	5.515806	1.340624	1.335680	1.311904	1.355575	1.337718
37.77778	6.894757	1.367416	1.363040	1.340524	1.383107	1.365478
37.77778	8.273709	1.401707	1.398353	1.379548	1.417209	1.401410
54.44444	0.101560	1.283014	1.278619	1.262233	1.291253	1.280429
54.44444	0.689476	1.285431	1.280867	1.263345	1.294468	1.282679
54.44444	1.378951	1.289002	1.284263	1.265466	1.298971	1.286084
54.44444	2.757903	1.298767	1.293772	1.272716	1.310547	1.295641
54.44444	4.136854	1.312465	1.307379	1.284661	1.325890	1.309355
54.44444	5.515806	1.330650	1.325687	1.302202	1.345425	1.327855
54.44444	6.894757	1.353891	1.349315	1.326299	1.369567	1.351784
54.44444	8.273709	1.382745	1.378866	1.357915	1.398701	1.381773

Table 8b: Isentropic Exponent (K); Metric Units

Temperature	Pressure	Heat Capacity (Btu/Lbm-F)				
° F	psia	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
32	14.73	0.506950	0.488994	0.477059	0.448710	0.432120
32	100	0.518114	0.500128	0.489423	0.458100	0.442493
32	200	0.532186	0.514205	0.505335	0.469826	0.455646
32	400	0.563920	0.546124	0.542691	0.495794	0.485648
32	600	0.601144	0.583864	0.589308	0.525400	0.521447
32	800	0.644486	0.628144	0.647377	0.558743	0.563887
32	1000	0.693897	0.678904	0.717702	0.595435	0.613040
32	1200	0.747987	0.734493	0.796947	0.634328	0.667301
50	14.73	0.511648	0.493747	0.482430	0.452580	0.436334
50	100	0.521749	0.503814	0.493600	0.461077	0.445689
50	200	0.534357	0.516412	0.507791	0.471596	0.457424
50	400	0.562282	0.544440	0.540281	0.494533	0.483658
50	600	0.594169	0.576644	0.579264	0.520103	0.514021
50	800	0.630235	0.613283	0.625738	0.548245	0.548845
50	1000	0.670243	0.654098	0.679782	0.578580	0.587951
50	1200	0.713203	0.697959	0.739439	0.610298	0.630260
100	14.73	0.526964	0.509059	0.499361	0.465094	0.449703
100	100	0.534780	0.516831	0.507931	0.471676	0.456882
100	200	0.544344	0.526357	0.518543	0.479681	0.465695
100	400	0.564789	0.546775	0.541706	0.496606	0.484641
100	600	0.586982	0.569016	0.567593	0.514686	0.505364
100	800	0.610810	0.592965	0.596203	0.533765	0.527779
100	1000	0.635996	0.618330	0.627234	0.553580	0.551626
100	1200	0.662074	0.644607	0.659951	0.573759	0.576432
130	14.73	0.537585	0.519568	0.510761	0.473714	0.458758
130	100	0.544378	0.526314	0.518166	0.479439	0.464972
130	200	0.552620	0.534509	0.527238	0.486349	0.472531
130	400	0.569986	0.551812	0.546667	0.500775	0.488524
130	600	0.588468	0.570272	0.567808	0.515928	0.505642
130	800	0.607928	0.589748	0.590549	0.531665	0.523762
130	1000	0.628141	0.610004	0.614615	0.547787	0.542670
130	1200	0.648786	0.630697	0.639530	0.564040	0.562046

Table 9a: Constant Pressure Heat Capacity (c_p); English Units

Temperature	Pressure	Heat Capacity (kJ/kg-K)				
° C	MPa	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
0	0.10156	2.12250	2.04732	1.99735	1.87866	1.80920
0	0.68948	2.16924	2.09394	2.04912	1.91797	1.85263
0	1.37895	2.22816	2.15287	2.11574	1.96707	1.90770
0	2.75790	2.36102	2.28651	2.27214	2.07579	2.03331
0	4.13685	2.51687	2.44452	2.46732	2.19974	2.18319
0	5.51581	2.69833	2.62991	2.71044	2.33935	2.36088
0	6.89476	2.90521	2.84243	3.00487	2.49297	2.56667
0	8.27371	3.13167	3.07517	3.33666	2.65581	2.79386
10	0.10156	2.14217	2.06722	2.01984	1.89486	1.82684
10	0.68948	2.18446	2.10937	2.06660	1.93044	1.86601
10	1.37895	2.23725	2.16212	2.12602	1.97448	1.91514
10	2.75790	2.35416	2.27946	2.26205	2.07051	2.02498
10	4.13685	2.48767	2.41429	2.42526	2.17757	2.15210
10	5.51581	2.63867	2.56769	2.61984	2.29539	2.29790
10	6.89476	2.80617	2.73858	2.84611	2.42240	2.46163
10	8.27371	2.98604	2.92222	3.09588	2.55520	2.63877
37.77778	0.10156	2.20629	2.13133	2.09073	1.94726	1.88282
37.77778	0.68948	2.23902	2.16387	2.12661	1.97481	1.91287
37.77778	1.37895	2.27906	2.20375	2.17104	2.00833	1.94977
37.77778	2.75790	2.36466	2.28924	2.26802	2.07919	2.02909
37.77778	4.13685	2.45758	2.38236	2.37640	2.15489	2.11586
37.77778	5.51581	2.55734	2.48262	2.49618	2.23477	2.20971
37.77778	6.89476	2.66279	2.58883	2.62610	2.31773	2.30955
37.77778	8.27371	2.77197	2.69884	2.76308	2.40221	2.41340
54.44444	0.10156	2.25076	2.17533	2.13845	1.98334	1.92073
54.44444	0.68948	2.27920	2.20357	2.16946	2.00732	1.94674
54.44444	1.37895	2.31371	2.23788	2.20744	2.03625	1.97839
54.44444	2.75790	2.38642	2.31033	2.28879	2.09665	2.04535
54.44444	4.13685	2.46380	2.38761	2.37730	2.16009	2.11702
54.44444	5.51581	2.54527	2.46916	2.47251	2.22598	2.19289
54.44444	6.89476	2.62990	2.55396	2.57327	2.29347	2.27205
54.44444	8.27371	2.71634	2.64060	2.67758	2.36152	2.35317

Table 9b: Constant Pressure Heat Capacity (c_p); Metric Units

Temperature	Pressure	Heat Capacity (Btu/Lbm-F)				
° F	psia	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
32	14.73	0.387265	0.374671	0.369665	0.340975	0.330630
32	100	0.389480	0.376927	0.372301	0.342837	0.332836
32	200	0.392083	0.379584	0.375442	0.345015	0.335446
32	400	0.397320	0.384949	0.381940	0.349356	0.340756
32	600	0.402606	0.390400	0.388807	0.353668	0.346213
32	800	0.407916	0.395913	0.396052	0.357921	0.351802
32	1000	0.413161	0.401382	0.403474	0.362048	0.357415
32	1200	0.418161	0.406590	0.410529	0.365939	0.362807
50	14.73	0.392092	0.379553	0.375178	0.344953	0.334963
50	100	0.394071	0.381570	0.377553	0.346614	0.336924
50	200	0.396389	0.383934	0.380363	0.348551	0.339230
50	400	0.401011	0.388666	0.386095	0.352385	0.343873
50	600	0.405612	0.393398	0.392009	0.356154	0.348560
50	800	0.410166	0.398106	0.398091	0.359831	0.353270
50	1000	0.414611	0.402719	0.404216	0.363370	0.357930
50	1200	0.418844	0.407113	0.410094	0.366705	0.362403
100	14.73	0.407690	0.395145	0.392419	0.357706	0.348592
100	100	0.409168	0.396646	0.394186	0.358944	0.350029
100	200	0.410885	0.398393	0.396254	0.360380	0.351705
100	400	0.414267	0.401835	0.400370	0.363195	0.355018
100	600	0.417562	0.405197	0.404454	0.365920	0.358268
100	800	0.420752	0.408458	0.408481	0.368537	0.361437
100	1000	0.423811	0.411588	0.412407	0.371029	0.364494
100	1200	0.426708	0.414554	0.416161	0.373373	0.367403
130	14.73	0.418440	0.405783	0.403959	0.366435	0.357766
130	100	0.419699	0.407059	0.405451	0.367490	0.358978
130	200	0.421160	0.408539	0.407189	0.368713	0.360386
130	400	0.424025	0.411444	0.410622	0.371104	0.363155
130	600	0.426802	0.414263	0.413987	0.373410	0.365849
130	800	0.429476	0.416979	0.417263	0.375619	0.368454
130	1000	0.432029	0.419574	0.420423	0.377718	0.370949
130	1200	0.434446	0.422028	0.423430	0.379695	0.373315

Table 10a: Constant Volume Heat Capacity (c_v); English Units

Temperature	Pressure	Heat Capacity (kJ/kg-K)				
° C	MPa	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
0	0.10156	1.62140	1.56867	1.54772	1.42760	1.38428
0	0.68948	1.63067	1.57812	1.55875	1.43539	1.39352
0	1.37895	1.64157	1.58924	1.57190	1.44451	1.40444
0	2.75790	1.66350	1.61171	1.59911	1.46268	1.42668
0	4.13685	1.68563	1.63453	1.62786	1.48074	1.44953
0	5.51581	1.70786	1.65761	1.65819	1.49854	1.47293
0	6.89476	1.72982	1.68050	1.68926	1.51582	1.49642
0	8.27371	1.75076	1.70231	1.71880	1.53212	1.51900
10	0.10156	1.64161	1.58911	1.57079	1.44425	1.40243
10	0.68948	1.64990	1.59756	1.58074	1.45120	1.41063
10	1.37895	1.65960	1.60746	1.59250	1.45931	1.42029
10	2.75790	1.67895	1.62727	1.61650	1.47537	1.43973
10	4.13685	1.69822	1.64708	1.64126	1.49115	1.45935
10	5.51581	1.71728	1.66679	1.66673	1.50654	1.47907
10	6.89476	1.73589	1.68611	1.69237	1.52136	1.49858
10	8.27371	1.75362	1.70450	1.71698	1.53532	1.51731
37.77778	0.10156	1.70692	1.65440	1.64298	1.49764	1.45948
37.77778	0.68948	1.71310	1.66068	1.65038	1.50283	1.46550
37.77778	1.37895	1.72029	1.66799	1.65904	1.50884	1.47252
37.77778	2.75790	1.73445	1.68240	1.67627	1.52062	1.48639
37.77778	4.13685	1.74825	1.69648	1.69337	1.53203	1.50000
37.77778	5.51581	1.76161	1.71013	1.71023	1.54299	1.51326
37.77778	6.89476	1.77441	1.72324	1.72667	1.55342	1.52606
37.77778	8.27371	1.78654	1.73566	1.74238	1.56324	1.53824
54.44444	0.10156	1.75193	1.69893	1.69130	1.53419	1.49790
54.44444	0.68948	1.75720	1.70427	1.69754	1.53861	1.50297
54.44444	1.37895	1.76331	1.71047	1.70482	1.54373	1.50886
54.44444	2.75790	1.77531	1.72264	1.71919	1.55374	1.52046
54.44444	4.13685	1.78693	1.73444	1.73328	1.56339	1.53174
54.44444	5.51581	1.79813	1.74581	1.74700	1.57264	1.54264
54.44444	6.89476	1.80882	1.75667	1.76023	1.58143	1.55309
54.44444	8.27371	1.81894	1.76695	1.77282	1.58971	1.56300

Table 10b: Constant Volume Heat Capacity (c_v); Metric Units

Temperature	Pressure	Specific Enthalpy (Btu/Lbm)				
° F	psia	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
32	14.73	235.100	224.943	214.460	208.312	197.589
32	100	232.112	221.980	211.209	205.820	194.867
32	200	228.542	218.437	207.298	202.855	191.610
32	400	221.187	211.127	199.136	196.788	184.873
32	600	213.549	203.517	190.486	190.553	177.837
32	800	205.649	195.628	181.334	184.182	170.514
32	1000	197.538	187.514	171.728	177.726	162.952
32	1200	189.316	179.284	161.838	171.266	155.254
50	14.73	244.267	233.787	223.095	216.423	205.405
50	100	241.470	231.014	220.055	214.092	202.860
50	200	238.139	227.711	216.415	211.327	199.826
50	400	231.321	220.940	208.879	205.699	193.594
50	600	224.303	213.957	200.996	199.960	187.151
50	800	217.113	206.792	192.779	194.139	180.520
50	1000	209.802	199.497	184.282	188.284	173.747
50	1200	202.448	192.156	175.629	182.455	166.911
100	14.73	270.219	258.845	247.628	239.354	227.546
100	100	267.866	256.515	245.078	237.398	225.411
100	200	265.085	253.759	242.051	235.091	222.886
100	400	259.460	248.183	235.887	230.448	217.768
100	600	253.770	242.537	229.589	225.782	212.577
100	800	248.043	236.849	223.188	221.118	207.338
100	1000	242.313	231.156	216.730	216.485	202.086
100	1200	236.626	225.506	210.277	211.917	196.864
130	14.73	286.185	274.272	262.777	253.435	241.171
130	100	284.050	272.159	260.467	251.662	239.237
130	200	281.535	269.669	257.735	249.579	236.956
130	400	276.476	264.656	252.206	245.404	232.360
130	600	271.393	259.617	246.610	241.235	227.734
130	800	266.311	254.577	240.974	237.090	223.100
130	1000	261.259	249.564	235.335	232.993	218.484
130	1200	256.267	244.613	229.737	228.968	213.919

Table 11a: Specific Enthalpy (H); English Units

Temperature	Pressure	Specific Enthalpy (kJ/kg)				
° C	MPa	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
0	0.101560	546.844	523.217	498.833	484.533	459.592
0	0.689476	539.892	516.325	491.272	478.738	453.262
0	1.378951	531.588	508.084	482.175	471.841	445.684
0	2.757903	514.481	491.081	463.189	457.729	430.014
0	4.136854	496.716	473.381	443.069	443.227	413.648
0	5.515806	478.339	455.030	421.782	428.407	396.615
0	6.894757	459.473	436.157	399.440	413.391	379.027
0	8.273709	440.350	417.015	376.436	398.364	361.122
10	0.101560	568.165	543.788	518.918	503.399	477.771
10	0.689476	561.658	537.339	511.849	497.978	471.853
10	1.378951	553.912	529.657	503.381	491.546	464.795
10	2.757903	538.051	513.906	485.854	478.456	450.300
10	4.136854	521.728	497.665	467.518	465.106	435.314
10	5.515806	505.006	480.999	448.404	451.568	419.889
10	6.894757	488.000	464.030	428.640	437.948	404.135
10	8.273709	470.894	446.955	408.514	424.391	388.235
37.77778	0.101560	628.530	602.072	575.982	556.738	529.272
37.77778	0.689476	623.056	596.653	570.051	552.187	524.307
37.77778	1.378951	616.587	590.244	563.012	546.822	518.432
37.77778	2.757903	603.503	577.273	548.672	536.022	506.527
37.77778	4.136854	590.269	564.140	534.024	525.169	494.453
37.77778	5.515806	576.947	550.910	519.136	514.319	482.269
37.77778	6.894757	563.621	537.670	504.114	503.543	470.053
37.77778	8.273709	550.392	524.527	489.105	492.919	457.906
54.44444	0.101560	665.666	637.956	611.220	589.489	560.964
54.44444	0.689476	660.701	633.042	605.845	585.366	556.465
54.44444	1.378951	654.851	627.249	599.490	580.520	551.160
54.44444	2.757903	643.082	615.590	586.631	570.810	540.470
54.44444	4.136854	631.261	603.870	573.614	561.111	529.709
54.44444	5.515806	619.440	592.146	560.505	551.471	518.930
54.44444	6.894757	607.687	580.487	547.388	541.941	508.195
54.44444	8.273709	596.077	568.970	534.369	532.579	497.576

Table 11b: Specific Enthalpy (H); Metric Units

Temperature	Pressure	Specific Entropy (Btu/Lbm-F)				
° F	psia	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
32	14.73	2.65254	2.57924	2.47804	2.45345	2.34134
32	100	2.42183	2.35881	2.27075	2.24586	2.14561
32	200	2.33472	2.27545	2.19178	2.16770	2.07147
32	400	2.24200	2.18651	2.10654	2.08491	1.99218
32	600	2.18272	2.12944	2.05079	2.03239	1.94110
32	800	2.13682	2.08507	2.00651	1.99209	1.90123
32	1000	2.09807	2.04751	1.96814	1.95845	1.86732
32	1200	2.06387	2.01424	1.93348	1.92906	1.83717
50	14.73	2.67085	2.59691	2.49529	2.46965	2.35695
50	100	2.44052	2.37686	2.28842	2.26239	2.16157
50	200	2.35389	2.29398	2.20999	2.18463	2.08788
50	400	2.26225	2.20611	2.12601	2.10271	2.00960
50	600	2.20420	2.15029	2.07179	2.05118	1.95971
50	800	2.15972	2.10738	2.02938	2.01198	1.92122
50	1000	2.12258	2.07144	1.99323	1.97954	1.88888
50	1200	2.09010	2.03996	1.96103	1.95142	1.86045
100	14.73	2.71941	2.64379	2.54119	2.51257	2.39838
100	100	2.48992	2.42458	2.33524	2.30600	2.20377
100	200	2.40431	2.34272	2.25797	2.22910	2.13104
100	400	2.31491	2.25710	2.17655	2.14903	2.05484
100	600	2.25936	2.20379	2.12531	2.09951	2.00730
100	800	2.21762	2.16365	2.08632	2.06249	1.97143
100	1000	2.18345	2.13073	2.05400	2.03234	1.94195
100	1200	2.15411	2.10242	2.02594	2.00659	1.91656
130	14.73	2.74720	2.67064	2.56756	2.53707	2.42209
130	100	2.51808	2.45181	2.36202	2.33083	2.22783
130	200	2.43295	2.37041	2.28526	2.25431	2.15552
130	400	2.34453	2.28577	2.20496	2.17506	2.08024
130	600	2.29004	2.23352	2.15494	2.12641	2.03368
130	800	2.24942	2.19451	2.11727	2.09029	1.99887
130	1000	2.21643	2.16277	2.08638	2.06107	1.97050
130	1200	2.18830	2.13568	2.05981	2.03627	1.94624

Table 12a: Specific Entropy (S); English Units

Temperature	Pressure	Specific Entropy (kJ/kg-K)				
° C	MPa	Gulf Coast	Amarillo	Ekofisk	High N ₂	High CO ₂
0	0.10156	11.10565	10.79876	10.37505	10.27211	9.80271
0	0.68948	10.13971	9.87588	9.50716	9.40298	8.98322
0	1.37895	9.77499	9.52686	9.17655	9.07574	8.67282
0	2.75790	9.38682	9.15449	8.81967	8.72910	8.34085
0	4.13685	9.13863	8.91553	8.58626	8.50920	8.12699
0	5.51581	8.94642	8.72979	8.40087	8.34049	7.96008
0	6.89476	8.78422	8.57249	8.24023	8.19962	7.81809
0	8.27371	8.64101	8.43324	8.09508	8.07660	7.69184
10	0.10156	11.18231	10.87272	10.44727	10.33995	9.86807
10	0.68948	10.21797	9.95144	9.58115	9.47216	9.05007
10	1.37895	9.85526	9.60442	9.25280	9.14659	8.74154
10	2.75790	9.47157	9.23656	8.90116	8.80362	8.41379
10	4.13685	9.22856	9.00284	8.67417	8.58786	8.20490
10	5.51581	9.04231	8.82317	8.49660	8.42377	8.04377
10	6.89476	8.88680	8.67272	8.34524	8.28793	7.90838
10	8.27371	8.75084	8.54090	8.21044	8.17019	7.78935
37.77778	0.10156	11.38563	11.06904	10.63946	10.51961	10.04154
37.77778	0.68948	10.42478	10.15122	9.77719	9.65476	9.22675
37.77778	1.37895	10.06638	9.80851	9.45366	9.33279	8.92222
37.77778	2.75790	9.69207	9.45004	9.11279	8.99756	8.60322
37.77778	4.13685	9.45950	9.22682	8.89826	8.79023	8.40417
37.77778	5.51581	9.28474	9.05876	8.73499	8.63523	8.25399
37.77778	6.89476	9.14167	8.92092	8.59967	8.50899	8.13057
37.77778	8.27371	9.01883	8.80241	8.48219	8.40117	8.02423
54.44444	0.10156	11.50197	11.18145	10.74985	10.62220	10.14082
54.44444	0.68948	10.54271	10.26522	9.88932	9.75870	9.32750
54.44444	1.37895	10.18625	9.92444	9.56794	9.43836	9.02475
54.44444	2.75790	9.81607	9.57008	9.23171	9.10654	8.70955
54.44444	4.13685	9.58792	9.35129	9.02230	8.90284	8.51462
54.44444	5.51581	9.41787	9.18795	8.86460	8.75162	8.36885
54.44444	6.89476	9.27973	9.05508	8.73526	8.62930	8.25007
54.44444	8.27371	9.16197	8.94166	8.62402	8.52544	8.14853

Table 12b: Specific Entropy (S); Metric Units

APPENDIX — C++ Language Example Implementation

A1. Overview of Computer Code

Two groups of computer code are included in Appendix A.

The first group of computer files demonstrates a C++ implementation of the AGA speed of sound calculation method. The primary goals of this implementation are clarity and compatibility with AGA Report No. 8. Consideration has also been given to secondary objectives of speed and efficiency.

The second group of files may be used to create a Windows-based example application for testing or demonstrating.

A1.1. File Group 1 — Calculation Library

File Group 1 is limited to mathematical calculations. User interface is not provided at this level but, recognizing the large community of Windows developers, support has been included for the creation of a Win32 DLL (dynamic link library).

The C++ implementation in this report is derived from an implementation in the FORTRAN programming language, as it appeared in the 1994 printing of AGA Report No. 8. Much of the original program structure and nomenclature was preserved for traceability and ease of conversion. Differences exist due to the syntax and grammar associated with each programming language but the code is not strongly idiomatic to the C++ language. Conversion to ANSI C or other computer languages is feasible.

Files included in Group 1 are:

- aga10.h header file for AGA 10 data structures, macros and prototypes
- aga10.cpp c++ source code for overall execution control
- detail.h header file for “detail” class
- detail.cpp “detail” class implementation
- therm.h header file for “therm” class
- therm.cpp “therm” class implementation
- entry.cpp Windows DLL entry code
- script1.rc Windows resource script; version information

As implemented, external processes communicate with the library through a single function call. The calling function supplies a pointer argument to a custom structure (defined in aga10.h) containing input as well as output data.

A1.1.1. Overview of Classes and Key Functions

In the C++ programming language, data and functions are typically grouped in structures called classes. Two classes were created for this implementation. The Detail class is responsible for

density-related computations. The **Therm** class is designed for additional thermodynamic calculations, including speed of sound.

The **Detail** and **Therm** classes are designed for efficient repeated operation. Any number of calculations can be executed between the creation and deletion of these objects.

A1.1.2. Detail Class

The **Detail** class contains all the data and methods required to compute gas compressibility and density-related parameters.

Those familiar with AGA Report No. 8 will note strong resemblance between this code and the original FORTRAN “Detail Characterization Method.” Several important design features were carried over to the C++ version, including the density search procedure.

Extending the original functionality, the **Detail** class contains the new functions for solving the partial derivatives of Z and the second virial coefficient, B .

A1.1.3. Therm Class

The **Therm** class contains data and functions for calculating heat capacity, enthalpy, entropy and the speed of sound.

In typical calculations involving the speed of sound, the user provides the process pressure, temperature and gas composition. For other calculations, such as those for critical flow nozzles, the **Therm** class supports a method of estimating pressure and temperature from enthalpy and entropy.

In the course of its execution, the **Therm** class calls on the **Detail** class to perform density-related work.

A1.1.4. Function SOS()

Function, **SOS()** is responsible for basic execution and memory management. It creates an object of each required class, launches calculations supported by the classes and then removes the objects from memory.

A1.1.5. Function Crit()

Function **Crit()** provides the same basic services of **SOS()**, but also estimates the critical flow function, C^* , an important parameter for critical flow calculations.

Crit() relies on support function **HS_Mode()** to predict gas pressure and temperature from enthalpy and entropy. **HS_Mode()** uses a nested algorithm and Newton’s Method to converge upon pressures and temperatures that satisfy given enthalpy and entropy states.

Crit() imposes a significantly larger computing burden than **SOS()** and is recommended only for situations where C^* is required.

As implented in this Appendix, function Crit() will accept gas velocity at the plenum as an optional input. The gas velocity is used to refine the estimate of enthalpy at the plenum.

A1.2. File Group 2 — Example Windows Application

The second set of code examples is intended as an example of applying a calculation DLL in an application with a graphical user interface.

A simple Win32 application can be created with this code. The application requires basic Win32 support, supported widely by vendors of software development systems. This implementation was created with Microsoft Visual C++, version 6 (SP5).

The interface consists of one non-modal dialog box and basic file operations, tested under the following Windows operating systems: Windows 95, 98, NT 4.0 (SP6), Windows XP.

Through a conventional dialog-based interface, the user may:

- collect user-defined inputs (keyed directly or loaded from file)
- request a calculation to be performed
- observe and/or save the calculation output

File operations consist of reading and writing AGA10STRUCT structures in binary format. Standard Windows and C++ run-time library process are used for file access.

The application interacts with aga10.dll in the following ways:

- initialization via DLL function AGA10_Init()
- de-initialization via DLL function AGA10_UnInit()
- creation of an AGA10STRUCT structure for exchanging data
- launching calculations by calling DLL function Crit() or SOS()

The files included in this group are:

- aga10win.h header file for application
- aga10win.cpp main source code for Windows application
- dlghlp.cpp utility functions supporting dialog box operations
- file.cpp functions supporting file input/output
- ga10win.rc Windows resource template

A2 Printouts of Computer Code

A2.1 File Group 1 — Calculation Code

The code begins on the following page.

```
*****
* File:          aga10.h
* Description:    function prototypes and defines for aga10.cpp
* Version:       ver 1.7      2002.11.17
* Author:        W.B. Peterson
* Revisions:
* Copyright (c) 2002  American Gas Association
*****/
```

```
#ifndef _AGA10_H
#define _AGA10_H

/* Windows-specific export macro and header #include */
#if WIN32
    #define DllExport __declspec (dllexport)
    #include <windows.h>
#else
    #define DllExport
#endif

/* other includes */
#include <strstream>
#include <iostream>
#include <fstream>
#include <iomanip>
#include <math.h>

/*      status codes */
#define NORMAL                9000
#define AGA10_INITIALIZED     9001
#define MEMORY_ALLOCATION_ERROR 9002
#define GENERAL_CALCULATION_FAILURE 9003
#define MAX_NUM_OF_ITERATIONS_EXCEEDED 9004
#define NEGATIVE_DENSITY_DERIVATIVE 9005
#define MAX_DENSITY_IN_BRACKET_EXCEEDED 9006

/*      number of components */
#define NUMBEROFCOMPONENTS    21

/*      maximum number of tries within search routines */
#define MAX_NUM_OF_ITERATIONS 100
```

```

/*    default tolerance limits */
#define P_CHG_TOL 0.001 /* 0.001 Pa */
#define T_CHG_TOL 0.001 /* 0.001 of a Kelvin */

/*    maximum allowable P & T */
const double P_MAX      =    1.379e8 ;    // maximum pressure (Pa) ~= 20,000 psi
const double P_MIN      =    0.0 ;        // maximum pressure = 0
const double T_MAX      =    473.15 ;     // maximum temperature (K) ~= 392 F
const double T_MIN      =    143.0 ;      // maximum temperature (K) ~= -200 F

/*    universal gas constant, in two configurations */
#define RGASKJ           8.314510e-3 /* in kJ mol^-1 K^-1 */
#define RGAS             8.314510    /* in J mol^-1 K^-1 */

/*    the main data structure used by this library */
typedef struct tagAGA10STRUCT
{
    /* corresponds to the control group in meter classes */
    long lStatus ;                /* calculation status */
    bool bForceUpdate ;           /* signal to perform full calculation */
    double adMixture[NUMBEROFCOMPONENTS] ; /* Composition in mole fraction */
    double dPb ;                  /* Contract base Pressure (Pa) */
    double dTb ;                  /* Contract base temperature (K) */
    double dPf ;                  /* Absolute Pressure (Pa) */
    double dTf ;                  /* Flowing temperature (K) */
    // basic output from AGA 8 Detail method
    double dMrx ;                 /* mixture molar mass */
    double dZb ;                  /* compressibility at contract base condition */
    double dZf ;                  /* compressibility at flowing condition */
    double dFpv ;                 /* supercompressibility */
    double dDb ;                  /* molar density at contract base conditions (moles/dm3) */
    double dDf ;                  /* molar density at flowing conditions (moles/dm3) */
    double dRhob ;                /* mass density at contract base conditions (kg/m3) */
    double dRhof ;                /* mass density at flowing conditions (kg/m3) */
    double dRD_Ideal ;            /* ideal gas relative density */
    double dRD_Real ;             /* real gas relative density */
    // additional output
    double dHo ;                  /* ideal gas specific enthalpy */
    double dH ;                   /* real gas specific enthalpy (J/kg) */
    double dS ;                   /* real gas specific entropy (J/kg-mol.K) */
}
    
```