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Using CPM Tools for Gas Quality Control

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ABSTRACT

The quality of gas entering the UK's National Transmission System (NTS) is controlled to ensure the energy content is within an acceptable range and that gas is within the strict safety limits set out by the Gas Safety (Management) Regulations (GS(M)R)[7]. Although the exact limits are negotiated between the NTS operator, National Grid, and the connecting party, once agreed, the Network Entry Quality Specification must be adhered to.

In the UK the major source of gas delivered through the NTS is from the gas fields in the North Sea. The composition and quality of the produced gas varies significantly depending on the field, location, well depth and also on the production age of the field. The many hundreds of miles of interconnected large pipe diameter gas gathering pipeline systems which are used to transport the produced gas to processing terminals are sufficiently complex to make optimum operations challenging; the required entry specifications add a further level of complexity to the operations of the pipeline system.

The role of balancing the commercial needs to maximize delivery whilst adhering to the NTS entry specifications falls on the pipeline operator. Given the unsteady production rates and varying qualities of produced gas at the offshore platforms the pipeline/platform operator needs advisory tools to help facilitate decisions about both plant and pipeline operations.

In this paper we discuss the development of such a tool based on a Computational Pipeline Model (CPM): a real time pipeline modeling system with predictive and look ahead capability that tracks the necessary gas qualities. The paper will discuss the specific gas qualities tracked (CO_2 mole fraction, Wobbe Index, Incomplete Combustion Factor and Soot Index), what role they play and how they are controlled. The paper will also demonstrate how predictive tools can also be used to provide plant output rates for both NGLs and Sales Gas.

The gas quality prediction tool has recently been deployed on the Frigg System and Frigg Terminal Processing plant which is owned and operated by Total E&P UK Ltd. The Frigg Pipeline System comprises over 625 miles (1,000 km) large bore pipeline and gathers rich gas from around 8 different areas in the Northern North Sea to the processing plant at St. Fergus. The Vesterled Pipeline System comprises 225 mile (363 km) large bore pipeline transporting gas from the Heimdal platform to the Frigg Terminal Processing plant. The Vesterled Pipeline System is owned by the Gassled partners and operated by Gassco with Total E&P UK acting as a technical service provider. The Frigg Pipeline System and Vesterled Pipeline System each have the capacity to transport around 1275 MMSCF of gas per day (36 MSCMD).The paper will report how the tool is to be used by the pipeline operators and how the system will be developed further.

INTRODUCTION

The majority of homes in the UK use natural gas as the source of fuel for their domestic heating system; many homes also use natural gas as the main source of fuel for cooking; furthermore approximately 45% of all electricity generated in the UK is from power stations that use natural gas as their main source of fuel. The UK consumes around 3.5×10^{15} BTU of natural gas per year – more than 60% of which is destined for power stations and domestic usage (see **Figure 1**).

Natural gas is an excellent fuel: it is safe, clean, efficient and in relatively plentiful supply. Simply stated, the stoichiometric equation for the combustion of methane, the major component

in natural gas, is

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

This chemical reaction, although needing an initial input of energy to kick start, is strongly exothermic and, *under the right conditions*, self-sustaining. The combustion of methane produces about 1010 BTU/ft^3 (38 MJ/m^3) of heat energy. The combustion process is somewhat more complex than the above statement as shown in **Figure 2**, and methane is only one component of natural gas; however, the other combustible components in natural gas behave in a similar way and produce proportionate amounts of energy.

Broadly speaking, *the right conditions* for sustainable combustion are

- **Sufficient oxygen**: Air is 20% Oxygen, hence for each volume of methane approximately 10 volumes of air are required for the combustion. If there is insufficient oxygen carbon monoxide will be produced: carbon monoxide is toxic.
- **Correct fuel rate**: Combustion is mostly observed as a flame, which is the region in the fuel/air mixture where the combustion is occurring. A flame will move through the fuel/air mixture at the "burning velocity". However, since the heat is to be delivered at a particular location, the flame must be at a fixed point and therefore the rate of fuel (and air) supplied to the combustion process must match the burning velocity otherwise the flame will move downstream and "blow-out" will occur, or the flame will move upstream into the fuel delivery system and (maybe) be extinguished through oxygen starvation.

Both the fuel rate and the oxygen supply must be precisely delivered to ensure safe and efficient combustion and it is the role of the burner to regulate the combustion process. Burners are designed for optimum efficiency and safety, but in the design assumptions must be made about the composition of the fuel gas and the amount of energy released by its combustion. It is therefore the assurance of burner efficiency, and most of all, safety that dictates the quality of natural gas that can be delivered into the UK NTS. Indeed, as is presented later, the quality metrics themselves are derived by consideration of the combustion of natural gas through a burner.

At the point of delivery we therefore see limits imposed on specific, defined quality parameters. However, at the other end of the supply chain the composition, and therefore the quality, of the gas is somewhat variable. Consider the UK pipeline network infrastructure as a whole (**Figure 3**): the three main sources of natural gas are from offshore gas fields, from LNG terminals and through interconnector pipelines to European neighbors. Whereas the supply of natural gas through the interconnector pipelines will already meet strict European guidelines on quality, LNGs and offshore gas require processing before being placed into the NTS. The specifications that the processed natural gas must meet are referred to as the NTS Entry Specifications: these will be discussed in more detail later on.

LNGs play an increasing role in meeting the demand for natural gas. LNGs can, and are, produced throughout the world and transported via tanker to their destination. LNGs typically contain 80%-90% methane, 10%-20% ethane and 2-3% propane and butane; although their composition may vary according to where they were produced and the processing that they underwent, within a shipment the composition will not change and therefore appropriate processing (usually ballasting, i.e. adding nitrogen) is relatively straightforward.

The majority of the natural gas used in the UK originates from the gas fields in the North Sea. As **Table 1** testifies, the composition of unprocessed gas can vary significantly within a single gas field and also between fields. Some processing of the gas may take place on a platform and that too will alter the composition. However, the variability in composition in itself isn't an issue, but when combined with variability in the export rate from a platform due to operational requirements it becomes clear that the composition of commingled gas can vary considerably within the pipeline and that predicting the composition, and therefore quality, of the gas entering the onshore plant is somewhat challenging.

Tracking the composition of the gas as it enters the pipeline, commingles at mixing points and moves along the main trunk towards the processing plant can only be carried out effectively by a Computational Pipeline Model (CPM). Knowing the composition of the gas that is due to arrive at the plant allows the plant operators to adjust the process parameters to ensure that the processed gas is within the quality limits expressed by the NTS Entry Specifications. Furthermore, a CPM furnished with Look Ahead or Predictive capability allows for predictions of compositions, quality indices and NGL rates under various operational scenarios and becomes an effective decision support tool for use by the control room operators.

Before considering how such a tool might be used in the control room the target quality parameters are discussed in more detail.

UK NTS Entry Specifications

For processed natural gas to be allowed entry into and transportation through the UK National (gas) Transmission System (NTS), that gas must meet a set of stringent quality limits: the Entry Specification.

As we have already noted, the main use of natural gas within the UK is for use as a source of energy, where that energy is produced by combustion. Safe and efficient combustion is a function, not only of the fuel, but also of the construction and design of the burners used in the various combustion processes. Today such burners are engineered to precise specifications of fuel rate, combustion rate, flame speed, (heat) energy production, etc. It is these specifications that played an important role in the development of some of the quality limits within the Entry Specifications.

Equally important is ensuring that the transportation of the natural gas does not impair the integrity of the transportation infrastructure.

Pipeline Specifications

The so called "pipeline specification" is a set of rules that govern permissible water and hydrocarbon dewpoints along with limits for contaminants such as oxygen and hydrogen sulphide. The objective is to ensure pipeline material integrity for reliable gas transportation purposes. The pipeline specification parameters place limits on:

- **Hydrocarbon Dewpoint**: When transporting gas it is undesirable for liquids to form in the pipeline. Hydrocarbon liquids may cause clogging through valves and orifices, especially within low pressure networks, and hence limits are placed on the hydrocarbon dewpoint of the shipped gas. In reality this means that the gas cannot be too rich i.e. have "large" fractions of heavier hydrocarbons.
- **Water Dewpoint**: The water dewpoint is similarly limited to prevent water dropout. As well as preventing clogging and constriction to flow, the presence of water will facilitate oxidation, corrosion and the formation of acids should other contaminant (e.g. carbon dioxide or hydrogen sulphide) be present. Furthermore, water can combine with hydrocarbons to produce hydrates which may block the pipeline.
- **Oxygen**: The presence of oxygen together with water and sulphur will promote corrosion.
- **Hydrogen Sulphide**: Hydrogen Sulphide reacts with copper in domestic systems to form copper sulphide which is black dust that may block pipes and burners.
- **Hydrogen**: The presence of hydrogen in steel pipes promotes brittling and makes them susceptible to stress fractures.

Interchangeability Parameters

The International Standards Organization (ISO) defines Natural Gas Interchangeability as a measure of the degree to which the combustion characteristics of one gas resemble those of another gas. Two gases are said to be interchangeable when one gas may be substituted for the other without affecting the operation of gas burning appliances or equipment.

Interchangeability Parameters are designed to place limits on the gas quality with the aim of ensuring safe and efficient combustion.

Wobbe Index (WI)

The first of such interchangeability parameters was developed in the late 1920's by Goffredo Wobbe. In a wide range of experiments in which he examined the combustion of gaseous fuels at atmospheric (low pressure) conditions he noted that:

- The heat output of the combustion process is proportional to the volumetric flow rate of the fuel
- The heating value of the fuel is proportion to the specific gravity of the fuel
- The volumetric flow rate of the fuel is proportional the reciprocal of the square root of the specific gravity of the fuel

These observations led to the development of the eponymously named Wobbe Index:

$$WI = \frac{HV}{\sqrt{SG}}$$

Here HV is the High (Gross) Heating Value in MJ/m^3 and SG is the specific gravity (relative density) of the gas.

The Wobbe Index alone does not provide much in the way of safety of the combustion process. Several undesirable effects can occur during combustion. These include:

- **Flashback**: Transfer of combustion from a burner port to a point upstream in the gas/air flow. Flashback can cause considerable damage to the burner equipment.
- **Lifting**: Separation of a flame from a burner port, whilst continuing to burn with its base some distance from the port. Lifting is indicative of an inefficient combustion process and production of Carbon Monoxide.
- **Yellow Tipping**: The appearance of a yellow color at the top part of the periphery of a flame. Again, this is indicative of an inefficient combustion process and the production of Carbon Monoxide and soot.

In the US work was undertaken by the AGA[3] which led to the development of a set of empirical equations for the derivation of numerical indices for flashback, lifting and yellow tipping. This work was further refined by E. R. Weaver of the U.S. National Bureau of Standards in the 1950's which resulted in

the Weaver Indices. However, much of the work by the AGA and Weaver considered Town Gas and, as a result, many of the indices are dependent on the hydrogen content of the gas. These indices were reasonable for the burners and appliance types available at the time but are not appropriate for the high efficiency, low emission burner technology available today. Also, the hydrogen component available in town gas, and key to some of the parameters, only occurs in trace amounts in natural gas.

The driving force behind the development of a new set of parameters to characterize interchangeability and combustion within the UK gas industry came with the rapid change from the use of Town Gas to Natural Gas in the 1960's and 1970's. However, over the past few years the rapidly developing world market in LNG has brought interchangeability back into the limelight[1, 4].

During the 1970's research was undertaken by B.C. Dutton of British Gas to better characterize interchangeability and combustion indices[5]. This work culminated in the development of several empirical indices for combustion and what is now referred to as the Dutton Diagram, which specifies the envelope of acceptability on gas quality and is effectively the NTS Entry Specifications. We shall outline the development of the Dutton Diagram in the following sections.

Interchangeability: Equivalent Mixtures

One of the key steps taken by Dutton was to consider "equivalent mixtures" of gas. An equivalent mixture, in this sense, is one in which all the hydrocarbon molecules are "replaced" by either methane or propane and all inert molecules are replaced by nitrogen. This simplification works well since it acknowledges the effects that higher hydrocarbon and inert species have on the flame characteristics by including propane and nitrogen respectively whilst recognizing that the burning velocity (the velocity of propagation of the flame front) is similar for all linear alkanes and that the effect of inert species is similar.

An equivalent mixture is defined as a mixture of methane, propane and nitrogen that has the same average number of carbon atoms per hydrocarbon molecule as the original fluid mixture and also has the same total number of carbon and hydrogen atoms for all hydrocarbon species as the original fluid mixture. All inert (non-hydrocarbon) molecules are replaced by nitrogen. Implicit in this definition is that there are equivalent numbers of moles of the equivalent mixture as there are in the original fluid. For example, if we consider ethane, then this can be replaced by an equivalent mixture as follows:

$$C_2H_6 = \frac{1}{2}C_3H_8 + \frac{1}{2}CH_4$$

Similarly, butane can be replaced by an equivalent mixture as follows:

$$C_4H_{10} = \frac{3}{2}C_3H_8 - \frac{1}{2}CH_4$$

Note that the above are equivalence relations and not traditional chemical stoichiometric equations. The first of the above relationships states that each mole of ethane in the original gas is replaced by half a mole of propane and half a mole of methane. A table of equivalent gas replacement values for the common hydrocarbons found in natural gas is shown in **Table 2**.

Wobbe Index vs. PN

One significant advantage of the equivalent mixture is that it is very easy to construct a chart of Wobbe Index versus either the mole fraction of methane in the equivalent mixture or, more commonly, the mole fraction of propane plus the mole fraction of nitrogen. The mole fraction of propane plus the mole fraction of nitrogen is referred to as "PN". Clearly for an equivalent mixture with a PN other than zero the non-methane content can be entirely nitrogen, entirely propane or anywhere in between. However, the two extremes (entirely nitrogen or entirely propane) provide the limits on the range of variability and hence on the Wobbe Index. Plotting the Wobbe Index vs. nitrogen plus propane mole fractions (PN) therefore provides an envelope for the range of Wobbe Index for each PN value. This diagram is shown in **Figure 6**. The top of the envelope is shown by the blue line which represents the mole fraction of nitrogen plus propane being made up entirely of propane; the bottom of the envelope is shown by the green line and represents the mole fraction of nitrogen plus propane being made up entirely of nitrogen. Lines parallel to the blue line represent the mole fraction of nitrogen plus propane consisting of fixed percentages of propane within the nitrogen/propane component. The lines parallel to the green line represent the mole fraction of nitrogen plus propane consisting of fixed percentages of nitrogen within the nitrogen/propane component.

From this diagram we can see immediately that the effect of ballasting (adding inerts to a natural gas) is to move down and to the right on the diagram since the mole fraction of propane plus nitrogen in the equivalent mixture will increase thus moving to the right, and the percentage of nitrogen in the propane plus nitrogen mixture will increase thus reducing the heating value, thus moving down. Similarly, the effect of propane enrichment (adding propane or heavier hydrocarbons) to a natural gas is to move up and to the right on the diagram.

Incomplete Combustion Factor, Lift Index and Soot Index

Much as Weaver had done in the 1950's, Dutton investigated the combustion process. Armed with the equivalent mixture approach and utilizing representative UK appliances of the time he devised three empirical interchangeability factors.

The **Incomplete Combustion Factor** (ICF) is a measure of ratio of the carbon monoxide to carbon dioxide produced during the combustion of the fuel gas:

$$ICF = \frac{WI - 50.73 + 3PN}{1.56}$$

The Gas Safety (Management) Regulations (GS(M)R) specified by the UK Health and Safety Executive (HSE) require an upper limit on the ICF of 0.48. This limit is pertinent to combustion in domestic water heaters within the UK.

The **Lift Index** (LI) is a measure of the flame detachment from the burner:

$$LI = 3.25 - 2.41\tan^{-1}\left(0.122\left(WI - 36.8 - 1.19PN\right)\right)$$

The GS(M)R specified by the UK HSE require an upper limit on the LI of 1.16.

The **Soot Index** (SI) is a measure of the amount of soot produced by the combustion of the fuel gas:

$$SI = 0.896\tan^{-1}\left(2.55P - 2.33N + 0.617\right)$$

Here "P" is the mole percent of propane in the equivalent mixture and "N" is the model percent of nitrogen in the equivalent mixture. The GS(M)R specified by the UK HSE require an upper limit on the SI of 0.6.

Note that the above definitions assume the fuel gas contains no hydrogen. Extended definitions of the three indices are given in Ennis, Botros and Engler[4]. Note also that the above definitions assume that the Wobbe Index (WI) is given in MJ/m^3.

The Wobbe Index, Soot Index, Lift Index and Incomplete Combustion Factor are all functions of base properties of individual components together with mixing rules to specify how those components mix.

The Dutton Diagram

The Incomplete Combustion Factor, Lift Index and Soot Index are all defined in terms of the Wobbe Index and the mole percentages of Propane and Nitrogen in an equivalent mixture. Thus the GS(M)R limits can be mapped onto the Wobbe Index vs. PN diagram. Doing this produces what is now referred to as the Dutton Diagram and is shown in **Figure 7**. The closed convex area within the Incomplete Combustion Factor, Wobbe Index, Lift Index and Soot Index limits on the Dutton diagram provides the range of acceptability for a natural gas based on the indices derived from its equivalent mixture and effectively forms the gas quality NTS Entry Specifications. The grey shaded area in **Figure 7** represents the typical range of UK gas quality.

Complete UK NTS Entry Specifications

The pipeline specifications and the gas quality indices shown in the Dutton Diagram comprise the UK NTS Entry Specification for natural gas: these are an embodiment of the GS(M)R limits on content and other characteristics of natural gas for usage in appliances in the UK. The full UK NTS Entry Specification is given in Appendix A.

It is worth noting that the Lift Index is not mentioned in the NTS Entry Specifications. The Lift Index is replaced by the requirement that the minimum Wobbe Index is 47.2 MJ/m^3 (1266.81 BTU/ft^3). Referring to the Dutton diagram, any gas whose quality indices are within the envelope defined by the NTS Entry Specifications and has a Wobbe Index greater than 47.2 MJ/Sm^3 (1266.81 BTU/ft^3) will have a Lift Index greater than 1.16.

The Frigg System

Overview

The Frigg Pipeline System (FPS) and Frigg Terminal Processing plant comprises 68 miles (110 km) of 24" pipe from the Alwyn field in the northern North Sea to the decommissioned Frigg field facility where it ties into a 225 mile (362 km) long 32" pipe transporting gas to the processing plant at St. Fergus. Several platform groups tie into the 32" main line at various points. A second 225 mile (363 km) long 32" line (Vesterled) takes gas from the Heimdal platform to the St Fergus plant. The two streams are processed on separate processing trains at the Frigg Terminal Processing plant at St. Fergus before being commingled and transferred into the NTS. A schematic of the pipeline system is shown in **Figure 4**.

Named after the Norse goddess (**Figure 5**), the Frigg field was discovered in 1971 and at that time was one of the largest

offshore gas fields to be discovered. The first gas transported through the original system was processed in 1977; since then the system has been extended to include the Alwyn field (1987), the Miller field (1991), the Bruce field (1993) and the Rhum field (2005). In 2014 the 145 mile (224 km) SIRGE pipeline, originating at the Shetland Gas Plant (SGP) at Sullom Voe on Shetland, will tie in to the Frigg Pipeline system.

Although the Frigg field ceased production in 2004, the Frigg Pipeline System gathers rich gas from around 8 different areas in the Northern North Sea. The Frigg Pipeline System has the capacity to transport around 1250 MMSCF of gas per day (36 MSCMD). The Vesterled pipeline has a similar capacity, and the output capacity of the processing plant is 2050 MMSCF of gas per day (59 MSCMD) and 2,425 tons (2,200 tonnes) of NGLs per day.

The Frigg Pipeline System and Frigg Terminal Processing is owned and operated by Total E&P UK Ltd.

FPS Entry Specifications

The Entry Specifications for shipper gas to be transported through the Frigg Pipeline System place upper limits on the cricondenbar of the exported gas and ranges for the entry pressure and temperature. As well as the operational limits there are limits on water content, hydrogen sulphide content, carbon dioxide content, oxygen content and other contaminants such as mercury and mercaptans: the full FPS Entry Specifications are given in **Table 3**. However, the key requirement is that the shipper gas must be capable of being processed to meet the National Grid redelivery specifications for Wobbe Index, Incomplete Combustion Factor and Soot Index.

Gas Composition Variability and Quality Control

The FPS gathers gas from eight areas in the North Sea. As shown in **Table 1** the composition of gas from fields in the North Sea can vary significantly. The gas gathered by the FPS has a huge variability in composition: Methane content varies between 70 – 98 mole percent, ethane plus propane content ranges from 0.01 – 20 mole percent, nitrogen content ranges from 0 – 5 mole percent and carbon dioxide content ranges from 0.5 – 4.5 mole percent. Fortunately, the gas fields that are producing exceedingly rich gas (high ethane and methane content) are nearing the end of their life and consequently have very low production rates.

The majority of the gas transported in the FPS originates from the Alywn area and is moderately rich and has a moderately high carbon dioxide content. Under normal operations gas from other fields mixes with the Alwyn gas at various mixing points in the pipeline and the resultant commingled gas has a lowered carbon dioxide content. However, for a multitude of reasons, platform export flow rates can vary significantly and hence it is not always guaranteed that the commingled gas will meet the required specification on carbon dioxide content. Thus it is important for the terminal operators to know the composition of the gas downstream of mixing points as this provides information on how best to process the gas.

The gas being transported in the Vesterled pipeline typically has a much leaner composition and a lower carbon dioxide content than the gas from the Alwyn area. Within the Vesterled pipeline there is much less variation in the gas composition as there is no commingling of gas.

Managing the quality of gas arriving at the terminal and the quality of the processed gas is one of the primary duties of the pipeline and plant operators. Typically, however, the operators have little control over the platform export rates and also have obligations on the volume of gas delivered into the NTS.

Thus, to some degree, a reasonable strategy for optimizing processed gas production is to provide the minimum controls necessary on the gas coming into the plant and deal with the gas as it arrives. Knowing the carbon dioxide content, Wobbe Index, Incomplete Combustion Factor and Soot Index of the gas due to arrive at the plant allows the plant operators to set the process parameters accordingly. During processing there are several mechanisms that can be employed to change the quality of the gas:

- **Ballasting**: Nitrogen or Carbon Dioxide is added to the gas. The effect of ballasting is to move the gas quality down and to the right on the Dutton diagram. The converse of this is carbon dioxide removal which moves the gas up and to the left on the Dutton diagram.
- **Enrichment**: LNGs or higher hydrocarbons are added to the gas to increase the heating value. The effect of enrichment is to move the gas up and to the right on the Dutton diagram. The converse of this is to remove NGLs (heavier hydrocarbons) from the gas by utilizing a Joule-Thomson valve or a turbo expander to reduce the temperature of the gas to the point where liquids drop out. The effect of NGL removal is to move the gas down and to the left on the Dutton diagram.

Considering the options available to the plant and how these options affect the position of the gas quality on the Dutton diagram clearly demonstrates why knowing the quality parameters of the gas prior to processing are useful. For example, if the Soot Index of the gas arriving at the plant is too high then NGL removal will be required to bring the quality within specification. The only downside of NGL removal is that it reduces the volumes of gas available to put into the NTS, so some ballasting may be required as well.

One further option available to the terminal operators is to

blend the two gas streams either before or after they have been processed. Again, knowledge of the gas quality indices ahead of time helps the operators decide whether or not this option is viable.

In all of the above scenarios the key to controlling the gas quality is knowing what the gas composition is in the pipeline upstream of the plant: forewarned is forearmed! To provide that information the operators turn to a Computational Pipeline Modeling tool.

The Use of CPM

The CPM comprises a Real-Time Pipeline Modeling System (RTM), an automatic Look-Ahead Modeling System (LAM) and a Predictive Modeling System (PM). The RTM receives frequent updates of export flow, pressure, temperature and composition data for the offshore platforms and plant inlet streams. The RTM uses this data to "drive" the mathematical model that describes the transient flow of fluids throughout the pipeline system. To be able to solve the transient flow equations the model only requires one of pressure or flow at pipeline system ingresses and egresses, the remaining "redundant" information being used for tuning. Tuning facilitates improved accuracy of the model.

For monitoring fluid quality the key functionality provided by the RTM is composition tracking. The RTM uses the computed local velocity to move "batches" of fluid along the pipeline. Each batch contains fluid that is within given mole fraction tolerances. When batches are introduced into the system at the offshore platforms or when fluids mix at mixing nodes (junctions in the pipeline with multiple ingresses), new batches may be created if the new fluid differs sufficiently from the fluid in the current batch. Although configurable, the batch creation tolerances are sufficiently low that fluid physical properties, such as density, within each batch are sufficiently accurate. Since the required quality indices are only dependent on the fluid composition these too can be computed for each batch and therefore only need to be calculated when a new batch is created at either a platform or a mixing node. Just having the ability to view profiles of the quality indices in the few miles upstream of the of the plant inlet (see **Figure 8** for example) provides the operators with the ability to set plant parameters appropriately; for example if they see a slug of very rich gas heading towards the plant they can decide how best to deal with it by either lowering the temperature on the Joule-Thomson valves and/or turbo expanders to increase NGL production and/or employing ballasting with CO_2.

Both the LAM and the PM provide prediction capability. Both use the current state of the pipeline as an initial state and then run forward in time either assuming all ingress and egress flow rates and pressures remain the same (LAM) or, with prescribed changes in e.g. platform export rates (PM).

Both the LAM and PM provide predictive trends of compositions and quality indices arriving at the plant. Additionally, a Vapor-Liquid Equilibrium (VLE) computation tool has been incorporated into the LAM/PM processing to compute liquid drop-out rates via flash calculations. Thus, given the plant Joule-Thomson Valve temperature set-point, trends of the NGL rates are also provided by the predictive tools.

The real value in using a CPM tool comes from the ability to predict the quality of the gas at specific points in the pipeline network, i.e. mixing nodes, and this functionality is provided by both the LAM and the PM. The LAM will provide trends of composition and quality indices assuming no changes occur in the export flow rates or pressures. The PM will make use of a scenario of prescribed events (such as the export flow rate of a platform being curtailed for a prolonged period) so that the effects on the fluid quality downstream of key mixing nodes or at the plant ingress can be assessed. Such "what-if" analyses allow the operators to examine various operational scenarios and make the appropriate operational decisions.

An overview of the CPM tool described above is shown in **Figure 9**.

The roles and usage of the three different models are:

- **Real-Time Model**: Runs constantly, provides current hydraulic state of the pipeline and profiles of fluid composition and quality indices. This gives the operators a snapshot of the current state of the pipeline and specifically the quality of gas currently in the pipeline.
- **Look Ahead Model**: Runs automatically every half hour and predicts the composition and quality indices of gas entering the plant for the next 8 hours based on current conditions. Trends of NGL rates are also computed. The tool provides the operators with a forecast of the gas qualities coming into the plant in the short term and therefore allows them to make operational decisions concerning how the gas will be processed.
- **Predictive Model**: Runs on demand. Predicts the composition and quality indices at mixing nodes and of gas entering the plant based on current conditions and a user defined scenario. Trends of NGL rates are also computed. This tool provides the operators with the ability to do "What-if" analyses: the effects of known scheduled operational changes can be calculated and mitigation strategies assessed. Specifically, forecasts of gas qualities downstream of mixing nodes and upstream of the plant can be used to support operational decisions concerning how the pipeline will be run and how gas will be processed.

Deployment of the CPM System on the FPS

Although an Energy Solutions CPM system was first deployed on the Alwyn Area pipeline in around 1995 as a Leak Detection System, the current system, which is used exclusively for composition tracking with Look Ahead and Predictive capability, was deployed in around 2005.

The CPM is a dual redundant system and receives pressure, flow, temperature and composition data for the exporting platforms and plant inlet as well as various valve statuses from the FPS SCADA system approximately every 10 seconds.

The system has been in continuous usage since it was first commissioned. During that time there have been various upgrades, both to the pipeline geometry, and to the CPM functionality. Over the years the pipeline operators have come to rely on the Look Ahead predictions of the gas composition and Wobbe Index arriving at the plant. Recently the CPM has been upgraded and now includes the computation of Soot Index and Incomplete Combustion Factor as well as utilizing the LDA (Liquid Drop Out Analyzer) module to compute NGL rates. Prior to the current release, the computation of Soot Index, Incomplete Combustion Factor and NGL rates were undertaken manually by the operator. Performing this functionality in the CPM reduces the work load of the operator and reduces the risk of error.

The basic functionality of the installed CPM is:

- Real-Time modeling of system flows, pressure and temperatures based on boundary condition changes
- Real-Time tracking of gas composition throughout the system including componential stock accounting and allocations (see Robinson, Spence & Barley[6])
- Real-Time tracking of Wobbe Index, carbon dioxide content, Soot Index and Incomplete Combustion Factor throughout the pipeline and specifically at platforms, mixing nodes and the plant inlet. Real-Time profiles of quality indices are available for all pipeline sections, specifically upstream of the plant inlet
- Look-Ahead predictions of the composition of the gas entering the plant
- Look-Ahead predictions of the quality indices of the gas entering the plant
- Look-Ahead predictions of the rates of NGL produced by the plant
- Predictive “what-if” modeling: specifically predictions of the composition and quality indices of the gas entering the plant assuming various operational scenarios and also the NGL rates produced by the plant under those scenarios

Although the upgraded CPM has only been installed for a few months the operator feedback has been very positive: all the information that they require is presented through the CPM GUI and they no longer have to enter data into spreadsheets.

Next Steps

Currently the CPM computes the CO_2 content, Wobbe Index, Soot Index and Incomplete Combustion Factor for the gas coming into the plant. Whilst this is indicative of the quality of the processed (sales) gas, the system could be extended to allow forecasts of the rates and quality indices of the processed gas itself. As part of the LAM this would provide early warning should the current process conditions be insufficient to ensure that the processed gas meets the NTS Entry Specifications. As part of the PM this extension would allow the plant operators to examine how (pipeline) operational changes will affect the quality of the processed gas. The above extension is shown in **Figure 9** in the dashed boxes.

CONCLUSIONS

The indices used to control the quality of natural gas shipped through the UK National Transmissions System (NTS) have their roots in maintaining the integrity of the pipeline network and also in the safety of the combustion process which most of the gas will inevitably undergo. These indices can be expressed as simple empirical quantities and are functions of the molecular composition of the gas and the molecular mass and gross heating value of each species of component within the gas.

The limits on these quality indices form a closed region on a chart of Wobbe Index versus non-methane content mole percent; this is known as the Dutton diagram and forms the basis for the Entry Specification for the NTS.

The majority of natural gas used in the UK comes from offshore gas fields: the export gas quality and export flow rates are highly variable and may often lie outside the limits defined by the specification. However, knowing the quality indices of the natural gas upstream of the processing plant allows the plant to process the gas efficiently and to within the specifications required.

The use of a Real-Time CPM allows the tracking of composition throughout the gathering system and allows the computation of the quality indices at any point in the pipeline but specifically upstream of the plant. Using the current state of the pipeline as the starting point, short-term Look Ahead modeling can provide trends of the fluid quality parameters and NGL production rates. Similarly, Predictive Modeling can be used to provide “what-if” analyses specifically focusing on fluid compositions downstream of mixing nodes. Real-Time, Look Ahead and Predictive Modeling provide the operators with a set of tools that allow them to make decisions based on

predictions of the quality of the fluid arriving at the plant. Knowing the expected gas quality ahead of time allows decisions to be made on how best to process the gas.

The currently implemented CPM is seen by the operators to be an effective decision support tool in the control of gas quality.

AUTHOR

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NOMENCLATURE

WI	Wobbe Index (MJ/m^3)
HV	High Heating Value (Gross Calorific Value) (MJ/m^3)
SG	Gas Specific Gravity
PN	The mole fraction of propane plus nitrogen in an equivalent gas mixture
P	The mole fraction of propane in an equivalent gas mixture
N	The mole fraction of nitrogen in an equivalent gas mixture
ICF	Incomplete Combustion Factor
LI	Lift Index
SI	Soot Index

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TABLES

Component	North Sea Field "A" Composition (Mole Percent)	North Sea Field "B" Composition (Mole Percent)
Methane (CH_4)	80.0	61.16
Ethane (C_2H_6)	7.95	15.01
Propane (C_3H_8)	3.81	10.12
N-Butane (C_4H_{10})	0.45	0.82
Iso-Butane (C_3H_7-CH_3)	1.04	2.24
N-Pentane (C_5H_{12})	0.24	0.28
Iso-Pentane (C_4H_9-CH_3)	0.33	0.33
Hexane+ (C_6+)	0.05	0.1
Hydrogen Sulphide (H_2S)	0.0	0.0
Water (H_2O)	0.01	0.01
Nitrogen (N_2)	0.28	2.5
Carbon Dioxide (CO_2)	6.24	7.4

Table 1 - Diverse Gas Compositions Found in the North Sea

Component	a	b
CH_4	1.0	0.0
C_2H_6	0.5	0.5
C_3H_8	0.0	1.0
C_4H_{10}	-0.5	1.5
C_5H_{12}	-1.0	2.0
C_6H_{14}	-1.5	2.5
C_7H_{16}	-2.0	3.0

Table 2 - The methane and propane replacement values for alkane hydrocarbon molecules: $aCH_4 + bC_3H_8 = C_nH_{2n+2}$

Gas Condition	Cricondenbar , 106 bara as calculated by the Peng-Robinson equation of state or such alternative method as may be agreed from time to time.
Pressure	< 163.8 barg
Temperature	-5°C to 35°C
Water Content	< 24 Kg per Mscm
H2S content	< 2.3 ppm
Total Sulphur Content	< 15 ppm expressed as H2S
CO2 Content	< 3.8% mole
O2 Content	< 7.5 ppm
Mercury	Maximum mercury content of 0.01 microgrammes per Standard Cubic Meter, unless otherwise agreed.
Mercaptans	< 1.0 ppm Vol

Table 3 - The Frigg UK Pipeline System Entry Specifications

FIGURES

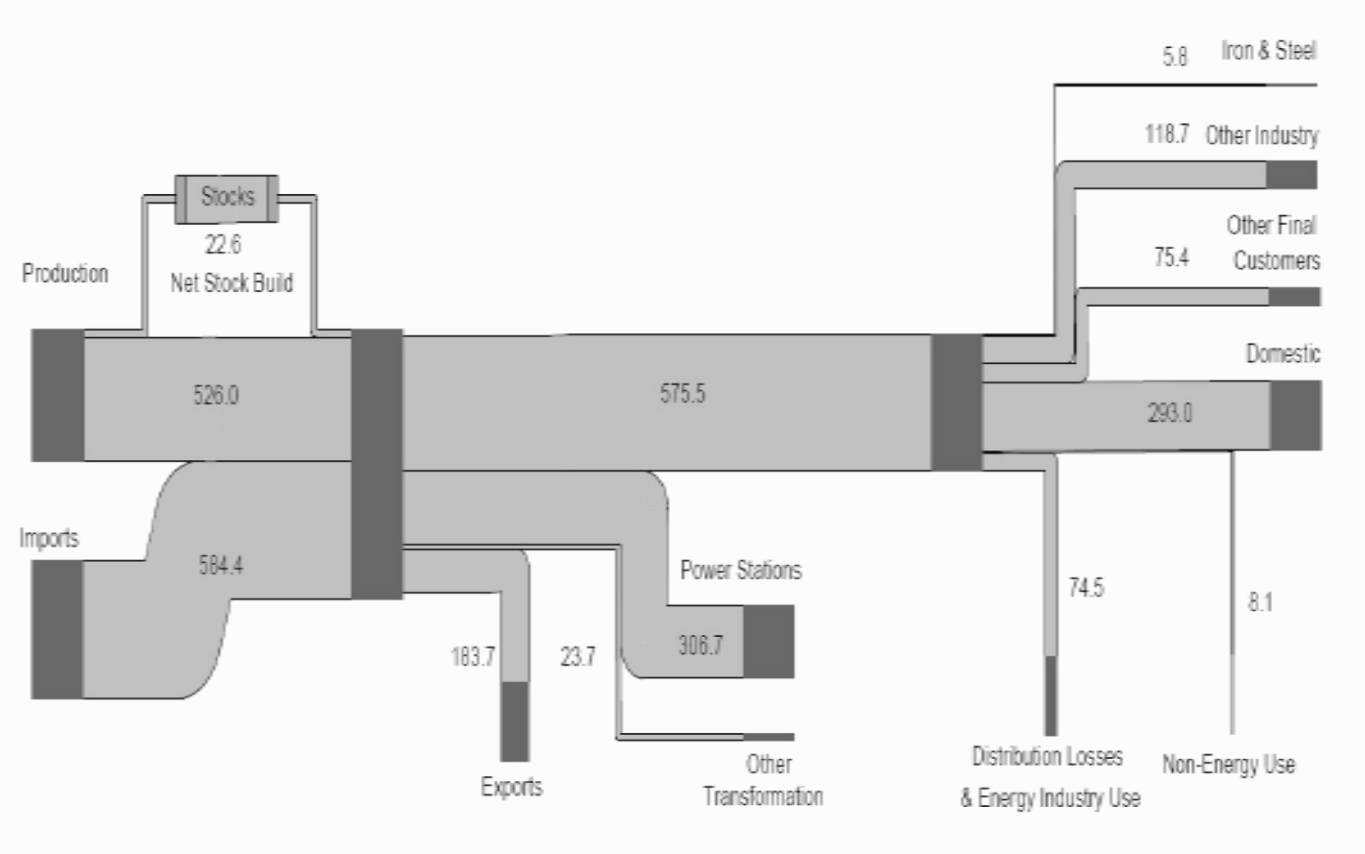

Figure 1 - Natural Gas Usage (TWh) in the UK in 2011 (Courtesy of DECC)

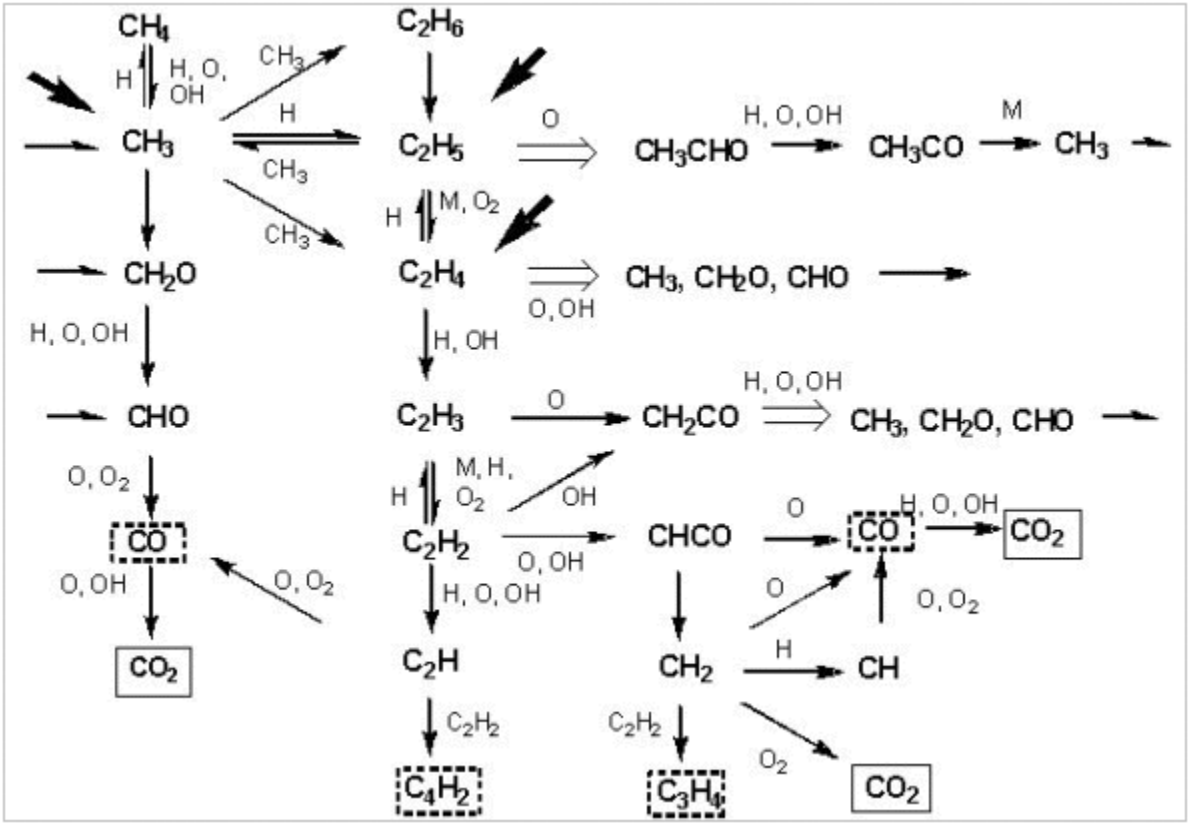

Figure 2 – The Combustion of Methane (Courtesy of the Combustion Institute)



Figure 3 – UK Natural Gas Infrastructure (courtesy of DECC)

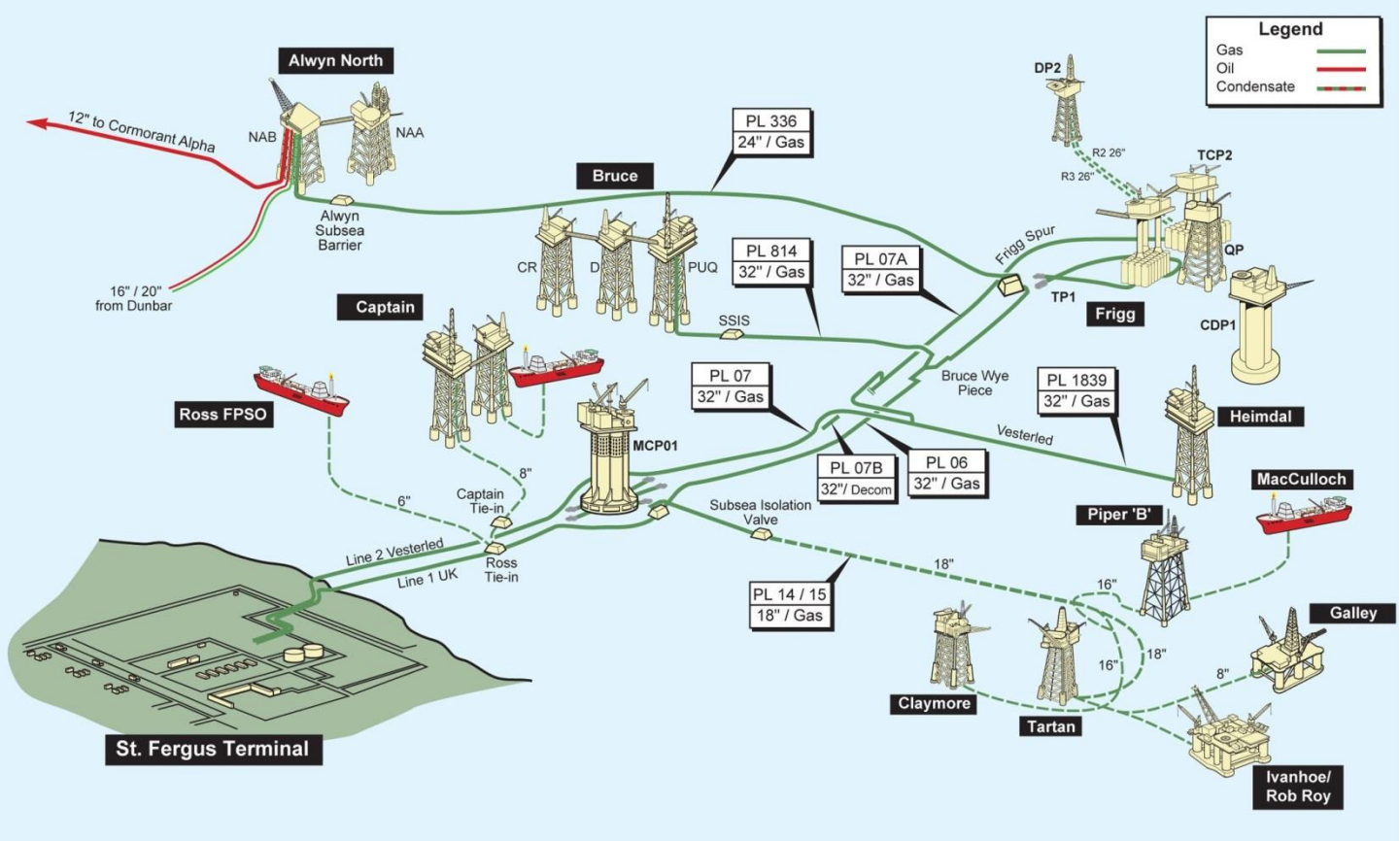

Figure 4 – The Frigg Pipeline System (Courtesy of Total E&P, UK)



Figure 5 –Frigg, the Norse Goddess and Wife of Odin

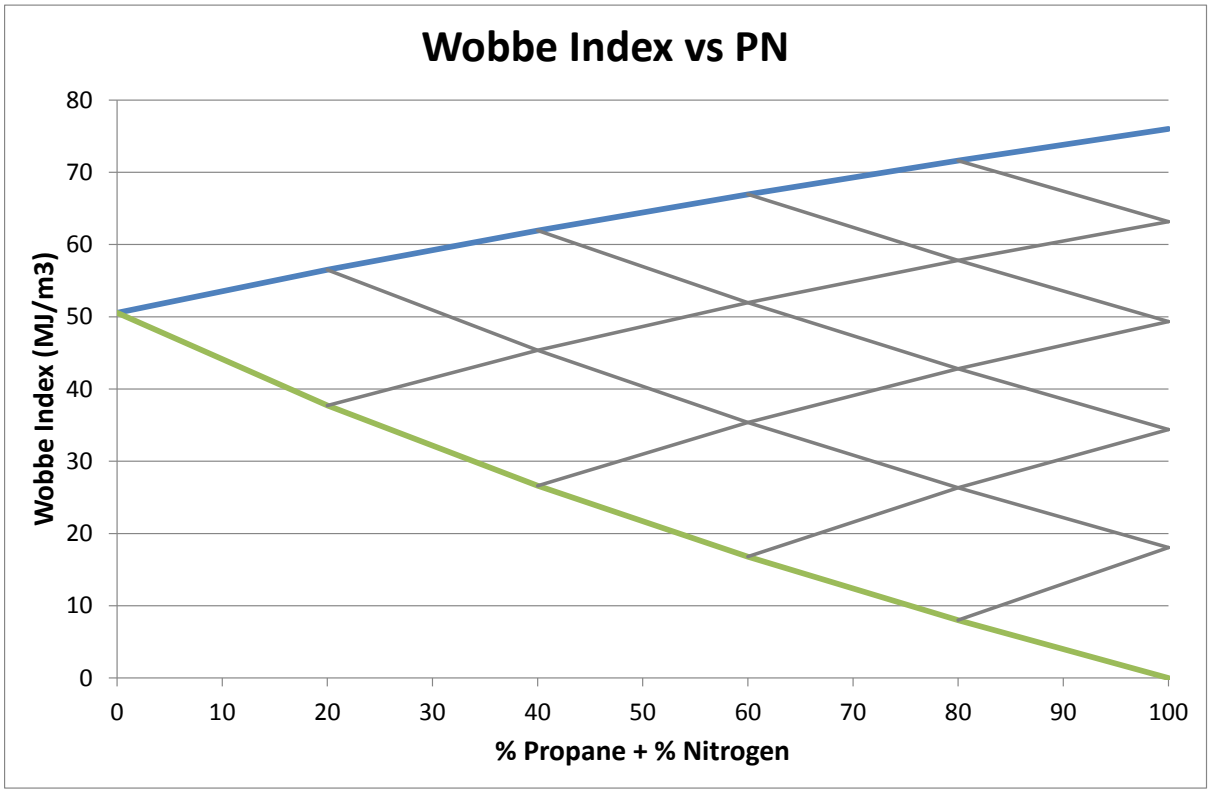

Figure 6 – Wobbe Index vs. Mole Percent Propane + Mole Percent Nitrogen

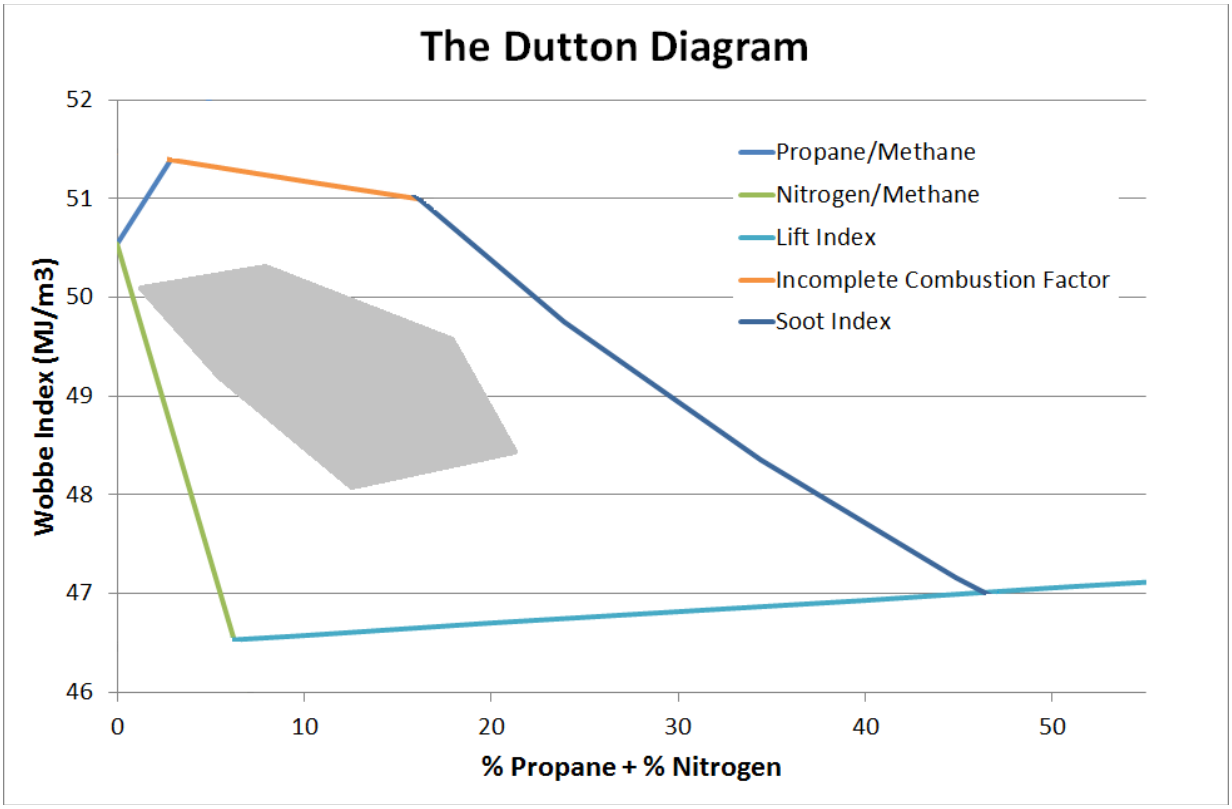

Figure 7 – The Dutton Diagram Showing Typical Range for UK Gas Quality (grey)

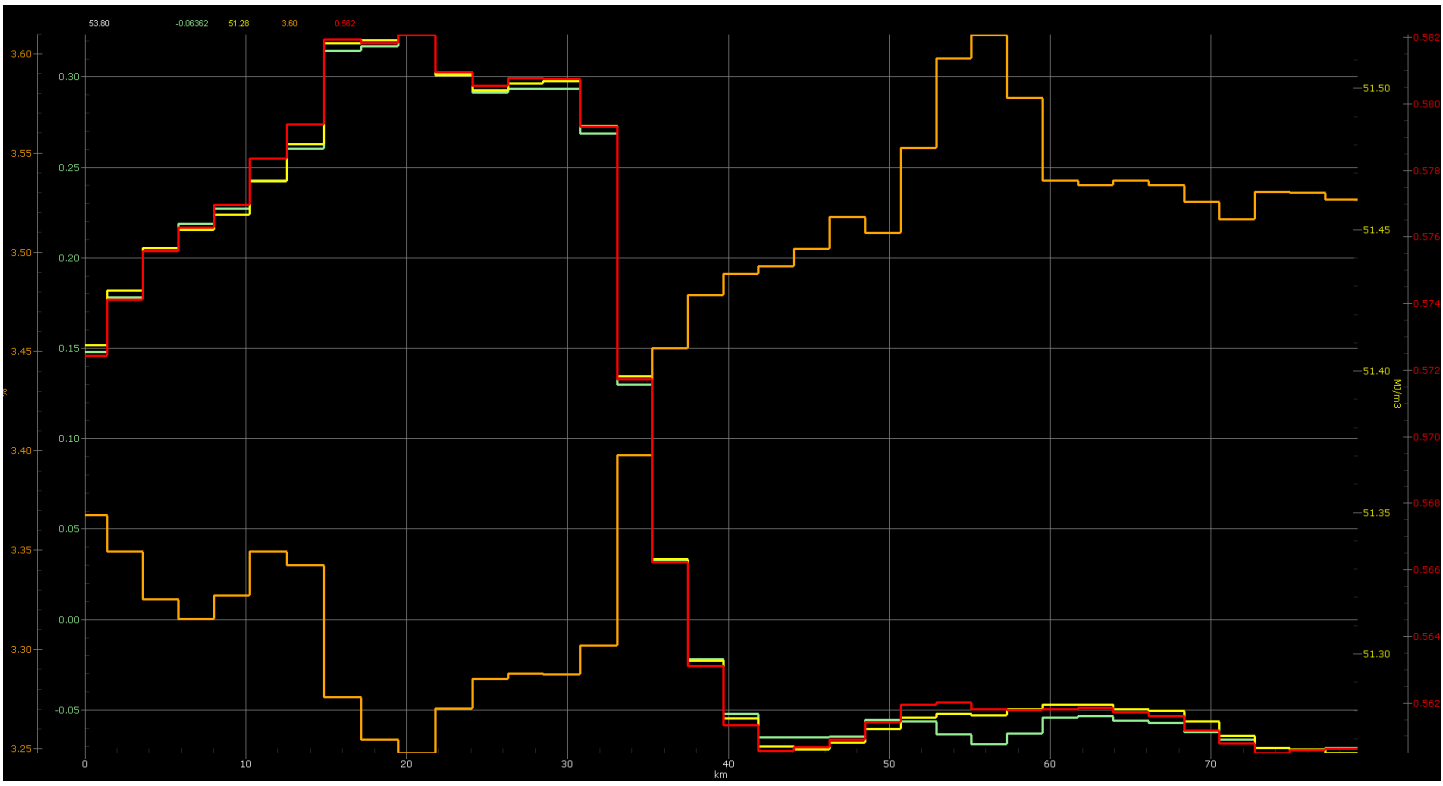

Figure 8 – Profile of ICF (green), SI (red), WI (yellow) and CO2 (brown) Content in Pipeline Upstream of Plant

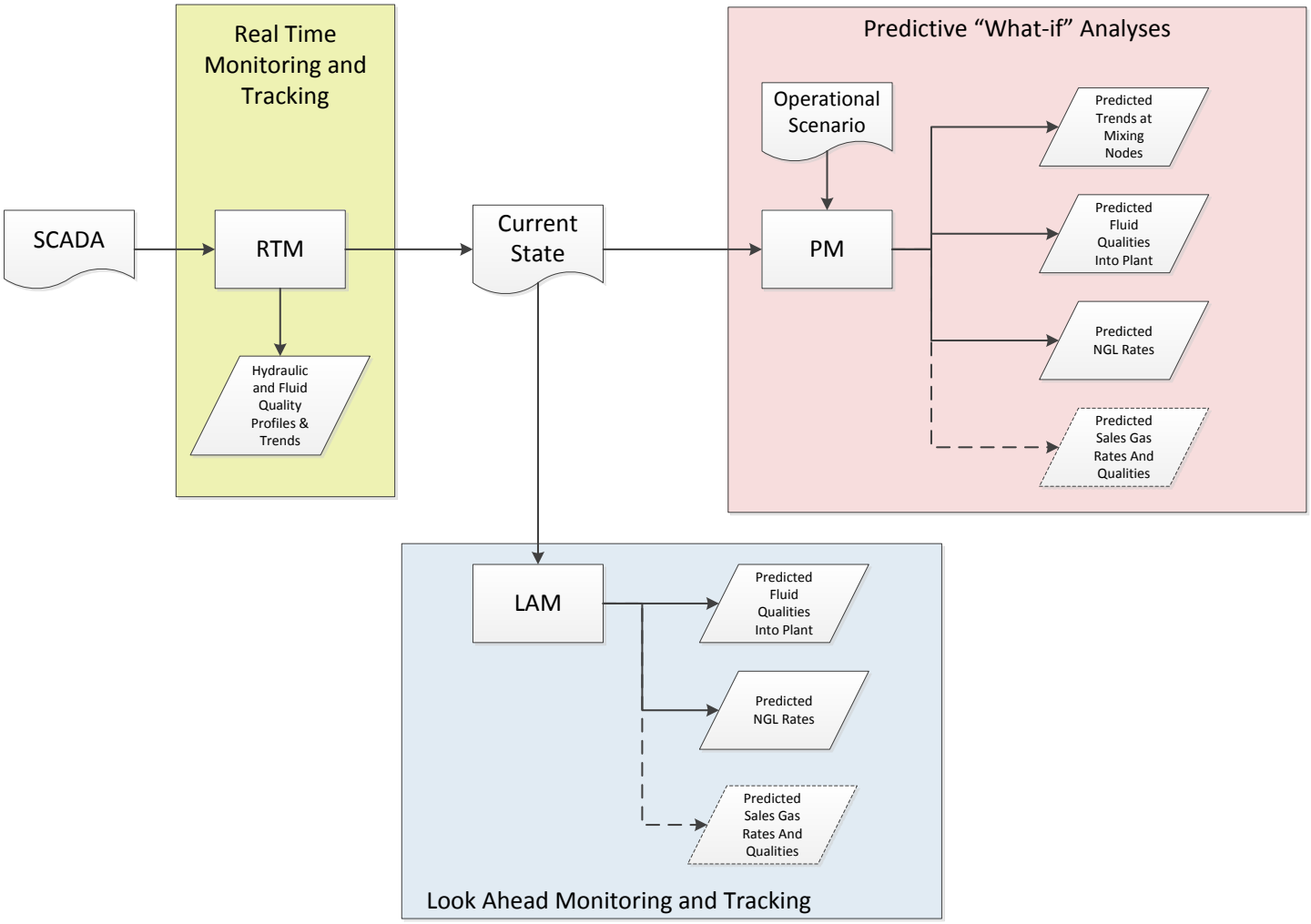

Figure 9 – The CPM Tool Providing Current and Predictive Composition and Quality Profiles and Trends

Appendix A – NTS Entry Specification

Although some elements below are subject to negotiation and alteration, as of January 2013 the NTS Entry Specifications laid out by the NTS operator, National Grid, are:

Gas tendered for delivery by System Users to the System at the System Entry Point shall not contain any solid, liquid or gaseous material which would interfere with the integrity or operation of the System or any pipeline connected to such System or any appliance which a consumer might reasonably be expected to have connected to the System. In addition, all gas delivered to the System at the System Entry Point shall be in accordance with the following values:

(a) Hydrogen Sulphide not more than 3.3 ppm.
(b) Total Sulphur not more than 15 ppm.
(c) Hydrogen Content not more than 0.1 mol%.
(d) Oxygen Content not more than 10 ppm.
(e) Hydrocarbon Dewpoint not more than minus two degrees Celsius (-2°C) at any pressure up to the delivery pressure provided in paragraph (p).
(f) Water Dewpoint not such as would cause a water dewpoint more than minus ten degrees Celsius (-10ºC) at the delivery pressure provided in paragraph (p).
(g) Wobbe Number shall be between 47.2 MJ/SCM, and 51.41 MJ/SCM.
(h) Incomplete Combustion Factor (ICF) not more than 0.48.
(i) Soot Index (SI) not more than 0.60.
(j) Odour [it shall have no odour that may cause National Grid to fail to meet its obligation under Part 1 of Schedule 3 of the Gas Safety (Management) Regulations 1996.] [it shall be odourised as follows: with odourant NB (80% tertiarybutyl mercaptan, 20% dimethyl sulphide), and the odourant injection rate will be 6 mg/scm and may be varied at National Grid's request by up to plus or minus 2 mg/scm to meet operational circumstances.]
(k) Carbon Dioxide not more than 2.0 mol%.
(l) Nitrogen not more than 5.0 mol%.
(m) Total Inerts not more than 7.0 mol%.
(n) Gross Calorific Value shall be within the range 36.9 to 42.3 MJ/SCM. (real gross dry);
(o) Delivery Temperature shall be between one and thirty eight degrees Celsius (1°C and 38°C).
(p) Pressure shall be that required to deliver gas into the System taking account of the back pressure as the same shall vary from time to time. The delivery pressure shall not exceed eighty five bar gauge (85 barg).
(q) Organo Halides Not more than 1.5 milligrams per SCM.
(r) Radioactivity Not more than 5 Becquerels per gram.
(s) Ethane Not more than 12 mol%.