ADVANTICA

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BLENDING AT BACTON TERMINAL PUBLIC VERSION

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Executive Summary

The UK is receiving increasing amounts of imported natural gas from a variety of sources. In the medium to longer-term, the gas quality of some streams may not be within the current UK gas specification as defined by the Gas Safety Management Regulations 1996 (GS(M)R).

There may be opportunities to take individual gas streams at National Grid terminals, which could be outside GS(M)R specification, and blend them with on-specification streams to produce an on-specification output stream. However, it is not known whether current terminal configurations, particularly at Bacton, allow complete mixing of all gas streams prior to NTS entry.

In order to determine whether blending could be carried out within the Bacton Terminal without endangering safety, confidence is needed that the incoming gases will mix to form a single homogenous mixture prior to their leaving the terminal. In particular, the capability of the terminal pipes and equipment to produce homogenised gas before the gas is either taken from the terminal or measured for the purposes of quality assessment has to be assessed. National Grid contracted Advantica to carry out a study to use pipeline modelling of terminal incoming and outgoing gas streams, using a number of tools including hydraulic analysis and computational fluid dynamics (CFD), to determine the extent of mixing of gas streams under a range of flow route scenarios and flow rates.

Advantica were not requested to examine the safety and operational matters associated with providing a possible blending service at Bacton, although a number of the findings of this study have implications for these areas. Advantica understands that National Grid has carried out a separate, preliminary review of safety and operational matters and that its high level findings have been publicised in its Winter 2006/07 Consultation Update Document, published on the 11th July 2006.

Findings and Recommendations

- Hydraulic pipeline analysis (using Stoner Pipeline Simulator (SPS)) and CFD have been used to model gas flows and gas mixing under the most commonly utilised modes of operation and for a substantial range of operational scenarios. These modes of operation are not however comprehensive, and the complexity of Bacton pipeline infrastructure means that there could be other, less frequently utilised configurations which may lead to different outcomes.
- Gas flow appears to be, under all modelled conditions, turbulent, with Reynolds Numbers two orders of magnitude greater than those assumed for transition from laminar to turbulent flow.
- Consequently, mixing of any two gases is assumed to be rapid. However velocities of gases in the pipe are likely to range from $1ms^{-1}$ to $10ms^{-1}$, for total feeder flows between 5mscm(d) and 50mscm(d), i.e. the modelled range for a single outgoing feeder.
- Transit time of gas across the terminal could be less than one minute.

- With analysis points between final mixing and gas composition measurement from 35m to 75m, gas could travel from a final mixing point to a measurement point within a few seconds. CFD analysis was used to determine whether, even with turbulent flow, full mixing of gases can be assumed in these short timescales. CFD simulations used a simple mixing header with gases of disparate compositions, and initialisation parameters designed to match as closely as possible, ideal pipeline conditions at Bacton Terminal, which would give lowest or worst case mixing rates.
- CFD simulations indicated that under all circumstances, homogeneous mixing was complete to a homogeneity of 1% CH_4 concentration within a pipe length of 20m from the Tee, and that the homogeneity was independent of the velocity, pressure, and ratio of mixing gases under the tested conditions. This independence of mixing distance reflects the linear increase of Reynolds Number with gas velocity. This result is in line with the recommendations of ISO 10715, which suggests that gas sampling should be at least 20 pipeline diameters from a disturbance point.
- However, at 5m or 10 m from the mixing point, there is still some inhomogeneity of gas composition across the pipe, which at 10m could correspond to a variation in Wobbe Number of around 0.6MJ/m^3 for gases with differences in Wobbe Number of around 3MJ/m^3 (i.e. around 20% for equi-mixtures of gases). This inhomogeneity decreases to below 10% for a 90%/10% gas mixture. Even at these distances from the mixing point the composition of the gas at the centre of the pipe is equal to the flow weighted average of the mixing gases.
- Under situations where gas is extracted from the pipe from a wall tapping, for analysis or consumption, the extracted gas may not be consistent with the flow weighted average of the mixing gases where the tapping is 5m or 10m from the mixing point. The use of insertion sample probes would reduce the error but may still not take a representative sample.
- There are potential configurations (not ordinarily used) where measurement could be less than 10m from mixing point. There will be very limited confidence that full mixing can be established in this distance so any analysis will always be unreliable. It is recommended that no off-specification gas is mixed at such points, as even with in-pipe mixing, there is no guarantee that homogeneity can be achieved.
- SPS has proved able to give validated information on flow compositions, both steady state and transient, across the Bacton Terminal. SPS is also capable of mapping gas quality parameters such as Wobbe Number and relative density. It is recommended that SPS and the model of Bacton is employed to map the acceptable envelopes of gas composition under all likely operational modes, static and transient. A similar model could be built for other terminals to give further confidence that GS(M)R limitations can be met as potentially off-specification gas imports increase.
- SPS analysis of transients during flow flexing illustrates that there is not a simple linear change of qualities of outgoing gas following loss of an incomer. Spikes (sudden changes) in gas composition of as little as 20 seconds can be observed in the Feeders as incomer flows are flexed to zero. These could lead to slugging

of gas with unexpected overall quality. With sampling times typically of the order of several minutes, these are unlikely to be measured using standard analytical equipment. It is therefore recommended that the control and instrumentation strategies used for gas quality assurance are reviewed prior to provision of any blending service.

- Although simulations give some confidence that near-complete gas blending is taking place inside 20m of mixing, this cannot be taken as a guarantee that such blending will take place. Validation through rapid sampling across the pipe diameter is recommended where there is any doubt that blending will take place, particularly in safety critical situations. There are simple static in-pipe mixing devices, which can be incorporated to reduce mixing lengths and increase the probability of mixing.

Contents

1 INTRODUCTION

The UK gas supply situation is undergoing significant change. Rising gas demand and depletion of indigenous reserves have resulted in an increasing requirement for importation of natural gas to the UK. Imports will be via pipeline from the Norwegian sector, interconnector pipelines from Continental Europe and LNG via shipping. The gas quality of these import streams may not be within the current UK gas specification as defined by the Gas Safety Management Regulations 1996 (GS(M)R). Furthermore, as existing UK fields decline, and as new fields are found and developed, the specifications of existing UK gas will change.

There may be opportunities to take individual gas streams at UK sub-terminals which could be outside the GS(M)R specification and blend them with on-specification gas streams to produce an on-specification output stream. However, it is not currently known whether current terminal configurations, particularly at Bacton, allow complete mixing of all gas streams prior to entry into the National Transmission System (NTS).

In order to determine whether blending could be carried out within the Bacton Terminal without endangering safety, confidence is needed that the incoming gases will mix to form a single homogenous mixture prior to leaving the terminal. In particular, the capability of the terminal pipes and equipment to produce a homogenised gas before the gas is either taken from the terminal or measured for the purposes of quality assessment must be assessed.

National Grid contracted Advantica to carry out a study to use pipeline modelling of terminal incoming and outgoing gas streams, using a number of tools including dynamic hydraulic pipeline simulation and CFD, to determine the extent of mixing of gas streams under a range of flow route scenarios and flow rates. Where confidence in complete mixing is not established by the modelling, changes to terminal configuration at the engineering level were to be considered.

This work comprised

A) Building of hydraulic pipeline models of the Bacton import terminal using SPS, based on pipeline and engineering drawings provided by National Grid.

B) Validation of the SPS models using flow data under conditions where input and output compositions were known.

C) Modelling the extent of mixing, using determination of Reynolds Number (i.e. extent of turbulence) for a range of flow routes or modes of operation for the terminal. For each mode of operation, flexes of flow were modelled, as specified by National Grid.

D) CFD analysis, using a simplified model intended to simulate mixing headers and appropriate pipe lengths. The CFD output allows further confidence to be established in extent of mixing.

E) Based on the outputs of the above, engineering solutions were to be recommended which will improve the likelihood of mixing of the gas streams prior to entry into the NTS.

Advantica were not requested to examine the safety and operational matters associated with providing a possible blending service at Bacton, although a number of the findings of this study have implications for these areas. Advantica understands that National Grid has carried out a separate, preliminary review of safety and operational matters and that its high level findings have been publicised in its Winter 2006/07 Consultation Update Document, published on the 11th July 2006

2 METHODOLOGY

2.1 Modelling Bacton Terminal

Bacton is considered to have the potential for blending as it has significant volumes of different specifications of gas flowing through it. The basic configuration of the pipelines conveying gas into (incomers) and out of (NTS feeders) for the Bacton Terminal is illustrated below:

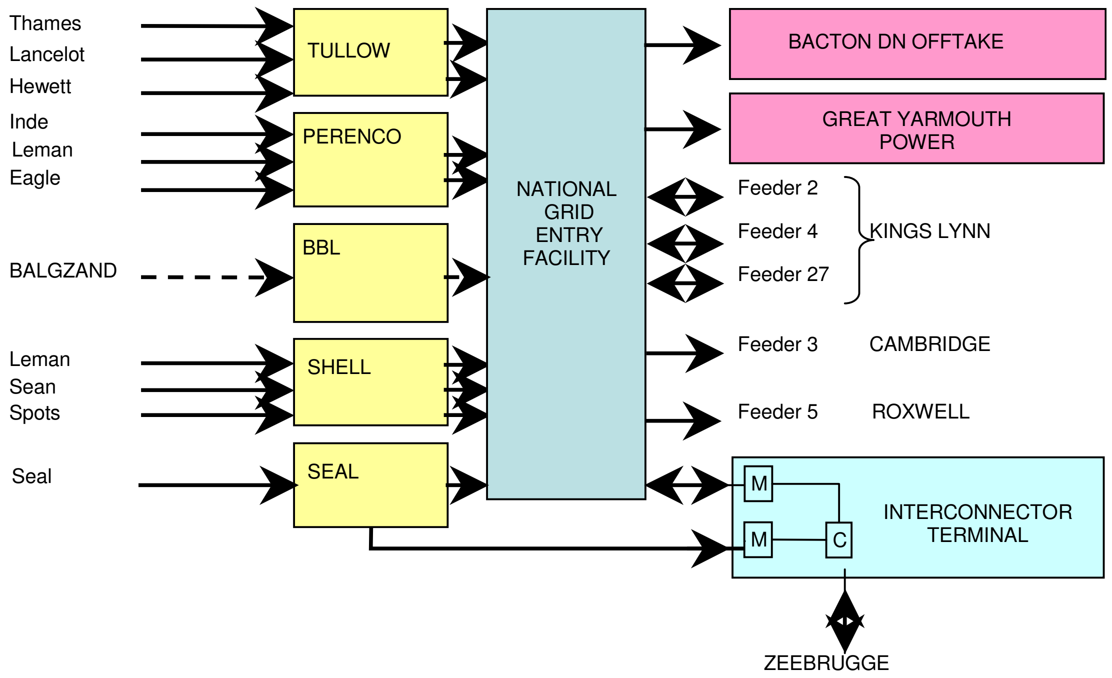


Figure 1: Schematic of Bacton Operation (Courtesy of National Grid June 2006)

The terminal, which was originally constructed in the 1960s, has at its core five manifolds, three of which correspond directly to three of the feeder pipelines taking gas out of the terminal. National Grid operates flow control valves and diverter valves to route gas from the sub-terminals, through manifolds, into particular feeders, subject to back pressure. The more recent incomer and feeder connections were retro fitted and are more complicated in their configuration. The National Grid distribution offtake and the Interconnector UK import/export facility are situated within the terminal boundary.

2.1.1 Stoner Pipeline Simulator (SPS)

The Bacton Terminal was simulated using the SPS package. SPS is an advanced transient hydraulic simulation application that simulates the dynamic flow of gases through a pipeline network. SPS can simulate any existing or proposed pipeline configuration and can predict the outcome of various control strategies both for normal operating scenarios and for abnormal conditions such as pipe rupture, equipment failure or other upset conditions. SPS calculates equipment performance and pipeline variables such as flow, pressure, density and temperature throughout the pipeline network. Equipment and pipeline parameters are displayed interactively as the simulation progresses, either in tabular reports or graphically, over time or distance. After the simulation, results are available for printing and/or plotting.

Internally, SPS uses the following partial differential equations to model flow along a pipeline:

1. Continuity Equation
2. Momentum Equation
3. Energy Equation
4. Flow Area Equation
5. Thermal Equation in Pipe and Surroundings

SPS has been used by many of the internationally recognized Engineering and Construction companies for pipeline design and analysis. SPS is also in daily use in the engineering and planning divisions of operating pipeline companies around the world, some of which have adopted SPS as a standard for pipeline analysis.

During the simulation, streams of fluids may blend (for example, at a pipe Y-junction). The specific volume of the mixed fluids is computed as the weighted average of the specific volumes of the fluids present. SPS has previously been installed on-line to track batches and compositions. The results have consistently demonstrated the capability of SPS in this type of application.

2.1.2 SPS Model

The Bacton numerical model simulated the inlet headers, plant piping and valves and feeders. The physical elevation profile and bends in the system were not simulated in this model. Equivalent lengths of pipe were used to generate the required pressure drops, but the extra turbulence that would be produced from a bend has not been simulated. Pressure drop due to friction within the pipeline was computed by means of the Darcy-Weisbach equation.

National Grid supplied schematics and flow diagrams of the Bacton Terminal.

The boundary conditions for the SPS model were the feeder outlet pressures (2, 3, 4, 5 and 27) and the manifold header flows. It was decided to simplify the model by having just one feed from each of the sub-terminals into each manifold. It was decided that modelling upstream of the inlet to the manifold would increase the model complexity (and hence simulation time) without providing any further results about whether mixing occurs.

As per regular terminal operation all flow goes via manifolds to the feeders depending on pressure.

The typical gas properties for the incomers were provided by National Grid to accurately model the mixing in the terminal.

2.1.3 Data Validation

A validation case was simulated to compare the SPS results to actual data. National Grid supplied data for 12 hours of operation relating to a particular day in January 2006 between midnight and midday. The operation saw the inlet header flows remain largely constant, but with a large increase in one particular supply flow at 6.00am. Figure 2 shows that initially this increase in flow is taken up by feeder 2 and feeder 4. After ~ 9 hours the flow is diverted to feeder 5.

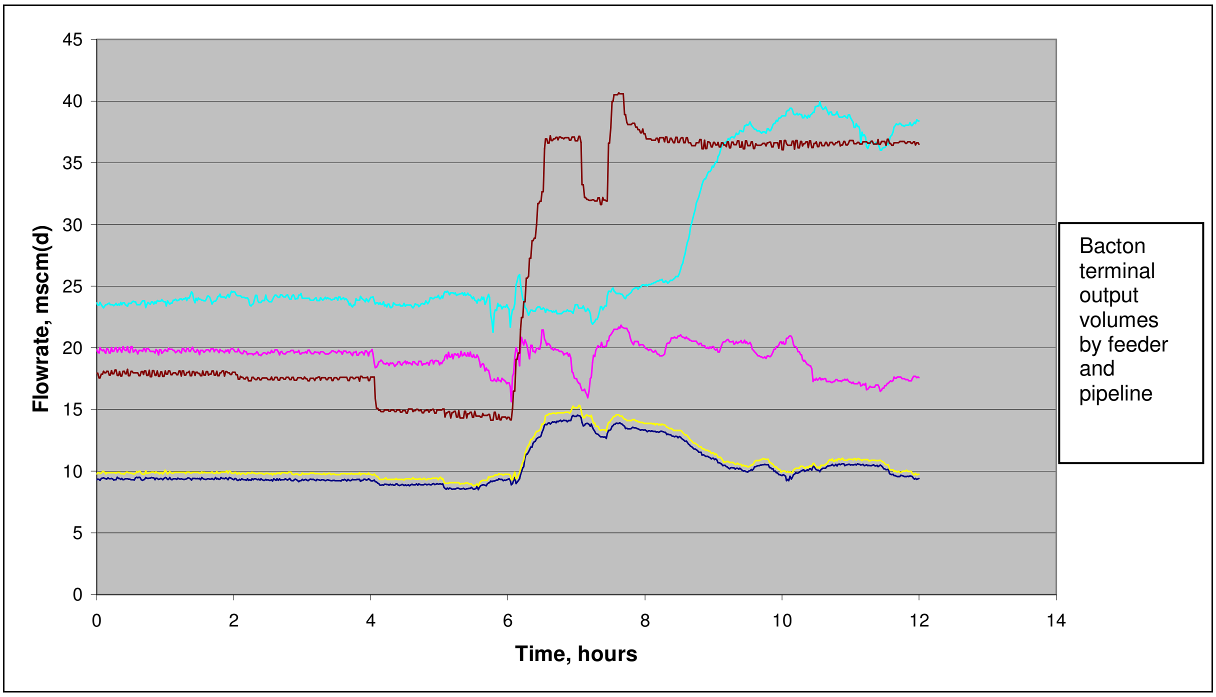


Figure 2: Comparison of Feeder Flows on the relevant day in January 2006

Steady state simulations were performed at time 0 and time 8 hours. Flows into each manifold were set and the feeder pressures varied to verify that the correct flows out of the terminal could be obtained.

SPS gives very good agreement with actual flows and shows that the flow routes through the Bacton Terminal can be accurately modelled. The validation model was also tuned to give ~0.5 bar pressure drop across the terminal pipe-work, valves, filters, meters, etc to give an accurate representation of the terminal. Table 1 shows actual and simulated flows and pressures at each feeder outlet at time = 0 hours.

Table 1: SPS Feeder Flows and Pressure, Validation Time = 0 hours

	Validation Data		SPS Simulated	
	Flow, mscm(d)	Pressure, bara	Flow, mscm(d)	Pressure, bara
Feeder 2	9.29	62.5	9.46	62.5
Feeder 3	19.84	66.2	19.90	66.2
Feeder 4	9.77	62.2	10.10	62.5
Feeder 5	21.01	66.9	21.00	66.9
Feeder 27	19.75	Unknown	18.90	61.1
Total	**79.66**		**79.36**	

The operational data supplied by National Grid showed that by 8am on the same day in January 2006, the flow from the same source of gas had doubled. Table 2 shows the actual and simulated flows and pressures at each feeder outlet at time = 8 hours.

Table 2: SPS Feeder Flows and Pressure, Validation Time = 8 hours

	Validation Data		SPS Simulated	
	Flow, mcmd	Pressure, bara	Flow, mcmd	Pressure, bara
Feeder 2	13.34	62.5	13.41	62.5
Feeder 3	20.02	66.2	19.90	66.2
Feeder 4	13.86	62.2	13.70	62.5
Feeder 5	23.21	66.9	23.19	66.9
Feeder 27	21.52	Unknown	21.60	61.1
Total	**91.95**		**91.80**	

The results in Table 2 show that SPS is able to accurately model the complicated flow paths and required splitting between the feeders.

Thus it has been verified that:

- SPS is able to model the complex network of pipes in the Bacton Terminal and accurately simulate the flow splitting between the feeders.
- SPS models the ~0.5 bar pressure drop across terminal.

2.2 SPS Scenario Development

A total of 12 basecase "modes of operation" were defined through discussion with National Grid. These were designed with the intent of simulating as many terminal configurations as possible under the widest range of flow conditions. The scenarios were based on a typical supply pattern and a distribution of flows across the feeders based on network analysis at the appropriate demand. All modes of operation are illustrated in APPENDIX B. They are described according to the total demand taken from the terminal during the day, each demand level being met by a number of different strategies of supply at the incomers. Hence, "60 Strategy 1" describes a total demand of 60mscm(d), first flow strategy. Total demands of 60, 90, 120 and 150mscm(d) were modelled.

2.2.1 Flow Flexes

Transient flow flexes were performed on the 120mscm(d) strategies to assess the effect of reducing the incomer flows to zero in turn. Closing the manifold inlet flow controllers linearly over 30s simulated the reduction in flow. The 120mscm(d) strategies were chosen because these best reflected the impact of the Interconnector UK and BBL flows. The cases were run from the above base-case strategies and the feeder composition during the transient was tracked.

2.3 CFD Analysis

2.3.1 Background

CFD has been used to support the SPS modelling and gain an understanding of the mixing lengths for two gas flows joined at a tee junction at high pressure. The CFD simulations can be regarded as indicators of the overall mixing process in an idealised system, but should not be taken as completely realistic as the geometrical set-up has been idealised for ease of comparison of different data sets.

The CFD software used was Fluent and the geometrical set-up was produced in the sister software (Gambit).

2.3.2 Geometrical Mesh and Set-up of the CFD model.

The intersection of two pipes in a standard 90° normal tee-junction has been set-up in separate models. The first model intersects a 10m long (branch connection) pipe with a 25m long pipe (header) to create a tee-junction with the connection mid-point along the 25m pipe (as shown in Figure 3).

The second simulation was similar to the first but with a longer "tail-piece" downstream of the tee connection on the outflow. Here the intersection is of a 10m long pipe (branch connection) with a 40m long pipe (header) and the connection is 10m from the first pipe inlet (as shown in Figure 4). Finally a pipe geometry allowing analyses up to 50m downstream of the mixing point was built. Results from the longer pipes were identical up to the 12m point to those for the shorter pipe, so only results from the longer pipes are presented here.

Models were set-up in 3-dimensions (3D) to provide the most comprehensive simulation possible.

The pipe diameter was set at 0.88m (the approximate internal diameter for a 900mm diameter pipe) and the pipe material was set to steel.

The computational domain was "meshed" (split into small volumes representing a distinct volume within the pipe using a Tetrahedral/hybrid TGrid[1] method). The mesh length input was 0.15m, but it should be noted that the use of the TGrid method ensures that the resolution of the results are greater than this figure, as the unstructured node layout gives points at pseudo-random intervals along any plane or line.

In addition to the mesh for the main volume of the tee-junction, a small boundary layer was added to the simulation. This layer was three cells thick and constituted a thin layer of gas next to the pipe wall, which was either static or flowing very slowly.

2.3.3 Turbulence Model Used

The numerical computations were generated using the 3D steady-flow finite volume solver and, in total, six transport equations were solved, including the continuity, momentum, turbulent kinetic energy and eddy dissipation rate equations. To obtain a solution, the First Order Upwind scheme and also the Quick scheme of Leonard (1979)[2] were employed for the convection of mean velocities, mixture fraction and the turbulence quantities. The SIMPLE model developed by Patankar (1980)[3] was used in the pressure correction algorithm.

A standard eddy viscosity model, k-e, of Launder & Spalding (1972)[4] was used for modelling the turbulence nature of the flows.

[1] Starting from a given boundary mesh, TGrid (licensed by FLUENT Inc) generates an unstructured triangular or tetrahedral (or hybrid) grid. The mesh includes hexahedral, pyramidal, and wedge elements where appropriate and consists of nodes and triangular and/or quadrilateral faces.

[2] Leonard, B.P., A Stable and Accurate Convective Modelling Procedure Based on Quadratic Upstream Interpolation, Comp. Maths. Appl. Mech. Eng., Vol. 19:59-98 (1979).

[3] Patankar. S.V., Numerical Heat Transfer and Fluid Flow, McGraw-Hill, New York (1980).

[4] Launder, B.E., and Spalding, D.B., The Numerical Computation of Turbulent Flows, Comp. Meth. Appl. Mech. Eng., vol. 3:269-289 (1972)

2.3.4 Boundary Conditions

At the start of the computations a series of boundary conditions was input to the simulation including the mass flow rate at the two input points, the absolute pressure (typically 50 bar) and the temperature (set to 280K).

Also, a velocity down the main header pipe of 1 m/s was set to establish the overall flow.

The inlet turbulent kinetic energy and the dissipation rate were assumed to be 5 and 50 m^2s^{-2} respectively.

A standard outflow boundary condition was used for the outlet pipe, i.e., a zero pressure gradient across the outlet plane.

Additionally, the following data set was used:

- Gases were assumed to be typical pipeline, and high CV LNG. Compositions as provided by National Grid were assumed, giving Wobbe numbers of approximately 50.3 MJ /m^3 and 53 MJ/m^3 respectively, i.e. the LNG was assumed to be significantly out-of-specification for GS(M)R.
- Both 50%/50% (50% of the flow through the branch connection, and 50% of the flow through the header pipe) flow and 90%/10% (90-10) flow mixes were used. Flows were increased from a low of 21kg/s through each pipe up to 210kg/s for the 50-50 case. These corresponded to flows through the pipe from 5mscm(d) to 50mscm(d). For the 90-10 case, the same maximum and minimum total flow limits were used, with the lower flow being switched from tee to header pipe for different simulation runs.

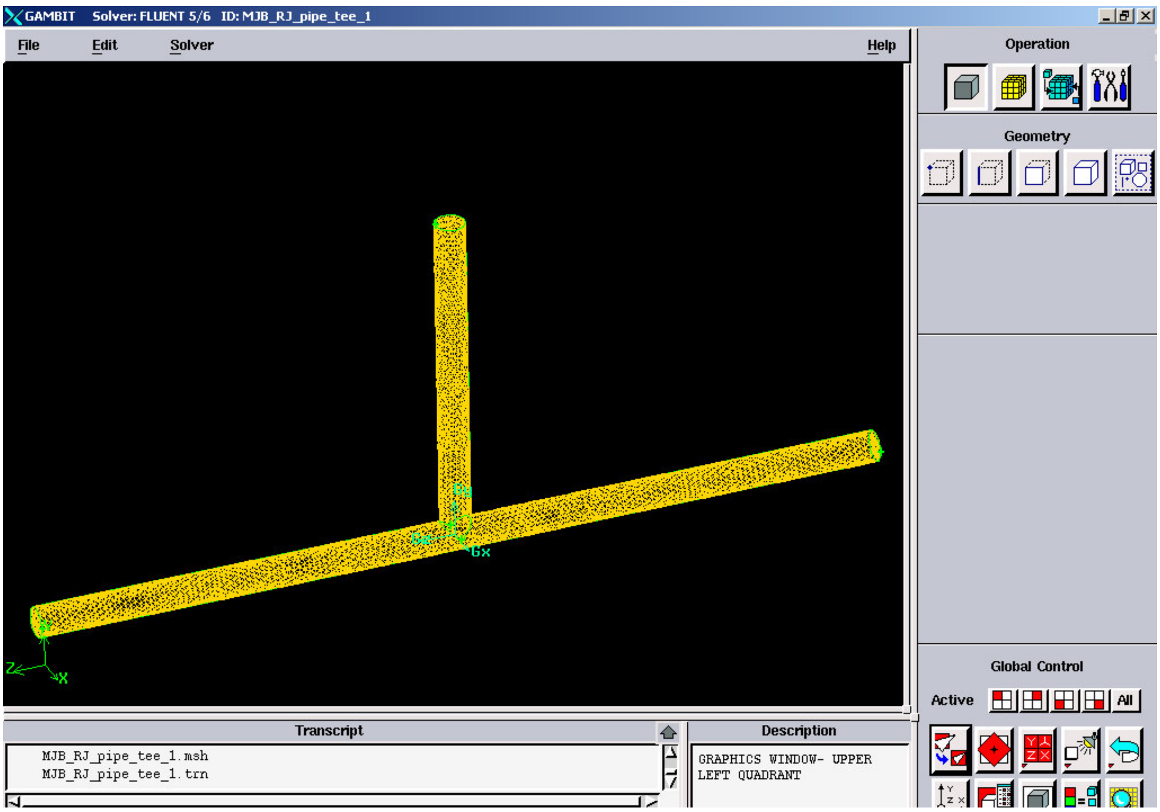


Figure 3: "Short" tee-junction simulation.

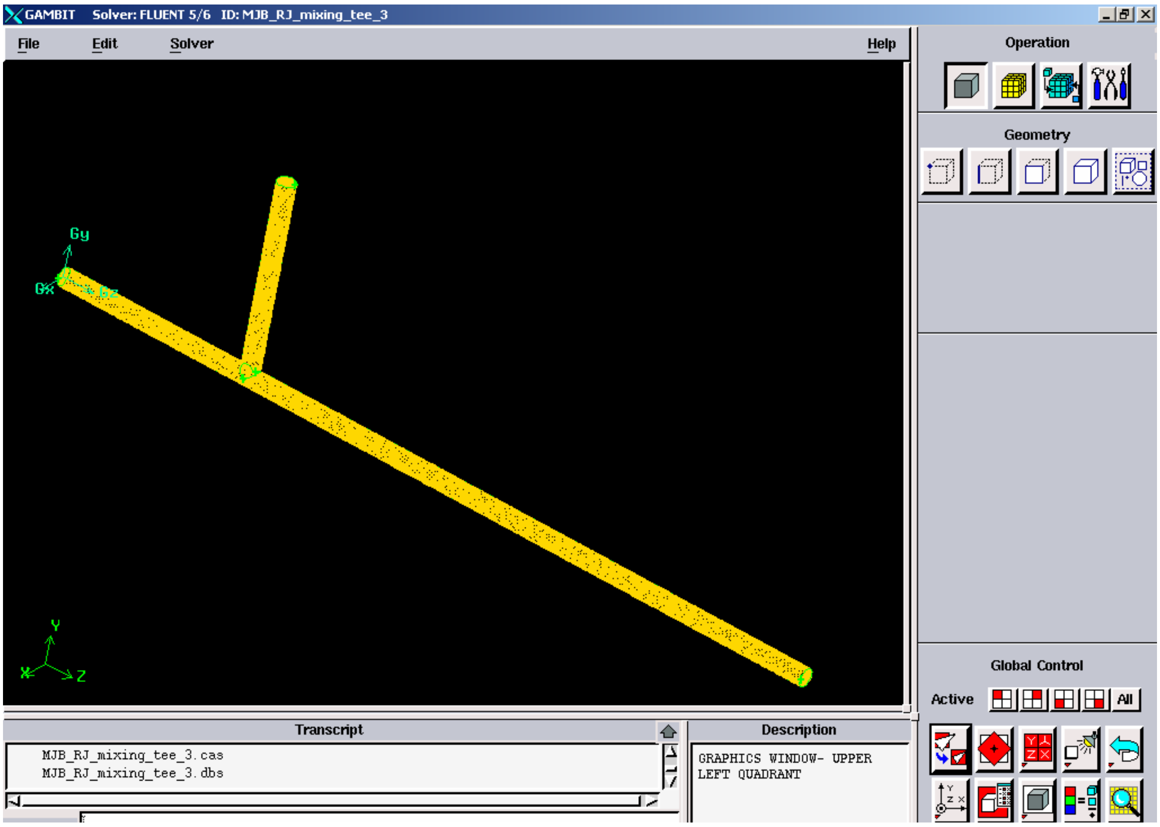


Figure 4: "Longer" tee-junction simulation.

3 RESULTS

3.1 SPS Results

3.1.1 Base-case Modes of Operation

The flow strategies described in section 2.2 were simulated using SPS to examine the Reynolds Number at the point of exit of the terminal (inlet to feeder) to determine if the flow was turbulent (i.e. above a Reynolds Number of 4,000). The feeder fluid mixture was also determined so that further analysis could be performed for the gas quality issues.

In all of the cases simulated the Reynolds Number was far above 4,000, with the smallest recorded (7,400,000) in feeder 2, but still a magnitude of 1,000 greater than that which corresponds to transition to turbulent flow. However, no scenarios simulated extreme low flows (e.g. flow restart), which would decrease the Reynolds Number.

It is important to note that although a significant number of modes of operation have been modelled here, the complexity of the Bacton Terminal means that this analysis can not guarantee to cover all modes which could possibly be used. Whilst the Bacton Terminal has considerable flexibility there could be major issues with respect to control and instrumentation, and the loss of one or more incomers could lead to conditions where there is no mixing. The following discussion on flow flexes also illustrates that it is an erroneous assumption that gas quality will follow loss of an incomer in a linear fashion.

All of the fluid mixtures and Reynolds Numbers, for static flow scenarios are shown in Table 3 - Table 14. Within the tables, the letters A – F represent the individual sub-terminals which input gas at the Bacton terminal.

Table 3: Scenario 1 – 60 Strategy 1

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	7	25.0	17.9	23.7	33.5	0.0	0.0	100.0	7500000
3	16	0.0	12.5	42.7	44.8	0.0	0.0	100.0	17000000
4	7	25.0	17.9	23.7	33.5	0.0	0.0	100.0	7400000
5	16	18.8	18.8	36.8	25.7	0.0	0.0	100.0	17000000
27	14	25.0	17.9	23.6	33.5	0.0	0.0	100.0	15000000

Table 4: Scenario 2 – 60 Strategy 2

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	7	25.0	25.0	16.6	33.4	0.0	0.0	100.0	7400000
3	16	0.0	18.8	61.8	19.4	0.0	0.0	100.0	17000000
4	7	25.0	25.0	16.6	33.4	0.0	0.0	100.0	7500000
5	16	18.7	0.0	30.4	50.9	0.0	0.0	100.0	17000000
27	14	25.0	25.0	16.6	33.4	0.0	0.0	100.0	15000000

Table 5: Scenario 3 – 60 Strategy 3

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	7	25.0	25.0	16.6	33.4	0.0	0.0	100.0	7400000
3	16	0.0	18.8	61.8	19.4	0.0	0.0	100.0	17000000
4	7	25.0	25.0	16.6	33.4	0.0	0.0	100.0	7400000
5	16	18.8	0.0	30.4	50.9	0.0	0.0	100.0	17000000
27	14	25.0	25.0	16.6	33.4	0.0	0.0	100.0	14000000

Table 6: Scenario 4 – 90 Strategy 1

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	11	24.7	18.3	23.9	33.2	0.0	0.0	100.0	12000000
3	22	0.0	9.4	31.0	32.4	27.2	0.0	100.0	23000000
4	11	25.1	18.1	23.6	33.3	0.0	0.0	100.0	12000000
5	22	13.9	14.0	26.6	18.5	27.0	0.0	100.0	23000000
27	24	6.6	4.9	6.3	8.8	73.4	0.0	100.0	25000000

Table 7: Scenario 5 – 90 Strategy 2

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	11	19.7	14.1	28.1	38.1	0.0	0.0	100.0	12000000
3	22	0.0	0.0	11.4	0.0	88.6	0.0	100.0	23000000
4	11	19.7	14.1	28.1	38.1	0.0	0.0	100.0	12000000
5	22	13.6	22.7	31.1	32.5	0.0	0.0	100.0	23000000
27	24	11.6	8.3	16.5	22.3	41.4	0.0	100.0	25000000

Table 8: Scenario 6 – 90 Strategy 3

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	11	15.4	10.3	39.4	35.0	0.0	0.0	100.0	12000000
3	22	18.8	0.0	0.0	0.0	81.2	0.0	100.0	23000000
4	11	15.4	10.3	39.4	35.0	0.0	0.0	100.0	12000000
5	22	0.0	27.3	17.7	27.8	27.3	0.0	100.0	23000000
27	24	11.8	7.9	30.2	26.8	23.3	0.0	100.0	25000000

Table 9: Scenario 7 – 120 Strategy 1

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	16	18.9	21.9	33.6	25.6	0.0	0.0	100.0	17000000
3	28	0.0	7.1	8.7	25.2	59.0	0.0	100.0	29000000
4	15	18.6	21.9	33.7	25.8	0.0	0.0	100.0	16000000
5	28	11.0	0.0	15.8	14.6	58.6	0.0	100.0	29000000
27	33	3.7	4.2	6.5	4.9	50.4	30.3	100.0	35000000

Table 10: Scenario 8 – 120 Strategy 2

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	16	16.9	16.9	34.6	31.7	0.0	0.0	100.0	17000000
3	28	0.0	10.7	0.0	0.0	89.3	0.0	100.0	29000000
4	15	16.9	16.9	34.6	31.7	0.0	0.0	100.0	16000000
5	28	11.0	0.0	17.4	27.2	44.4	0.0	100.0	30000000
27	33	5.7	5.7	11.6	10.6	36.2	30.3	100.0	35000000

Table 11: Scenario 9 – 120 Strategy 3

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	16	18.9	21.6	33.7	25.7	0.0	0.0	100.0	17000000
3	28	0.0	7.2	8.7	25.3	58.9	0.0	100.0	29000000
4	15	18.9	21.6	33.7	25.7	0.0	0.0	100.0	16000000
5	28	11.0	0.0	15.8	14.6	58.6	0.0	100.0	29000000
27	33	3.7	4.2	6.6	5.0	50.1	30.3	100.0	35000000

Table 12: Scenario 10 – 150 Strategy 1

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	25	10.1	10.1	56.9	23.0	0.0	0.0	100.0	27000000
3	28	0.0	10.7	0.0	0.0	89.3	0.0	100.0	29000000
4	24	10.1	10.1	56.9	23.0	0.0	0.0	100.0	25000000
5	20	16.1	0.0	0.9	21.6	61.4	0.0	100.0	21000000
27	53	4.0	4.0	22.5	9.1	22.8	37.7	100.0	56000000

Table 13: Scenario 11 – 150 Strategy 2

		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	25	12.9	11.3	52.5	23.3	0.0	0.0	100.0	27000000
3	28	0.0	10.7	24.3	11.4	53.6	0.0	100.0	29000000
4	24	12.9	11.3	52.5	23.3	0.0	0.0	100.0	25000000
5	20	10.8	0.0	0.0	15.0	74.2	0.0	100.0	21000000
27	53	3.3	2.9	13.3	5.9	36.9	37.7	100.0	56000000

Table 14: Scenario 12 – 150 Strategy 3

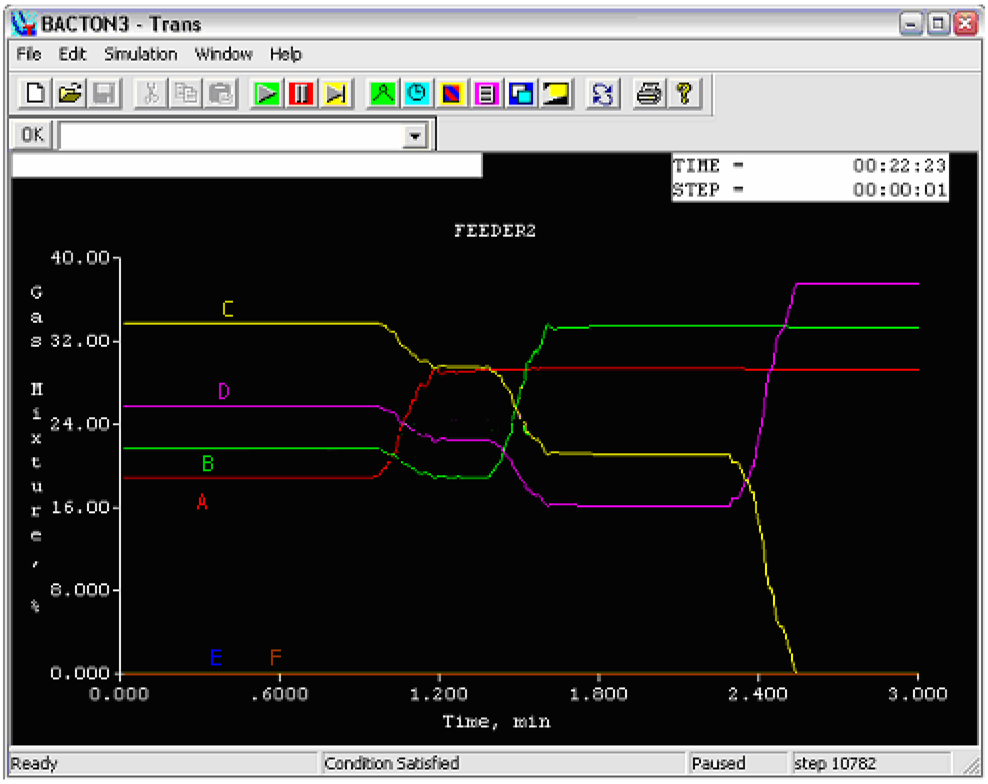
		% Flows							
Feeders	Total Flow, mscm(d)	A	B	C	D	E	F	∑	Reynolds No.
2	25	12.9	12.9	49.2	25.0	0.0	0.0	100.0	27000000
3	28	0.0	7.3	14.3	0.0	78.4	0.0	100.0	29000000
4	24	12.9	12.9	49.2	25.0	0.0	0.0	100.0	25000000
5	20	10.8	0.0	23.7	26.2	39.4	0.0	100.0	21000000
27	53	3.3	3.3	12.7	6.4	36.7	37.5	100.0	56000000

3.1.2 Flow Flexes

The flow flexes were performed to assess the effects of reducing a single incomer flow to zero. Closing the manifold inlet flow controllers linearly over 30s simulated the reduction in flow. The pressure boundary at the inlet to the feeders was assumed to remain constant. The fluid mixture at the inlet to the feeders was examined to determine the change in composition during and after the flow flex. Where compositions are known this can then be analysed further in terms of gas quality.

Figure 5 shows the gas mixture exiting the terminal in to feeder 2 for the duration of the flow flex ("120 Strategy 1" – Flex Gas C). It clearly shows the importance of modelling the transient because the fluid mixture does not change from one steady state to another instantaneously (i.e. before and after flow flex). The proportion of Gas C in the gas mixture decreases in 3 distinct stages. It also shows that Gas B and Gas D first decrease before increasing in proportions. This transient effect could have a large impact on the gas quality during the flow flex. Also as the transient is over in less than 3 minutes the existing analysers might not detect it.

Figure 5: Feeder 2 Gas Mixture



The feeder 3 gas mixture during the flow flex is shown in Figure 6. This follows a similar trend to feeder 2 but is not as distinct (due to a lower initial proportion of Gas C flow). The Gas C proportion this time declines in 2 distinct stages and the Gas D first decreases before increasing in proportion.

Figure 6: Feeder 3 Gas Mixture

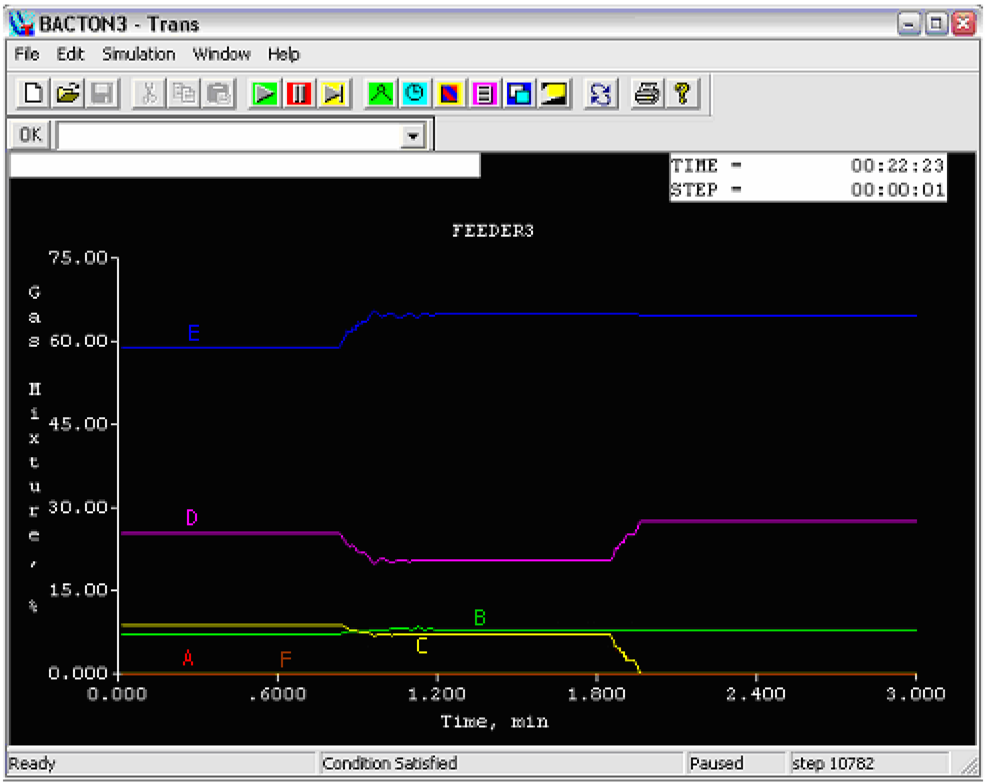
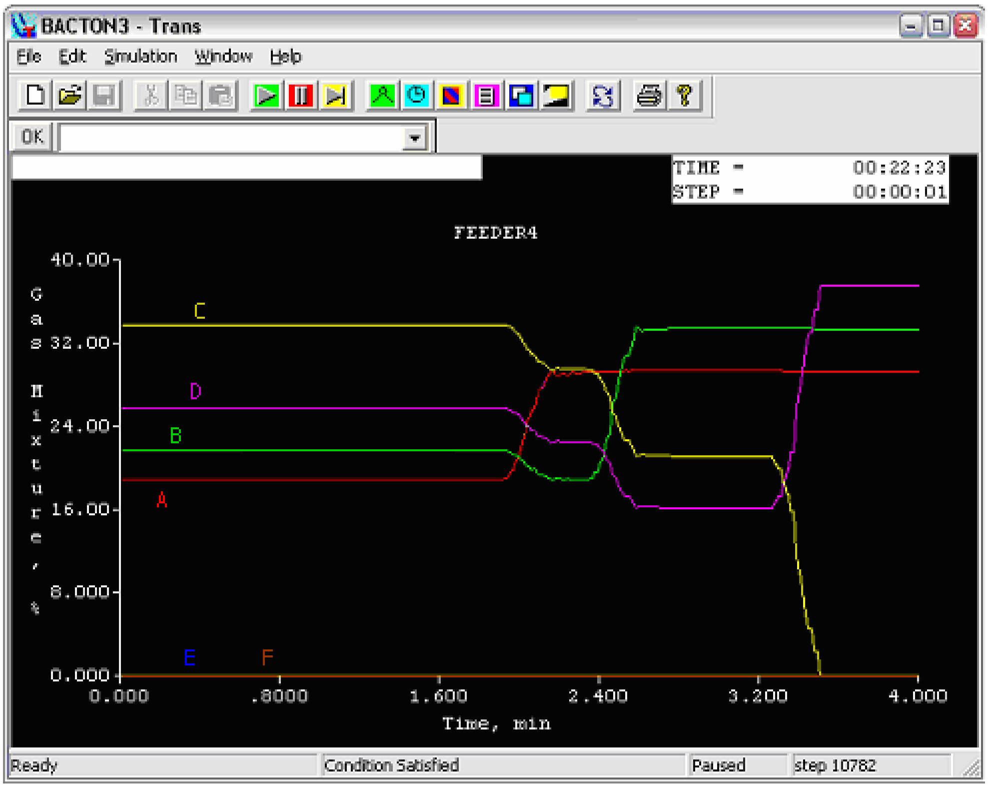


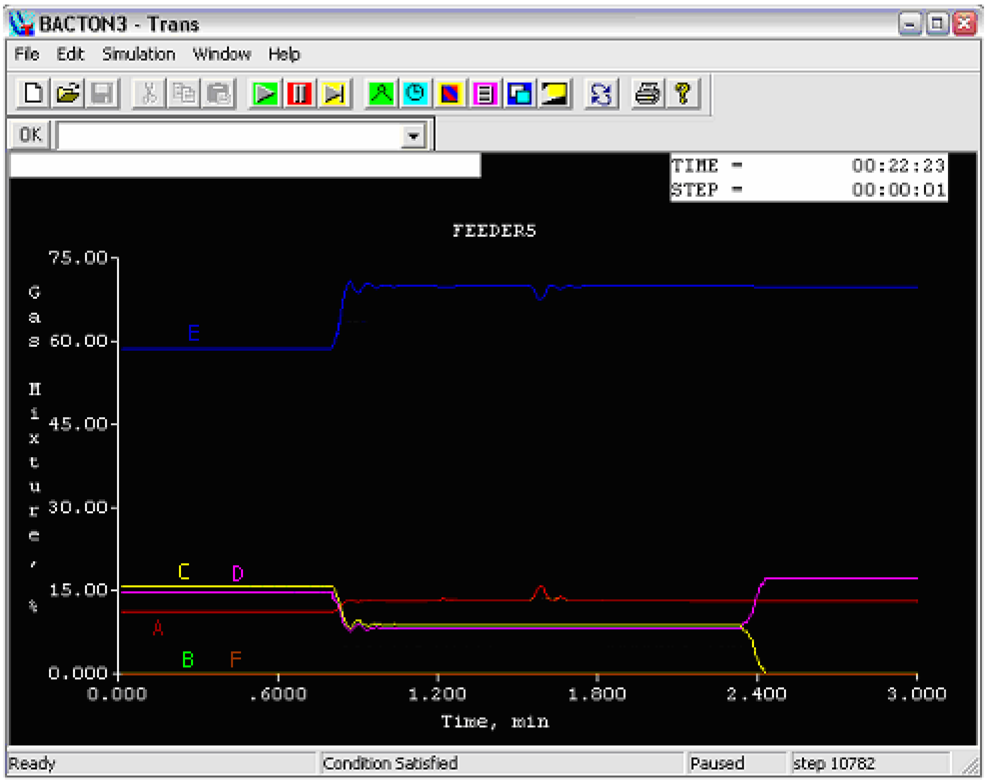
Figure 7 shows the feeder 4 gas mixture. As feeder 2 and feeder 4 are in parallel with each other the transient shows the same effect on the gas mixture.

Figure 7: Feeder 4 Gas Mixture



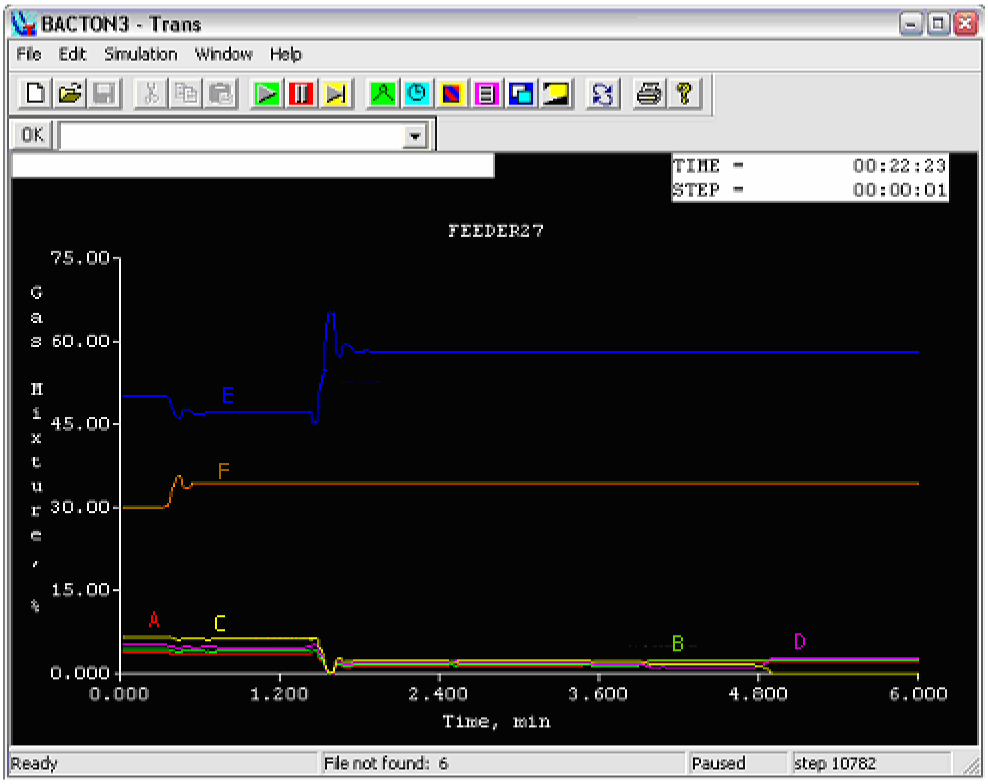
The importance of modelling the transient is also shown in Figure 8, where the feeder 5 gas mixture is shown. It shows that an instantaneous switch from one steady-state condition to another (before and after flow flex) cannot be assumed.

Figure 8: Feeder 5 Gas Mixture



The gas mixture of feeder 27 illustrated in Figure 9 shows another important transient effect that needs to be modelled as it could have a large effect on gas quality. At ~1.5 minutes the Gas C proportion drops to zero, after about 20 seconds the proportion rises back up to ~5%. At the same time the Gas E flow increases to ~65% before decreasing to ~58%. This “spike” in composition is likely to be missed by the current sampling time of the analysers. However, it could under certain circumstances result in the gas being off-specification for a short period of time.

Figure 9: Feeder 27 Gas Mixture



The following conclusions can be drawn from all of the flow flex cases simulated:

- An instantaneous switch from one steady-state condition to another (before and after flow flex) cannot be assumed.
- Spikes of compositions occur over ~20s.
- The gas quality during the flow flexes should be analysed by tracking the Wobbe Number.

3.1.3 Transit Times

SPS was also used to investigate the transit times across the terminal from incomer to feeder and the Bacton offtake. The transit times for 120 mscm(d) Strategy 1 and 150 mscm(d) Strategy 2 are shown in Table 15. It shows that the transit times could be as little as 35 seconds. National Grid would only have this short length of time to alter the control of the system to prevent off specification gas entering the NTS.

Table 15: Bacton Transit Times

Feeder	Transit Time, sec	
	120 mscm(d)	150 mscm(d)
2	117	48
3	41	45
4	150	60
5	50	55
27	86	43
Offtake	35	40

3.2 CFD Simulations

CFD was used to determine the extent and dynamics of mixing for simple "worst case" scenarios. These assumed that 2 disparate gases, one of them off-specification, could mix less than 10m from an analysis or off-take point (a situation which can only occur under exceptional configuration modes). In other circumstances, the distance to analysis will be at least 36.5m.

Simple geometries were also used which were not intended to mimic the conditions of pipe-work at the Bacton Terminal, but give the least encouragement to blending of the gas. Gases were assumed to mix at the tee, and no mechanism for inducing swirl or mixing was assumed or incorporated. Boundary or initialisation conditions were identical in each case other than the parameters of pressure, relative gas flows and absolute flows. As such it is likely that real blending distances will, if anything, be shorter than those estimated by CFD. The initial geometries only allowed for 10m downstream of mixing. However, as subsequent analysis showed that some incomplete mixing was observed in this distance, models of longer pipes were built allowing analysis of the system to 50m.

Selected results of the CFD simulations are shown in Figure 10 and Figure 11. Results in Figure 10 are presented as palletised representations of methane concentration through the pipe (i.e. different methane amounts were assigned different colours so that across a section of pipe, homogenised gas appears as a single colour and an inhomogeneous mix appears as several colours), and also as vertical (assuming the tee connection is to the top of the header pipe) slices through the pipe downstream of the mixing point at 5, 10, 12, 15 20 and 25m. Although the simple palletised representations indicate full mixing within the pipe, the cross sections are able to give more detail on the overall extent of mixing as a function of pipeline cross sectional position. Note that a fully homogenised mixture would have a flat profile. Figure 11 plots similar vertical slices for a long pipe model at distances up to 50m for four different flow cases.

Some observations emerge:

- Initial observation of the flow patterns indicates that mixing occurs rapidly and is largely complete within 5-10m downstream of the mixing point (tee connection).
- The high-flow 90-10 cases seem at first sight to show a degree of incomplete mixing in the CH_4 contour plots, which is greater than for other cases. It is likely that gas at low velocity is being entrained alongside the high flow gas at the pipe wall leading to some stratification. However, analysis of the sectional profiles across the pipe from top to bottom (assuming the tee is at the top) gives more information:
    - The high flow, 50/50 cases appear to indicate a change in CH_4 concentration from top to bottom of the pipe of the order of 0.8% at 10m from mixing point. As the gases used have CH_4 concentration differences of 6%, and Wobbe differences of approximately 3 MJ/m^3, this could correspond to differences in Wobbe across the pipe of the order of 0.4MJ/m^3. Low flow 50/50 cases gave similar levels of variation. This corresponds to an inhomogeneity of approximately 13% (i.e. 0.8% in 6%).
    - In the 90-10 cases, the profile across the pipe gives a concentration gradient of 0.4%CH_4 or 0.2% CH_4 at 10m, depending on whether the low

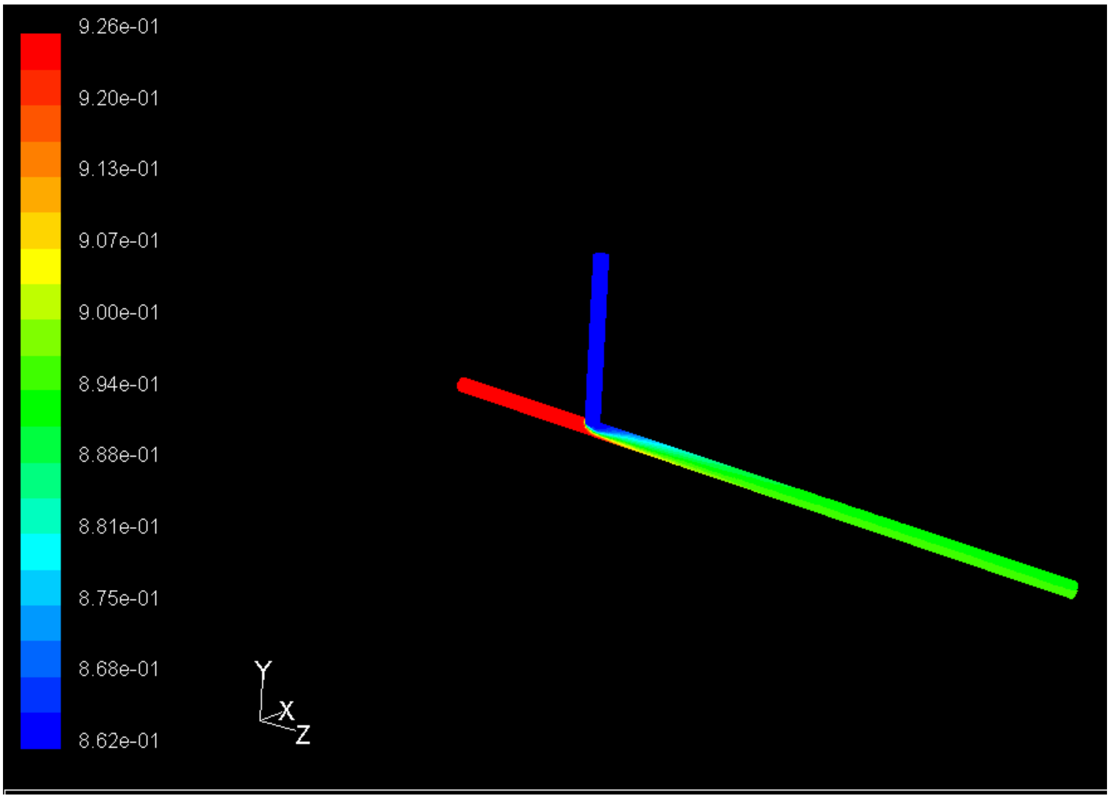
- flow is from the tee, or along the main pipe run, respectively. This corresponds to inhomogeneity of 6% or 3% i.e. the concentration gradient is smaller for the 90-10 case, despite the apparent stratification. This probably reflects the smaller overall change in Wobbe Number on mixing with a small quantity of different gas of different calorific value.
- At 5m from the mixing point, the variation in concentration is typically 3% CH_4 across the pipe for the 50-50 cases, and 1% CH_4 for the 90-10 cases. This suggests a Wobbe variation between top and bottom of pipe of about 1.5MJ/m^3 for the 50-50 cases at 5m (50% inhomogeneity), and 0.4MJ/m^3 in the 90-10 cases (13% inhomogeneity). This could have some consequences for analysis under possible exceptional configurations at Bacton. In all cases for this geometry, if analysis samples from pipe centre, an average concentration would be observed.
- By 20m downstream the concentration profile across the pipe is virtually flat to within 0.1% homogeneity in CH_4 concentration, and there are unlikely to be any problems with blending as long as off-takes or measurement are at distances greater than this. These results seem to confirm the assumptions of the ISO recommendations on gas sampling[5], which suggest that for accurate measurement of gas composition, measurement devices should be placed more than 20 pipeline diameters from mixing points.

- It is important to note that these are simulations, and for an ideal or 'worst' case. Real pipeline conditions and geometries are likely to lead to higher turbulence and more mixing due to additional flow perturbations.
- Interestingly, for a specific gas mixture, CFD outputs indicate that mixing lengths remain identical, virtually independent of the total flow or the pressure through the system. This can be explained as follows:
  - There is no randomisation in the boundary conditions used to initialise the CFD runs.
    - CFD is using turbulent Reynolds Number and gas properties to calculate the composition in each cell. Reynolds Number has a very simple linear relationship to density and velocity. As velocity of gas increases with flow, Reynolds Number will increase linearly with the velocity.
  - The time taken to mix will consequently be inversely proportional to the Reynolds Number, resulting in an identical mixing length as velocity changes.
  - A similar argument applies to pressure. Reducing pressures by a factor of ten will increase pipeline velocities by a similar amount for equivalent flows, and therefore the effect on Reynolds Number will be by the same factor. However, gas density will decrease by the same factor, cancelling the effect of increased velocity.

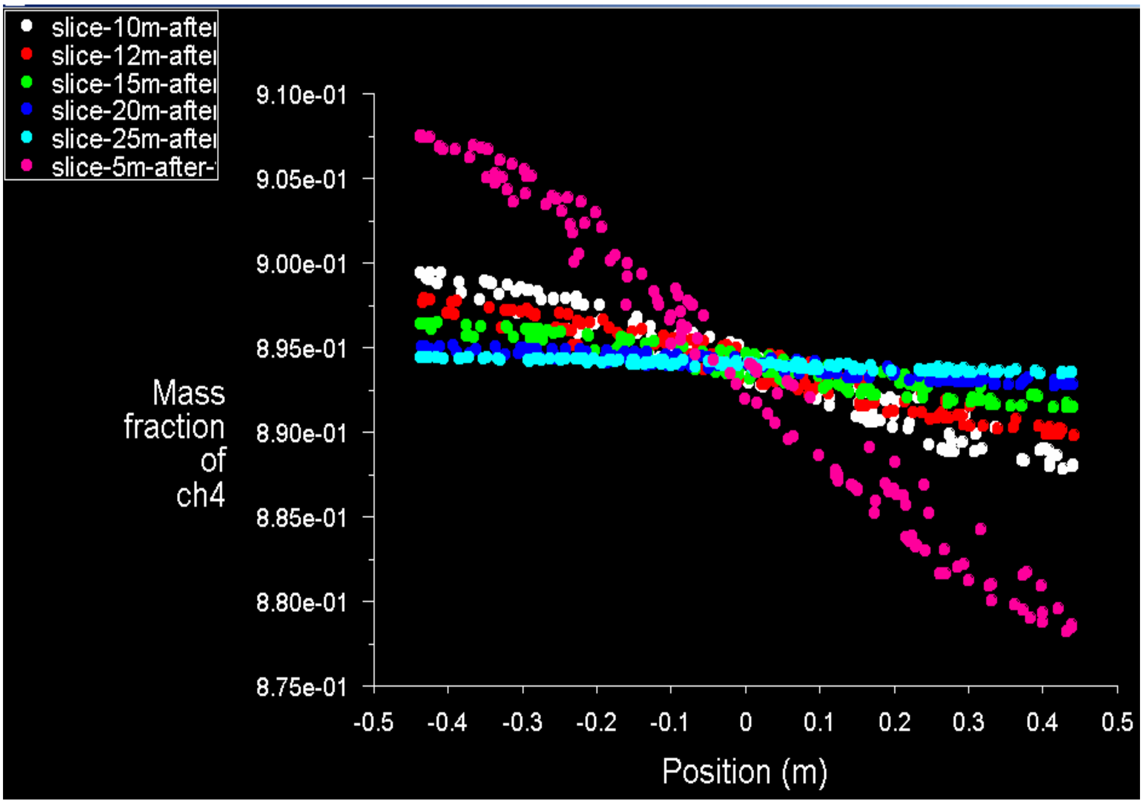
[5] BS EN ISO 10715:2001 Natural Gas sampling Guidelines

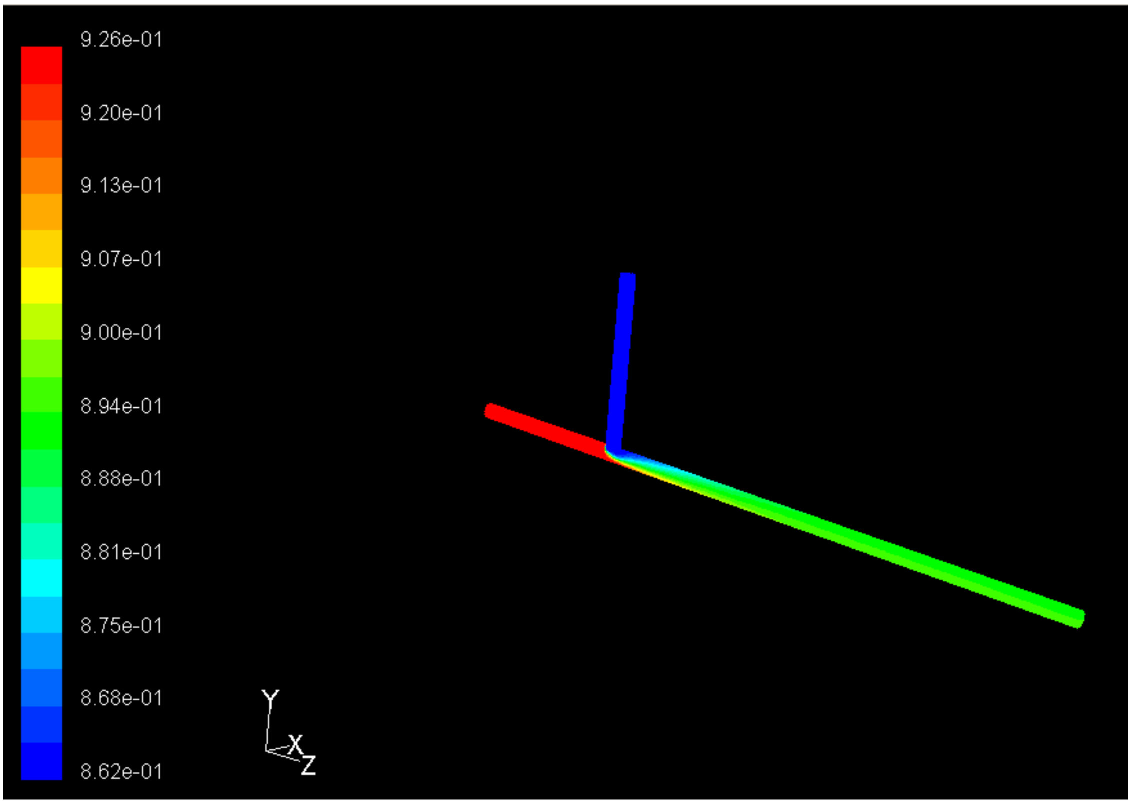
Figure 10: CFD simulation results. All at 50 bar

(top frame: Contours of CH4 Concentration top frame, bottom frame, vertical pipeline slices downstream of mixing point, CH4 mass fraction)

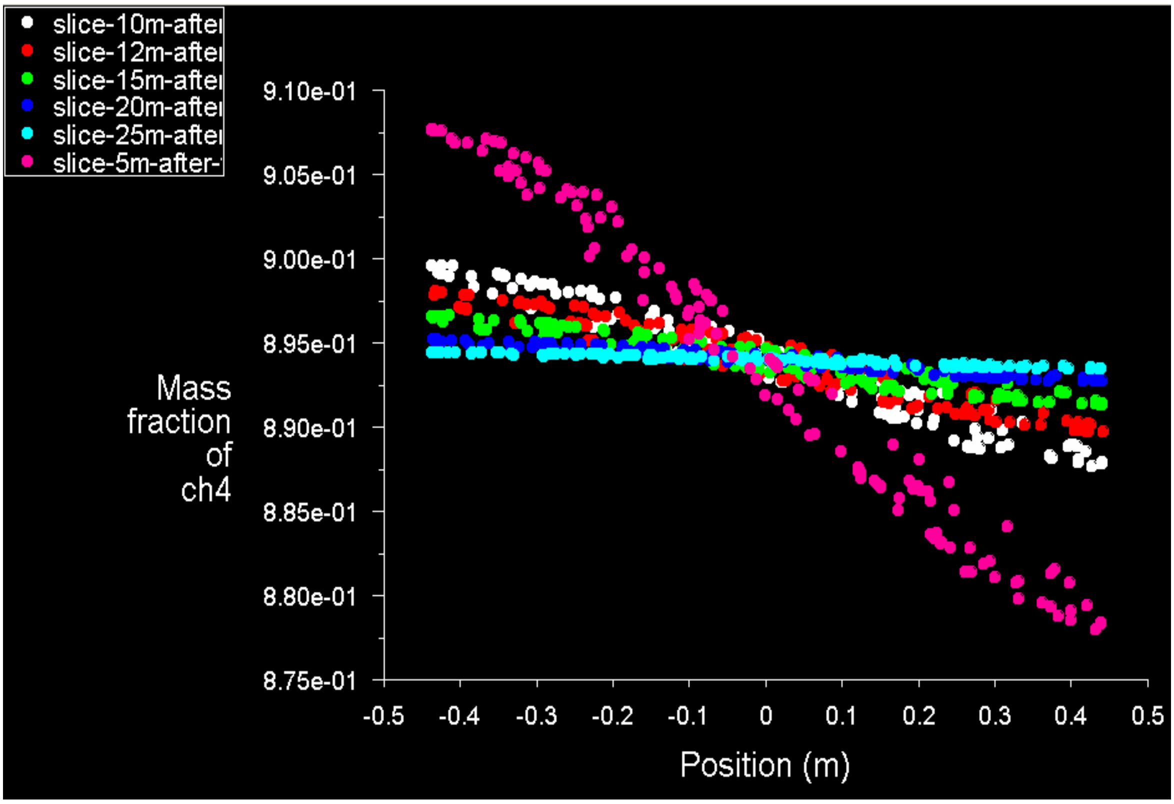


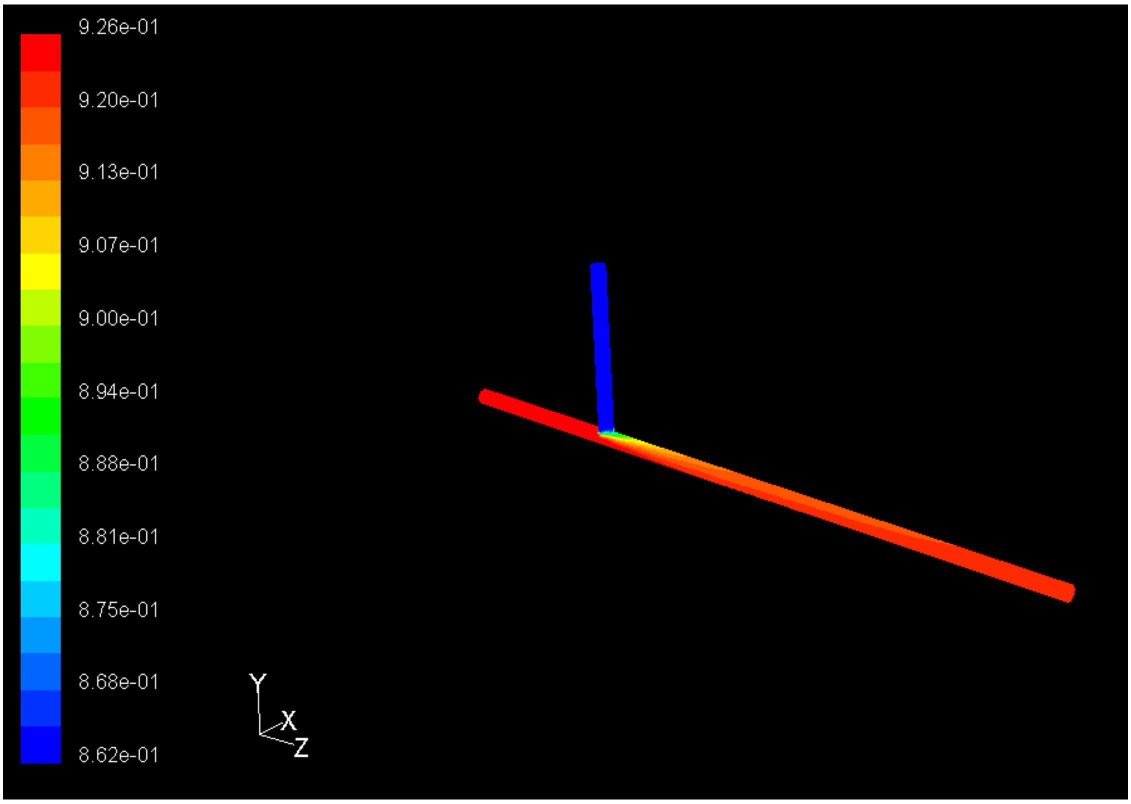
a) 5mscm(d) total flow, 50/50 gas mixture (Average velocity 1m/s)



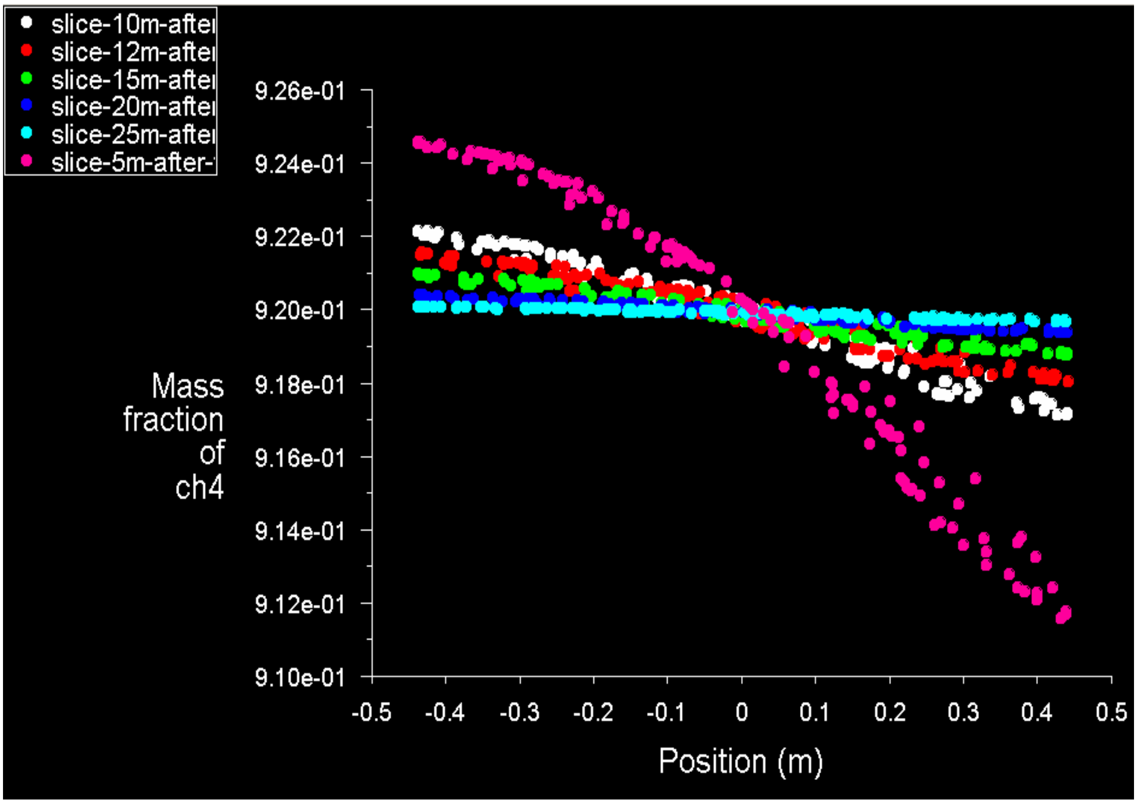


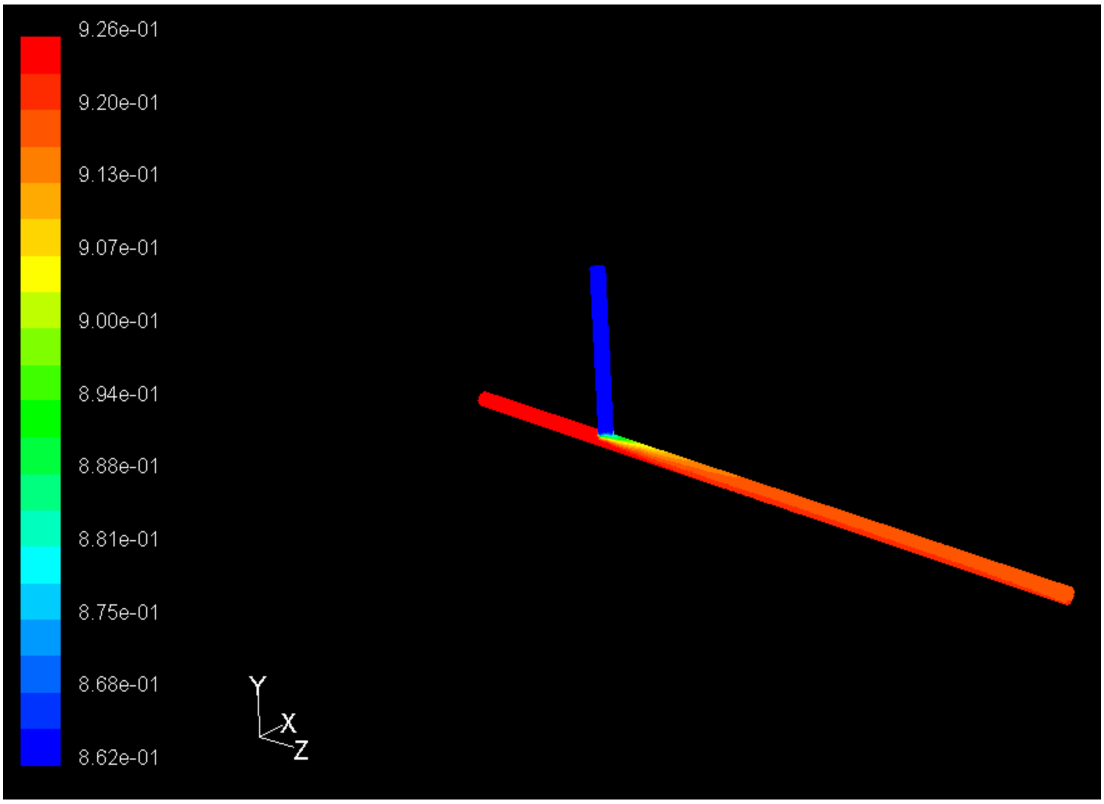
b) 50mscm(d) total flow 50/50 mixture (Average velocity 10m/s)



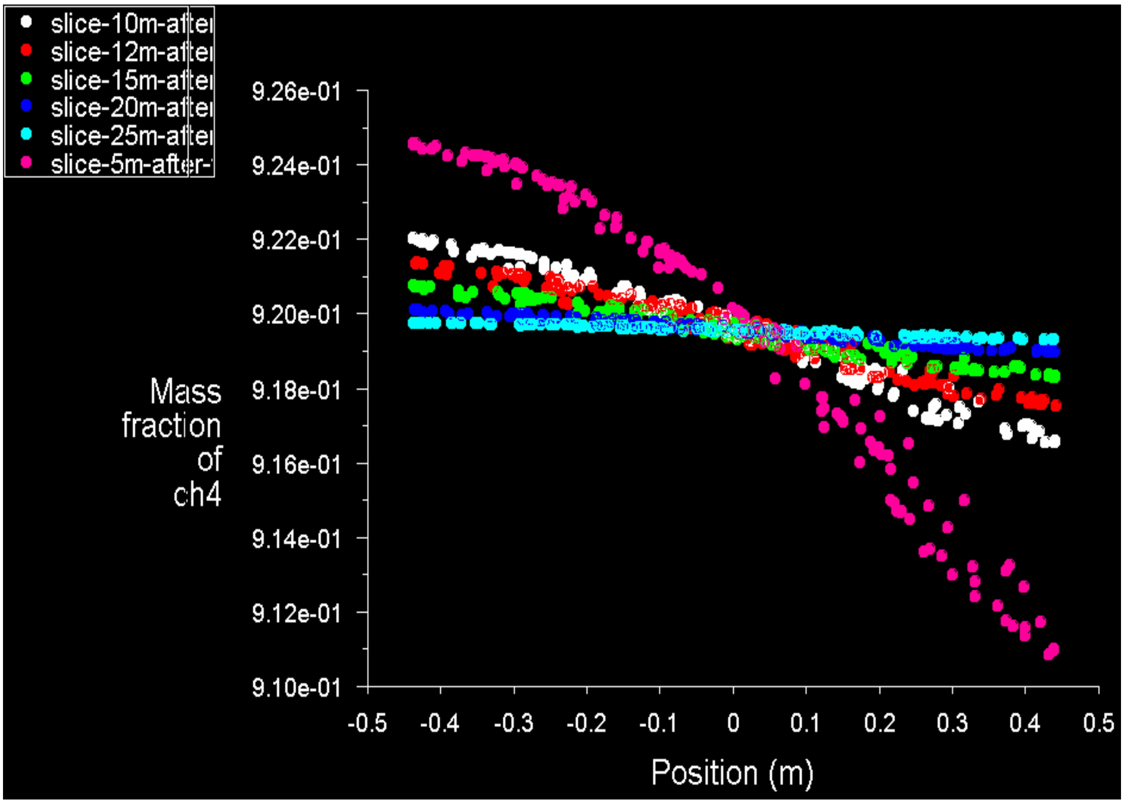


c) 5mscm(d) 90% Pipeline gas down header, 10% LNG down branch Average velocity 1m/s





d) 90% pipeline gas down header, 10% LNG down branch , total 50mscm(d) Average velocity 10m/s



STONERSOFTWARE

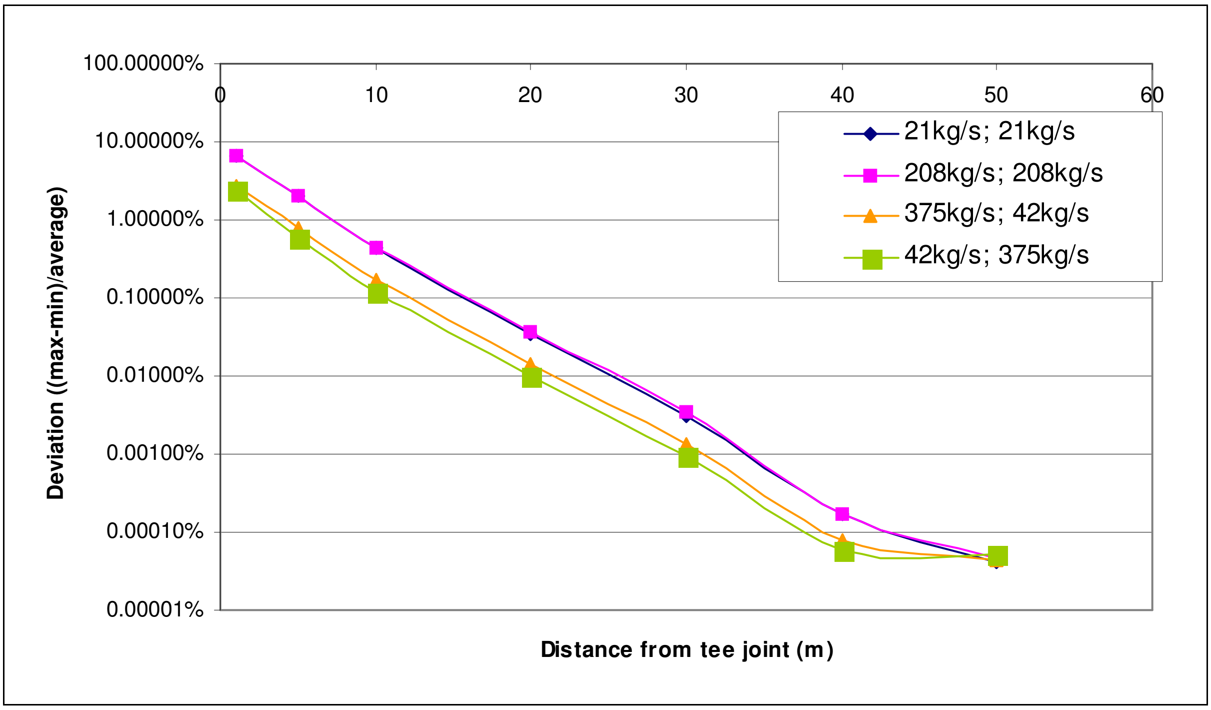


Figure 11: CFD results: Comparison of Mixing for 4 test cases

(Mass flows correspond to equivalent of 5 to 50mscm(d) through pipe, first number is header flow)

CONCLUSIONS AND RECOMMENDATIONS

- Hydraulic pipeline analysis (using SPS) and CFD have been used to model gas flows and gas mixing under the most commonly utilised modes of operation and for a substantial range of operational scenarios. These modes of operation are not however comprehensive, and the complexity of Bacton Terminal means that there could be other, less frequently utilised configurations which may lead to different outcomes.
- Gas flow appears to be, under all modelled conditions, turbulent, with Reynolds Numbers two orders of magnitude greater than those assumed for transition from laminar to turbulent flow.
- Consequently, mixing of any two gases is assumed to be rapid. However velocities of gases in the pipe are likely to range from $1ms^{-1}$ to $10ms^{-1}$, for total feeder flows between 5mscm(d) and 50mscm(d), i.e. the modelled range for a single outgoing feeder.
- Transit time of gas across the terminal could be less than one minute.
- With analysis points between final mixing and gas composition measurement being from 35m to 75m, gas could travel from a final mixing point to a measurement point within a few seconds. CFD analysis was used to determine whether, even with turbulent flow, full mixing of gases can be assumed in these short timescales. CFD simulations used a simple mixing header with gases of disparate compositions, and initialisation parameters designed to match as closely as possible, ideal pipeline conditions at Bacton, which would give lowest or worst case mixing rates.
- CFD simulations indicated that under all circumstances, homogeneous mixing was complete to a homogeneity of 1% CH_4 concentration within a pipe length of 20m from the tee, and that the homogeneity was independent of the velocity, pressure and ratio of mixing gases under the tested conditions, or whether an equi-mixture or an unbalanced mixture of gases was used. This independence of mixing distance reflects the linear increase of Reynolds Number with gas velocity. This result is in line with the recommendations of ISO 10715, which suggests that gas sampling should be at least 20 pipeline diameters from a disturbance point.
- However, at 5m or 10 m from the mixing point, there is still some inhomogeneity of gas composition across the pipe, which at 10m could correspond to a variation in Wobbe Number of around $0.6MJ/m^3$ for gases with differences in Wobbe Number of around $3MJ/m^3$ (ie around 20% for equi-mixtures of gases). This inhomogeneity decreases to below 10% for a 90%/10% gas mixture. Even at these distances from the mixing point, the composition of the gas at the centre of the pipe is equal to the flow weighted average of the mixing gases.
- Under situations where gas is extracted from the pipe from a wall tapping, for analysis or consumption, the extracted gas may not be consistent with the flow weighted average of the mixing gases where the tapping is 5m or 10m from the mixing point. The use of insertion sample probes would reduce the error but may still not take a representative sample.
- There are potential configurations (not ordinarily used) where measurement could be less than 10m from mixing point. There will be very limited confidence that full mixing can be established in this distance so any analysis will always be

unreliable. It is recommended that no off-specification gas is mixed at such points, as even with in-pipe mixing, there is no guarantee that homogeneity can be achieved.

- SPS has proved able to give validated information on flow compositions, both steady state and transient, across the Bacton Terminal. SPS is also capable of mapping gas quality parameters such as Wobbe Number and relative density. It is recommended that SPS and the model of Bacton is employed to map the acceptable envelopes of gas composition under all likely operational modes, static and transient. A similar model could be built for other terminals to give further confidence that GS(M)R limitations can be met as potentially off-specification gas imports increase.
- SPS analysis of transients during flow flexing illustrates that there is not a simple linear change of qualities of outgoing gas following loss of an incomer. Spikes (sudden changes) in gas composition of as little as 20 seconds can be observed in the Feeders as incomer flows are flexed to zero. These could lead to slugging of gas with unexpected overall quality. With sampling times typically of the order of several minutes, these are unlikely to be measured using standard analytical equipment. It is therefore recommended that the control and instrumentation strategies used for gas quality assurance are reviewed prior to provision of any blending service.
- Although simulations give some confidence that near-complete gas blending is taking place inside 20m (or 20 pipeline diameters) of mixing, this cannot be taken as a guarantee that such blending will take place. Validation is recommended where there is any doubt that blending will take place, particularly in safety critical situations.
- There are simple in-pipe mixing devices, which can be incorporated to reduce mixing lengths and increase the probability of mixing[6].

[6] for example http://www.airblender.com/industrial_division/ind_catalog.htm

APPENDIX A REYNOLDS NUMBER AND TURBULENT FLOW

The Reynolds Number is the ratio of inertial forces to viscous forces, and is used to determine whether flow is laminar or turbulent.

The definition of Reynolds Number is

$$R_e = \frac{d v \rho}{\mu}$$

where,
d = pipe inner diameter in mm
v = velocity in m/s
ρ = density in kg/m^3
μ = viscosity, cP

Transition from laminar to turbulent flow occurs at a characteristic Reynolds Number, typically above 2000 for circular pipes. The region of Reynolds Numbers between 2000 and 4000 is often referred to as a transition region, where flow can be partly laminar and partly turbulent. For Reynolds Numbers above 4000, it is usually assumed that flow is turbulent.

Therefore for Bacton, for natural gas at a pressure of 70bar we have,

$$R_e = \frac{(914 - 31.8) * 55.7 * v}{0.01126}$$
$$= 4363991 v$$

Hence, to obtain a $R_e \leq 4000$ the minimum gas velocity required is,

$$v = \frac{4000}{4363991}$$
$$= 0.001 \text{m/s}$$

APPENDIX B FLOW STRATEGIES

Within the tables, the letters A – F represent the individual sub-terminals which input gas to the Bacton terminal.

Scenario 1 – 60 Strategy 1

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	28	25.0	17.9	25.0	32.1	0.0	0.0	100.0
3	16	0.0	12.5	43.8	43.8	0.0	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	16	18.8	18.8	37.5	25.0	0.0	0.0	100.0
Spare	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Scenario 2 – 60 Strategy 2

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	28	17.9	17.9	28.6	35.7	0.0	0.0	100.0
3	16	0.0	31.3	37.5	31.3	0.0	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	16	31.3	0.0	37.5	31.3	0.0	0.0	100.0
Spare	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Scenario 3 – 60 Strategy 3

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	28	25.0	25.0	17.9	32.1	0.0	0.0	100.0
3	16	0.0	18.8	62.5	18.8	0.0	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	16	18.8	0.0	31.3	50.0	0.0	0.0	100.0
Spare	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Scenario 4 – 90 Strategy 1

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	28	25.0	17.9	25.0	32.1	0.0	0.0	100.0
3	22	0.0	9.1	31.8	31.8	27.3	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	22	13.6	13.6	27.3	18.2	27.3	0.0	100.0
Spare	18	0.0	0.0	0.0	0.0	100.0	0.0	100.0

Scenario 5 – 90 Strategy 2

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	35.5	19.7	14.1	29.6	36.6	0.0	0.0	100.0
3	22	0.0	0.0	11.4	0.0	88.6	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	22	13.6	22.7	31.8	31.8	0.0	0.0	100.0
Spare	10.5	0.0	0.0	0.0	0.0	100.0	0.0	100.0

Scenario 6 – 90 Strategy 3

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	40	15.0	10.0	40.0	35.0	0.0	0.0	100.0
3	22	18.2	0.0	0.0	0.0	81.8	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	22	0.0	27.3	18.2	27.3	27.3	0.0	100.0
Spare	6	0.0	0.0	0.0	0.0	100.0	0.0	100.0

Scenario 7 – 120 Strategy 1

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	37	18.9	21.6	35.1	24.3	0.0	0.0	100.0
3	28	0.0	7.1	8.9	25.0	58.9	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	28	10.7	0.0	16.1	14.3	58.9	0.0	100.0
Spare	17	0.0	0.0	0.0	0.0	100.0	0.0	100.0

Scenario 8 – 120 Strategy 2

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	41.5	16.9	16.9	36.1	30.1	0.0	0.0	100.0
3	28	0.0	10.7	0.0	0.0	89.3	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	28	10.7	0.0	17.9	26.8	44.6	0.0	100.0
Spare	12.5	0.0	0.0	0.0	0.0	100.0	0.0	100.0

Scenario 9 – 120 Strategy 3

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	41.5	16.9	16.9	36.1	30.1	0.0	0.0	100.0
3	28	0.0	10.7	17.9	26.8	44.6	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	28	10.7	0.0	0.0	0.0	89.3	0.0	100.0
Spare	12.5	0.0	0.0	0.0	0.0	100.0	0.0	100.0

Scenario 10 – 150 Strategy 1

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	69.5	10.1	10.1	57.6	22.3	0.0	0.0	100.0
3	28	0.0	10.7	0.0	0.0	89.3	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	20	15.0	0.0	0.0	22.5	62.5	0.0	100.0
Spare	12.5	0.0	0.0	0.0	0.0	100.0	0.0	100.0

Scenario 11 – 150 Strategy 2

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	62	12.9	11.3	53.2	22.6	0.0	0.0	100.0
3	28	0.0	10.7	25.0	10.7	53.6	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	20	10.0	0.0	0.0	15.0	75.0	0.0	100.0
Spare	20	0.0	0.0	0.0	0.0	100.0	0.0	100.0

Scenario 12 – 150 Strategy 3

		% Flows						
Manifolds	Flow, mscm(d)	A	B	C	D	E	F	Σ
2	62	12.9	12.9	50.0	24.2	0.0	0.0	100.0
3	28	0.0	7.1	14.3	0.0	78.6	0.0	100.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	20	10.0	0.0	25.0	25.0	40.0	0.0	100.0
Spare	20	0.0	0.0	0.0	0.0	100.0	0.0	100.0