

Errors Arising from the Use of AGA8 Outside its Valid Range

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1 INTRODUCTION

For custody-transfer standard flow measurement of dry, processed gaseous hydrocarbons in the UK sector of the North Sea, DECC's 'Guidance Notes for Petroleum Measurement' specify that the flow rate measurements may be in either volumetric or mass units [1]. They also stipulate that where volume is the agreed measurement unit, it should be referred to the standard reference conditions of 15 °C temperature and 1.01325 bar absolute pressure. This requires determination of the gas density at the flow meter.

The AGA8 method [2] is widely used for the calculation of thermodynamic properties of natural gas mixtures, allowing determination of properties from measurement of gas composition. In particular, it is used for the calculation of the density and compressibility of gas produced from the North Sea and forms an integral part of the measurement infrastructure, being programmed into flow computers and written in to many gas sales agreements.

Gas compositions from North Sea fields may or may not lie within the pipeline quality gas specifications required to obtain the 0.1% uncertainty with the AGA8 method. This can pose particular problems where new wells are tied to existing pipelines, making it difficult to determine the uncertainty of the density and hence the quantity of gas being produced, with implications for allocation between operators, and tax liabilities.

For a typical gas metering system the actual volume flow measurement is likely to use:-

- orifice plate
- ultrasonic flow meter
- turbine meter

In each of these cases the other measurements will be:-

- temperature (T)
- pressure (P)
- density (ρ), or gas composition (mole%) which is then used to calculate density

The overall system uncertainty is a function of the uncertainties of the individual measurement devices making up that system. Pressure, temperature, differential pressure, flow measurement and mole% uncertainties can be (reasonably) confidently assessed.

Gas density is a much more interesting problem and this paper addresses some of the questions surrounding density determination using AGA8 and discusses a potential solution as well as some of the limitations of that solution.

2 MEASURED OR CALCULATED DENSITY

Gas density can be *measured*, or it can be *calculated* from knowledge of the gas characteristics.

- *Measurement* normally uses a Transducer such as the Micromotion 7812 (previously Solartron) density transducer. The DECC Guidelines [1] give details on the advantages, and disadvantages of measurement and it is not considered further here.
- *Calculation* uses a chromatograph to evaluate the percentage of each of the various gases that go to make up the flowing gas.

Density can then be calculated from the gas composition, the flowing pressure and the flowing temperature.

3 CALCULATING DENSITY

Basic schoolboy science taught that the density of a gas is directly proportional to the absolute pressure and inversely proportional to the absolute temperature.

This comes from the ideal gas laws known as Boyle's law (for pressure), dating from 1662, and Charles's law (for temperature) dating from the 1780s.

This gives a simple equation for density:-

$$\rho_{T,P} = \frac{k * m.w. * P_{abs}}{T_{abs}}$$

Unfortunately it is not as simple as this as the density of gas is not directly proportional to the absolute pressure or inversely proportional to the absolute temperature. The compressibility of the gas, Z, has to be taken in to account, giving

$$\rho_{T,P} = \frac{m.w. * P_{abs}}{Z * R * T_{abs}}$$

This is where the problems really start. All calculation methods use an "equation of state" – a thermodynamic equation describing the state of matter under a given set of physical conditions, or EOS for short.

There is no such thing as a universal EOS. All are a compromise in some way, so rather like mathematical curve fitting routines, the application has to be fully understood before the appropriate solution can be chosen.

The earliest approach to a better model was the Van der Waals equation which formed the foundation for later developments including:-

- NX-19
- Redlich-Kwong
- Peng-Robinson

These are cubic equations of state, which are not particularly complicated to solve and do not require a great deal of computer processing power.

It is important to note that the cubic equations of state only provide limited accuracy, particularly as the gas mixture moves towards the critical conditions.

4 DENSITY CALCULATIONS FOR CURRENT METERING SYSTEMS

The DECC Measurement Guidelines – Issue 8 state that an export system from a production platform or a gas import system has clearly defined uncertainty limits of ±1.0% (mass) for gas.

Gas metering systems in this category generally use the AGA8 equations of state to calculate gas density.

The AGA8 equations are only applicable to gas in the vapour phase and cannot be relied on if used when process conditions are approaching the critical conditions. The use of high export pressures means that this is happening more frequently.

The AGA8 methods have been adopted in **ISO 12213 Natural Gas – Calculation of compression factor** [3].

5 ISO 12213 NATURAL GAS – CALCULATION OF COMPRESSION FACTOR

As ISO 12213 uses the AGA8 equations, the same problems occur as the critical region is reached.

The standard defines the applicable limits of operation as follows:-

Table 1 – Limits of operation defined in ISO 12213

Parameter	Lower Limit	Units	Upper Limit
Pressure	0	MPa	12
Temperature	263	K	338
Superior Cal. value	30	MJ/m ³	45
Relative density	0.55		0.80
Methane	70.0	Mole%	100.0
Ethane	0.0	Mole%	10.0
Propane	0.0	Mole%	3.5
Butanes	0.0	Mole%	1.5
Pentanes	0.0	Mole%	0.5
Hexanes	0.0	Mole%	0.1
Heptanes	0.0	Mole%	0.05
Octanes+	0.0	Mole%	0.05
Hydrogen	0.0	Mole%	10.0
Carbon Monoxide	0.0	Mole%	3.0
Helium	0.0	Mole%	0.5
Water	0.0	Mole%	0.015
Nitrogen	0.0	Mole%	20.0
Carbon dioxide	0.0	Mole%	20.0

If the gas and the operating conditions are **ALL** within these limits the uncertainty is predicted to be $\pm 0.1\%$.

Paragraph 4.4.2 of the standard gives a “wider range of applications”, but in order to evaluate uncertainty, reference has to be made to Annex E, where uncertainty data is given separately for gases with high nitrogen, carbon dioxide, ethane or propane, and also for combinations of these gases as shown below:-

“The overall results at pressures up to 10Mpa, and temperatures within the range 263K to 338K can be summarized as follows. Only gases having mole fractions within the limits below will have uncertainties within $\pm 0,1\%$, $\pm 0,2\%$ and $\pm 0,5\%$, respectively, within the given pressures and temperatures.

Table 2 – Estimated uncertainty limits from Annex E of ISO 12213

Component	Mole fraction for an uncertainty within		
	$\pm 0,1\%$	$\pm 0,2\%$	$\pm 0,5\%$
Nitrogen	<0.50	-	-
Carbon dioxide	<0.23	<0.26	<0.28
Ethane	<0.13	<0.20	-
Propane	<0.06	<0.10	-

Table 2 provides a useful extension for heavier gases, but as there is nothing “heavier” than propane it is of limited help in relation to the rich natural gases we are now seeing in the North Sea.

Table 3 shows data for 5 different cases which lie outwith the limits of ISO 12213.

Table 3 – Some Typical North Sea Gas Process Conditions

	1	2	3	4	5	ISO 12213 limits		
Carbon Dioxide	4.00	4.00	0.70	2.00	2.35	0.0	<%<	20.0
Nitrogen	3.91	3.91	0.80	0.50	1.28	0.0	<%<	20.0
Methane	73.79	73.79	70.60	95.60	47.83	70.0	<%<	100.0
Ethane	7.96	7.96	13.80	1.80	14.33	0.0	<%<	10.0
Propane	9.60	9.60	9.30	0.10	19.70	0.0	<%<	3.5
Butanes	2.44	2.44	3.70	0.00	11.42	0.0	<%<	1.5
Pentanes	0.20	0.20	0.90	0.00	2.77	0.0	<%<	0.5
Hexane	0.00	0.00	0.20	0.00	0.33	0.0	<%<	0.2
Pressure	156	121	172	120	176		<barg	119
Temperature	64	40	5	13	51	-10.0	< ^o C<	65.0

The highlighted areas show where the gases are outwith the AGA8/ISO 12213 limits where uncertainty can be declared.

Cases 1, 2, 3 and 5 are clearly considerably outside the stated limits. Case 4 is only just outside the limit for pressure and it would be reasonable to attribute the 0.1% uncertainty limit to this case, provided that this composition mix was truly representative of the operating gas composition and was not just a single “spot” sample.

The AGA8 equations are only applicable in the true vapour phase, which means that uncertainties increase as the operating envelope approaches the liquid phase and cannot even be quantified outside a narrow range of operating conditions.

In order to overcome this limitation and provide an equation of state that could be used for any phase state, the GERG-2004 equations were developed.

4 THE GERG-2004 EQUATION OF STATE FOR NATURAL GASES AND OTHER MIXTURES

The GERG-2004 Monograph [4] states:-

To overcome the weaknesses and limitations of existing equations of state used in the natural gas industry, several years ago the Chair of thermodynamics of the Ruhr-Universität Bochum decided to develop a new wide-range equation of state for natural gases and other mixtures of a quality that enables the equation to be adopted as a standard international reference equation suitable for all natural gas applications where thermodynamic properties are required. The work was supported by the DVGW (German Technical and Scientific Association on Gas and Water) and European natural gas companies (E.ON Ruhrgas, Germany; Enagás, Spain; Gasunie, The Netherlands; Gaz de France, France; Snam Rete Gas, Italy; and Statoil, Norway), which are members of GERG (Groupe Européen de Recherches Gazières). Based on the new formulation, robust and efficient calculation routines (software) were developed in a second project, supported by the European natural gas companies mentioned before. The routines allow for “blind” calculations of the thermodynamic properties of mixtures at arbitrary conditions. This monograph thoroughly presents the new equation of state, adopted by GERG in 2004 and called GERG-2004 equation of state or GERG-2004 for short.

The monograph also sets out the requirements for the new equation of state as follows:-

The new equation of state for natural gases should be valid in the entire fluid region, i.e. in the gas phase, the liquid phase, the supercritical region, and for vapour-liquid equilibrium (VLE) states.

It is also states that:-

The highest demands on the accuracy of the new mixture model occur in standard natural gas applications, including gas metering, transmission, and storage. This requires the accurate description of the thermodynamic properties of different types of natural gases in the temperature range from 250 K to 350 K and at pressures up to 30 MPa. Therefore, the new equation of state had to achieve a very high accuracy in the gas phase with uncertainties of less than 0.1% in density and speed of sound.

For natural gases of uncommon compositions, the uncertainties in density and speed of sound should not exceed 0.2% in the mentioned temperature and pressure ranges.

Although not explicitly stated in the monograph it is reasonable to interpret “standard natural gas applications” as being the equivalent of “pipeline quality gas” as defined in AGA8/ISO 12213.

The great majority of experimental densities for various rich natural gases, containing comparatively large amounts of carbon dioxide (up to 20%), ethane (up to 18%), propane (up to 14%), n-butane (up to 6%), n-pentane (0.5%), and n-hexane (0.2%), are reproduced by the new equation of state to within $\pm(0.1 - 0.3)\%$ over the measured temperature (280 K to 350 K) and pressure ranges (up to 30 MPa).

GERG-2004 has now been modified to include n-nonane, n-decane and hydrogen sulphide as well as the original GERG-2004 gases which were methane, nitrogen, carbon dioxide, ethane, propane, n-butane, i-butane, n-pentane, i-pentane, n-hexane, n-heptane, n-octane, hydrogen, oxygen, carbon monoxide, water, helium, and argon. This revised EOS is now known as GERG-2008.

Table 4 – Some Typical North Sea Gas Process Conditions with GERG-2004/2008 limits

	1	2	3	4	5	GERG 2004/2008 limits		
Carbon Dioxide	4.00	4.00	0.70	2.00	2.35	0.0	<%<	20.0
Nitrogen	3.91	3.91	0.80	0.50	1.28	0.0	<%<	20.0
Methane	73.79	73.79	70.60	95.60	47.83	0.0	<%<	100.0
Ethane	7.96	7.96	13.80	1.80	14.33	0.0	<%<	18.0
Propane	9.60	9.60	9.30	0.10	19.70	0.0	<%<	14.0
Butanes	2.44	2.44	3.70	0.00	11.42	0.0	<%<	6.0
Pentanes	0.20	0.20	0.90	0.00	2.77	0.0	<%<	0.5
Hexane	0.00	0.00	0.20	0.00	0.33	0.0	<%<	0.2
Pressure	156	121	172	120	176		<barg	299
Temperature	64	40	5	13	51	7.0	<°C<	77.0

The highlighted areas show where the gases are outwith the GERG-2004/2008 limits where uncertainty can be declared.

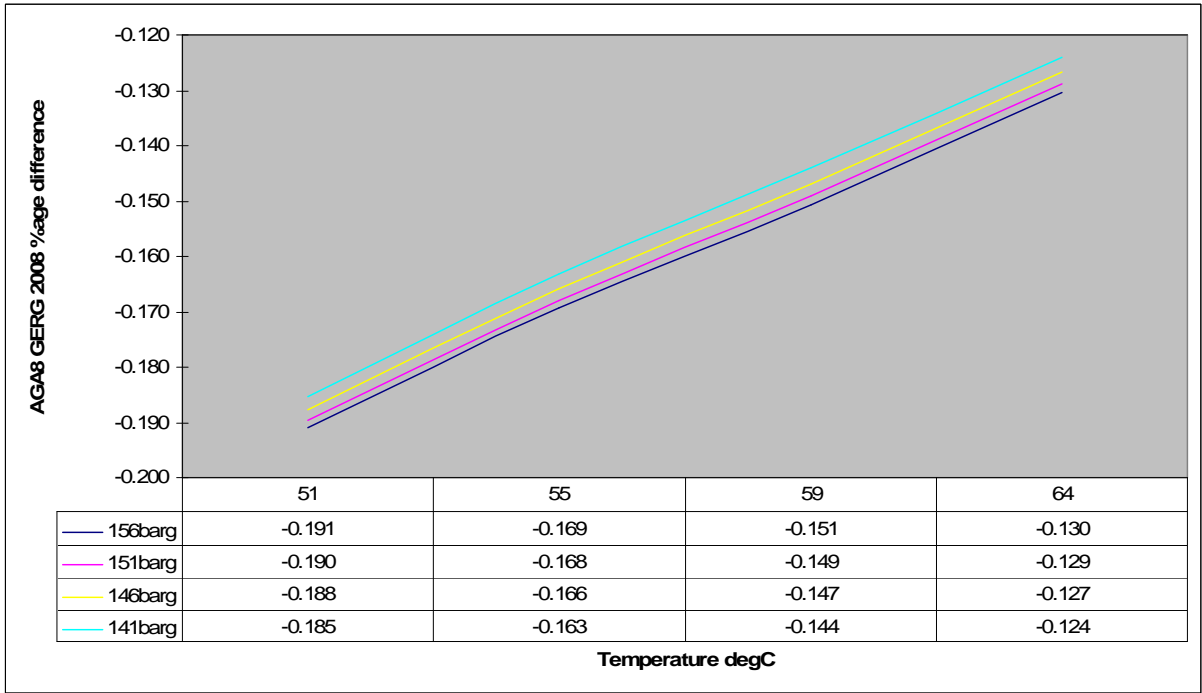
5 CALCULATED DENSITY DIFFERENCES BETWEEN GERG-2008 AND AGA8.

In all cases a range of temperatures and pressures have been used in order to produce a family of curves.

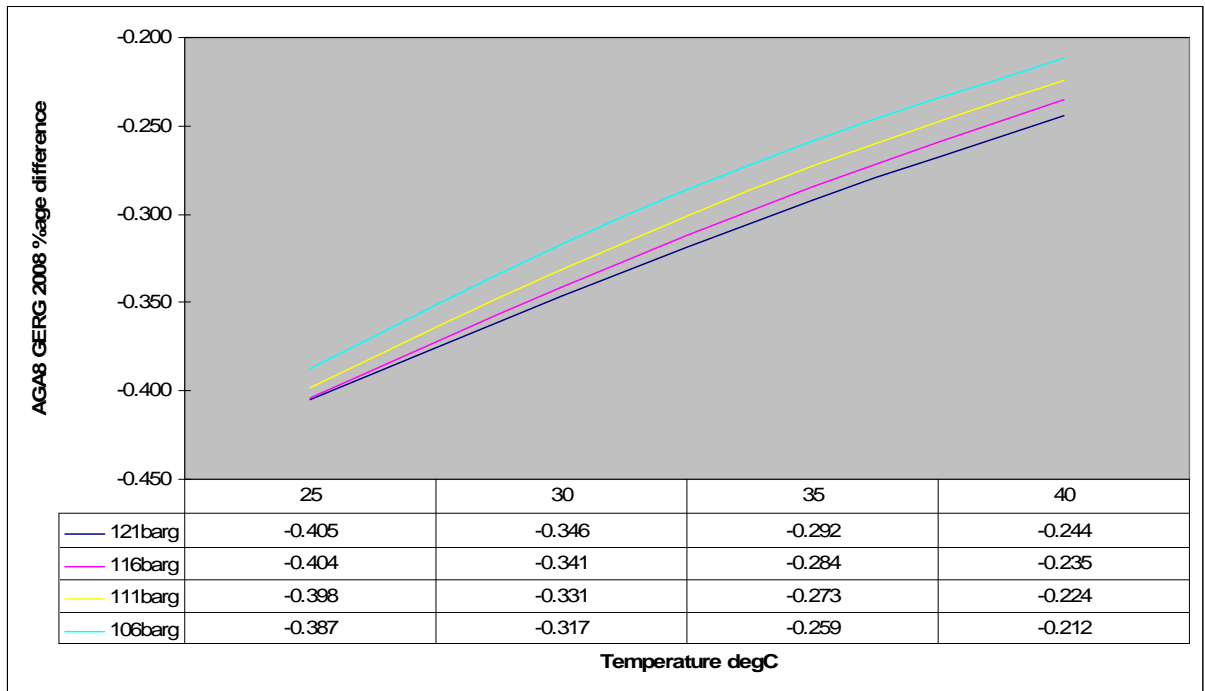
Negative differences indicate AGA8 calculated density *higher* than GERG-2008 calculated density.

The five cases in the tables 3 and 4 have been calculated using REFPROP version 9.0 [5]

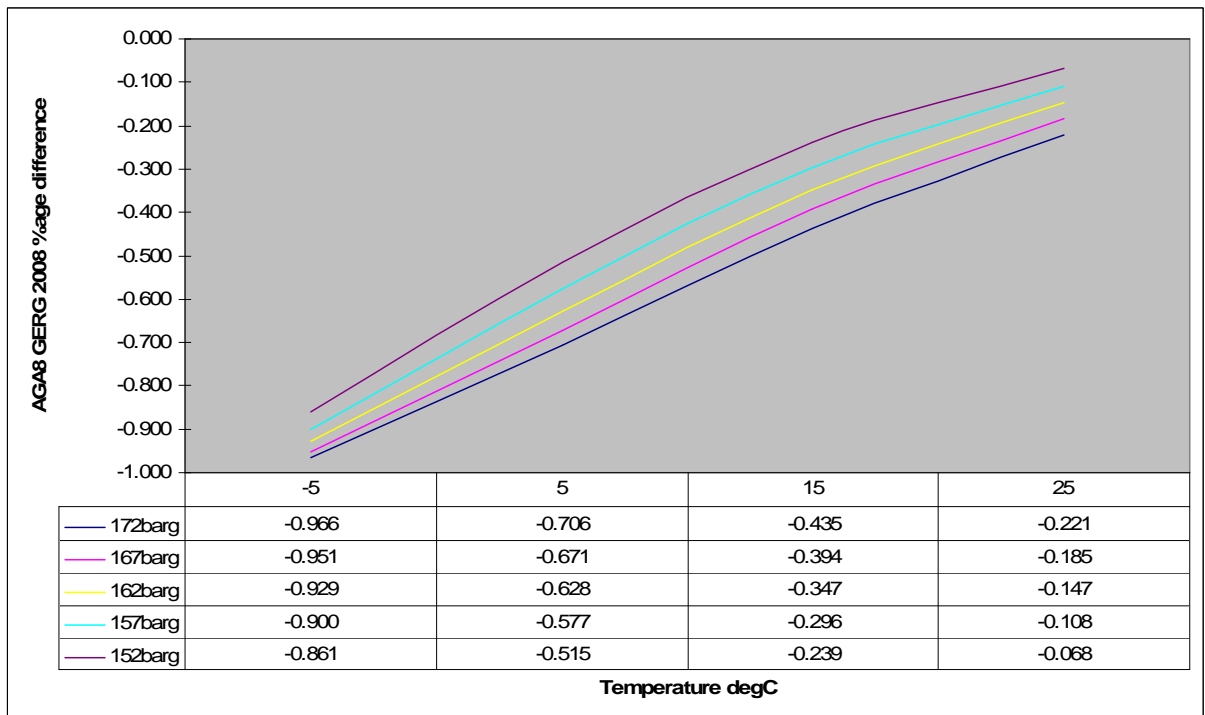
5.1 Column 1, Table 4



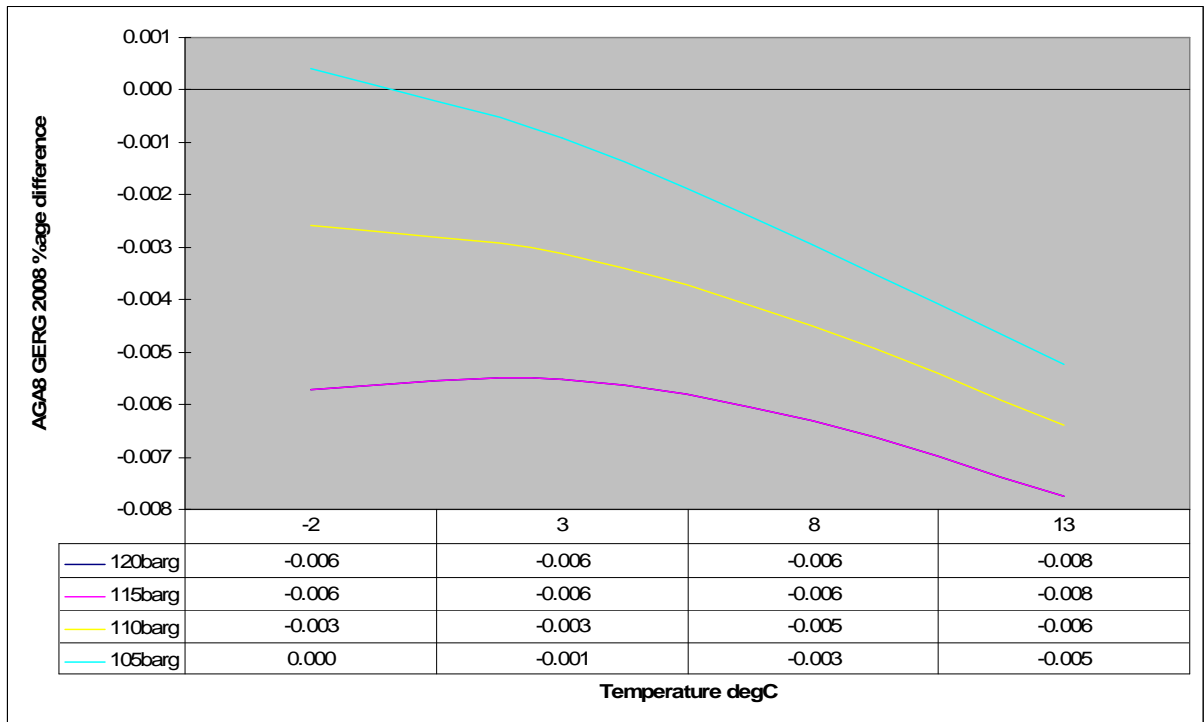
5.2 Column 2, Table 4



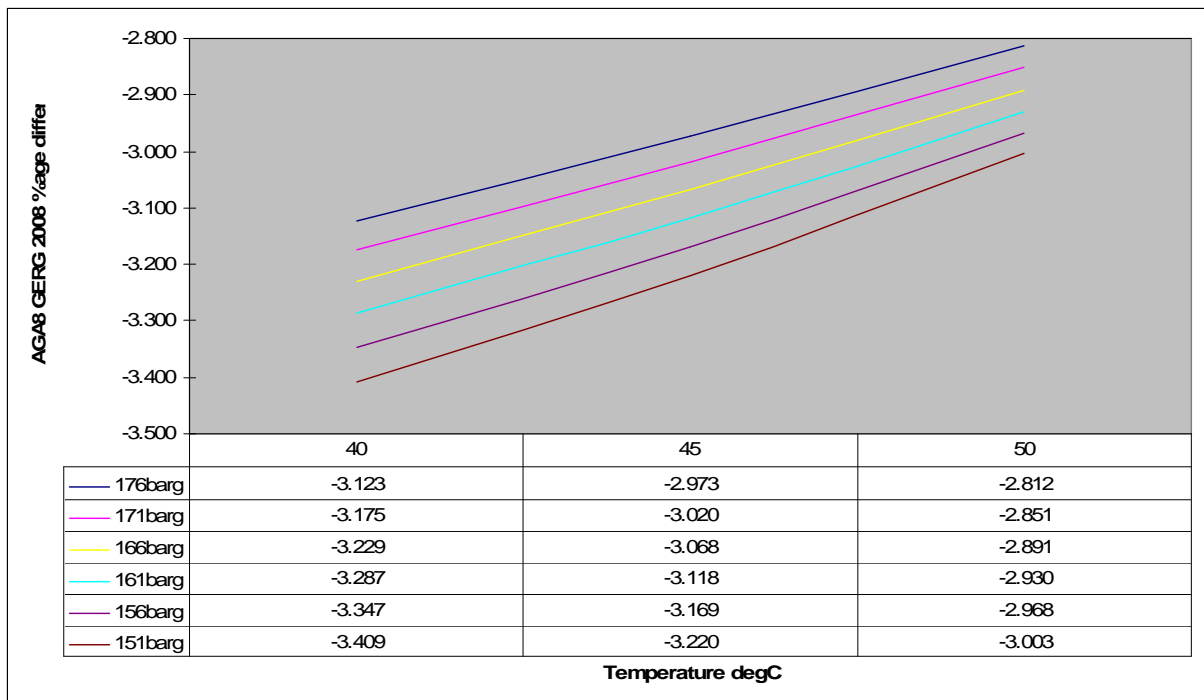
5.3 Column 3, Table 4



5.4 Column 4, Table 4



5.5 Column 5, Table 4



6 DISCUSSION OF RESULTS AND CONCLUSIONS

6.1 Discussion of Results

As can be seen from Table 3, none of the gas compositions and process conditions lies completely within the ISO 12213 limits, although column 4 data could reasonably be included as it is only the pressure which is marginally outside the pressure limit. It is perhaps not surprising that the correlation between the AGA8 and the GERG-2008 results is high in this case.

The comparison between columns 1 and 2 show the danger of “jumping to conclusions”; just because the pressure for column 2 is only marginally outside the ISO 12213 limit does not mean that the high levels of propanes and butanes can be ignored.

Column 3 results show large differences between the AGA8 and GERG-2008 calculations and even though the pentanes and temperature are not within the GERG-2008 limits, the results clearly show that AGA8 does not model the density at all well.

Column 5 results show very large differences between the two calculation methods. Even though the propanes, butanes, pentanes and hexane are all outside the GERG-2008 limits, a difference of ~3.0% in calculated density clearly demonstrates that using AGA8 is not an appropriate equation of state to use for these conditions. We could equally well say that as these components are also outside the GERG-2008 limits that we should not use the GERG equations either! To counter this second point, it would be very surprising if the GERG equations suddenly ceased to work once the limits shown in Table 4 were exceeded, so although we cannot entirely rely on the density results obtained, we can be confident that they represent a closer approach than the AGA8 method.

Based on a flow rate of 20,000kg/h for the various cases, and assuming that the difference figure represents an error in flow rate – an over simplification – but useful to illustrate the extent of the problem, the five cases given represent a range of results from over reporting from > £300k/annum, to >£1.9M/annum.

6.2 Conclusions

Paragraph 6.6 of DECC – Guidance Notes for Petroleum Measurement Issue 8 states:-

Where the composition, pressure or temperature lies outwith the expanded limits of AGA8, DECC may require that a new equation of state is derived. New or upgraded systems will be expected to take account of ISO 12213 (Table 1) for the treatment of other components outwith the normal AGA8 component list. Where a new equation of state cannot be implemented, the additional uncertainty resulting from the use of AGA8 should be quantified.

DECC would accept the use of the GERG-2008 equation of state, which covers a wider range of components and conditions than AGA8. However, at present it is not believed that this equation of state has been implemented in commercially-available flow computer systems.

From the data presented in this paper it can be seen that GERG-2008 provides an improved method of calculating gas density over a wider range of compositions and process conditions than AGA8.

However, it is not an answer which is simple to apply.

Modern flow computers have the processing power to cope and can perform the necessary routines in an acceptable time – but at the moment, as the Guidance Notes comment, the GERG-2008 option is not yet available. Even if a GERG implementation were available it may still be necessary to carry out laboratory checks on representative gas samples for comparison with the calculated density values for gases with high proportions of heavier fractions as the database of results used to check the GERG-2008, although very large, does not extend very far into the area in which we are interested for these “heavy gases”.

In the meantime, for gases that lie within the GERG limits, but outwith the AGA8 limits, using GERG versus AGA8 to check the difference between the two calculation methods would enable a reasonable

assessment of the likely uncertainty to be made. Since composition is one of the parameters normally available for pipeline allocation purposes, this method is nearly always available. Increased confidence in the equation of state may allow regulators and pipeline authorities to review the need for direct density measurement with consequent savings in capex and opex costs.

Existing pipeline agreements may also present a problem where AGA8 is referenced – although this is not a technical issue it is still a problem!

As a final note, the GERG-2008 equation of state is under consideration to be adopted as an ISO Standard (ISO 20765-2 and ISO 20765-3) for natural gases under the auspices of the ISO group ISO TC 193/SC 1/WG 13.

7 NOTATION

$\rho_{T,P}$	density at line conditions
k	constant
$m.w.$	molecular weight
P_{abs}	operating pressure (absolute)
T_{abs}	operating temperature (absolute)
Z	compressibility
R	universal gas constant
GERG	European Gas Research Group
DECC	Department of Energy and Climate Change

8 REFERENCES

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- [2] Starling, K.E. and Savidge, J.L. Compressibility Factors of Natural Gas and Other Related Hydrocarbon Gases. Transmission Measurement Committee Report No.8, American Gas Association (1515 Wilson Boulevard, Arlington, Virginia 22209, USA), 2nd Edition, November, 1992.
- [3] BS EN ISO 12213:2005 Natural gas - Calculation of compression factor. BSI, London.
- [4] Kunz, O., Klimeck, R., Wagner, W., Jaeschke, M. The GERG-2004 Wide-Range Equation of state for Natural Gases and Other Mixtures, Fortsch.-Ber. VDI, Reihe 6, Nr. 557, VDI, Düsseldorf (2007).
- [5] Lemmon, E.W., Huber, M.L., McLinden, M.O. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2010.