GAS INHIBITORS FOR HYDROGEN PIPELINES – PHASE 2
FINAL REPORT

CLIENT: NGT

REVISION: 0

DATE: 05.09.2025

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1 INTRODUCTION

National Gas (NG) and ROSEN have completed an initial project to investigate the "Inhibition of hydrogen embrittlement effects in pipeline steels using gaseous inhibitors". Following completion of this initial project which identified some inhibiting effect from the presence of Oxygen (O2) on hydrogen (H2) embrittlement; NG have requested a Phase 2 to consider the operational feasibility of using a gas inhibitor.

2 SCOPE OF WORK

ROSEN agreed with NG to deliver the following work packages:

Work Package 1 (WP1) – Feasibility of Maintaining Oxygen Inhibitor in Gas Flow Analysis

This work package will review current available data and model gas flow to understand how the oxygen concentration can be controlled within the gas flow, consider where you would want to measure the gas composition and where to inject more oxygen.

Work Package 2 (WP2) – Feasibility of Technology Implementation

The following scope of work and deliverables were agreed with the NG project team on 27th June 2025:

1. Comprehensive list of technology requirements identifying areas of further work for consideration in Phase 3 scope
2. Conduct a feasibility level HAZID following the principles of Section 3.2 of T/SP/HAZ/8 to reflect the current stage and knowledge of the project.
3. Integrity management (technical report) – as proposed in item (2) from Gas inhibitors WP2-WP3 prioritisation[1] including review of CPChem R&D program summary received from NG on 30th June 20252
4. High level CBA (technical report) – as proposed in item (3) from Gas inhibitors WP2-WP3 prioritisation[1]

Note: it was agreed with NG that the term HAZID should not be used to describe the safety exercise executed as part of WP2 as it was not possible to fully meet the requirements of HAZ/8 – it is therefore referenced in the following documentation as a high level hazard review.

This report consolidates all deliverables from this phase into a single document. Each deliverable is presented in the following Appendices.

[1] K.Hamadi, National Gas Transmission – Gas Inhibitors WP2-WP3 – Prioritisation-NGT.xlsx – 18.06.2025

APPENDIX A – WP1: FEASABILITY OF MAINTAINING OXYGEN INHIBITOR IN GAS FLOW ANALYSIS

PHASE 2 – GAS INHIBITORS FOR H2 PIPELINES – WP1 REPORT

CLIENT: National Gas

PROJECT NUMBER: 19878

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1 EXECUTIVE SUMMARY

National Gas Transmission (NGT, part of National Gas) and ROSEN have completed an initial project to investigate the "*Inhibition of hydrogen embrittlement effects in pipeline steels using gaseous inhibitors*". Following completion of this initial project which identified some inhibiting effect from the presence of Oxygen (O_2) on hydrogen (H_2) embrittlement; NGT have requested a Phase 2 to consider the operational feasibility of using a gas inhibitor.

NGT have specified that there will be three work packages to the project, Ref. [1].

Work Package 1 (WP1) – Feasibility of maintaining Oxygen inhibitor in gas flow analysis.

This work package will review current available data and model gas flow to understand how the oxygen concentration can be controlled within the gas flow, consider where you would want to measure the gas composition and where to inject more oxygen.

Work Package 2 (WP2) – Feasibility of technology implementation

High level review of business case and technical feasibility for oxygen inhibition to see if it fits into existing infrastructure and can be safely managed. Consider if customers can accept oxygen in gas.

Work Package 3 (WP3) – Economic Considerations

Based on the output of WP2 and WP3, a high level review of the cost of injection and monitoring against the operational benefits will be conducted.

A kick-off meeting was held on the 16th of December with representatives from NGT, ROSEN and the Computational Fluid Dynamics (CFD) specialist, where ROSEN presented the modelling basis and methodology and received comments from NGT, Ref. [2]. Following this a formal basis of modelling document was issued by ROSEN and approved by NGT which defined the approach to addressing the WP1 scope [3]. This report presents the findings of WP1 which includes the development of Excel and OLGA models to investigate the feasibility of maintaining the oxygen inhibitor using gas flow analysis.

Simulations were performed for all the sensitivities shown in the modelling basis for a simple pipe system including[a]:

- Hydrogen mixtures of 100, 20 and 5% in natural Gas
- Concentrations of oxygen of 500, 250 and 1000 PPM
- Most of the modelling assumed 0th order reaction kinetics, however a single sensitivity also considered a 1st order reaction.

Following agreement with NGT, further modelling was conducted on a complex network based on the north section of the NTS, considering the following cases:

- CASE-1: Investigate the current "North" network and the way it is operated. Does the system have consistently low periods of velocity for NG?
- CASE-2: As for CASE-1, but with 20% H_2

[a] The base case value is the first number in each list.

- CASE-3: As for CASE-1, but with 100% H_2
- CASE-4: 500-1000-500 PPM square wave O_2 concentration perturbation representing a high oxygen concentration fault scenario

The flowrate ranges associated with the 100% hydrogen network are not currently known, but it anticipated that that may be significantly less than the equivalent NG flows (at same combustion energy).

In addition to the OLGA modelling described above, additional modelling has been performed using CFD to determine three dimensional (3D) aspects of flow that cannot be defined using the pseudo one dimensional OLGA model. Of particular concern was the potential for density based stratification of the gases and molecular diffusion.

1.1 Conclusions and Observations

The conclusions and observations based on the modelling work relative to the scope requirements are summarised in Table 1-1. Findings from the Excel and OLGA models are shown in text with a white background, whereas findings based on the CFD modelling is shown with a grey background.

One of the most important findings is that if O_2 consumption is equivalent to circa 10 micron/year steel corrosion, it would take more than 30 days of residence time for O_2 to fall below 250 PPM, with the associated velocity of 2 m/s in L1 & 3 and 0.02 in the L2 branch. However, the operating procedures must guard against system shut-in scenarios of no/very low flow.

It should be noted that square wave O_2 concentration perturbations were partly modelled to represent:

1. A temporary loss of O_2 generation/supply e.g. one train of a two train supply was lost or suffered a reduction in output.
2. Or a temporary increase of O_2 either through a fault in generation / supply or due to a period of low flow (and or flow reversals) in the gas branch such that a local plug of higher concentration O_2 built up (at inlet of L1) before being swept forward on resumption of normal flow.

However, it also covers a more general case for the NTS where gas flows from different parts of the network meet at pipe junctions. If the gases come from different sources (gas terminals or interconnectors etc.) then they may have had different residence times and O_2 consumption. The diurnal swings will give transient concentration perturbations as gas is redirected around the system. The 1000 PPM O_2 concentration perturbation provides a useful insight on controlling high (i.e. greater than 500 PPM) O_2 concentrations.

Table 1-1 Summary of Main Conclusions / Observations for WP1

#	Issue	Conclusion / Observation
i	Can O_2 concentration be controlled within the prescribed safe operating limits? (250 – 1000ppm)	Preliminary assessment suggests implementation should be possible if O_2 consumption is equivalent to circa 10 micron/year steel corrosion. At this consumption rate it would take > 30 days of residence time for O_2 to fall below 250 PPM, with the associated velocity of 2 m/s in L1 & 3 and 0.02 in the L2 branch. However, operating procedures must guard against system shut-in scenarios of no/very low flow.
ii	Initial findings on adding O_2 to form the mixture.	Without static mixer, it would typically take 80 to 100 pipe diameters to get uniform mixture for gas streams that are closely matched in rate. However, this can be far more difficult if the flow rates of the mixing streams are widely different as is the case here. It may be worth considering a pre-dilution skid whereby O_2 is partially dispersed into a slipstream of the network gas to form an intermediate concentration, before mixing into the main network stream. However, there would be a safety implication[Note1] if mixtures were too high in O_2.
iii	Where is a suitable location to inject and measure oxygen to maintain and manage the concentration?	As noted above, for normal network velocities (>1 m/s) it would require >> 1000 kilometres of residence time to reduce the O_2 concentration to 250 PPM. This suggests injection as close as possible to the source of H_2, measuring either side of injection with alarms to warn of flow reversals or similar leading to a slug of higher concentration O_2 building up. The complex model (§5) suggests that average velocities are > 1 m/s, so no significant reduction in O_2 based on consumption rates considered in this work.
iv	Define the positions / intervals of injection points.	Recommendation to incorporate injection with existing measuring or equipment sites on the network. If average velocities are greater than 1 m/s, possibly no need for additional injection sites apart from the H_2 injection point (as above). Likely requirement for multiple measurement points. If O_2 is injected in sections with potential for low or shuttle type flow, then provision must be made for monitoring High/Low O_2 concentration either side of injection.
v	Are positions / intervals of injection points dependant on pipe condition or other factors?	Residence time of gas through the pipework is the primary controlling factor. Flowrates would have to be extremely low to produce a significant reduction of O_2 over distances between key operating sites (i.e. circa 100 km). Pipe condition in terms of: (a) pipe roughness, is likely to have little impact since most flows highly turbulent. (b) MAOP may have to be lowered for H_2 service. This would actually give lower residence times since density of gas would be lower. It should be noted that residence time can be averaged over many days, so if O_2 injection is stopped completely for a short period 1 hour it likely have minimal impact on the average O_2 concentration seen by the majority of the pipework.
vi	Impact of key features of the model:	At normal flows the system is highly turbulent, so mixing is likely to be rapid. The CFD work has shown that if a significant spike in concentration does arise then the combination of forced turbulence and diffusion would take circa a hundred pipe diameters at 0.2 m/s velocity (flat pipe). At very low velocities such as 0.02 m/s diffusion and turbulence will take many hundreds pipe diameters to re-establish a homogeneous mixture[Note2]. Branches and fittings will only make a small difference since they typically contribute circa 50 extra diameters of effective mixing / pressure drop (see below).
	• Flow velocity	Large Mol. Wt. difference between H_2 and O_2 leads to significant density difference with a 500 PPM conc. difference in O_2. At low flows (0.02 m/s) this is sufficient to allow stratified flow to establish and potential for counter current flow. At normal flows (~2m/s) momentum dominates over buoyancy effect (i.e. stratified flow not expected) and rate of O_2 migration is close to the mean flow velocity.

#	Issue	Conclusion / Observation
	• Terrain	At low flow velocities, transport of O_2 becomes dependent upon the local slope of the pipeline, particularly when the slope is near to horizontal. For horizontal and downward terrain, O_2 migrates within the lower part of the spur at a rate that is faster than the mean flow velocity. For slight upward terrain, the rate of O_2 migration is reduced compared to horizontal and downward terrain, but remains above the mean flow velocity.
	• Branches	A perturbation of increased O_2 concentration entering a spur at a tee junction will be lower than the concentration of O_2 within the main line due to mixing at the junction. This is most apparent if the slope of the spur off the main line is horizontal or downward. If the slope of the spur off the main line is upward, the concentration of O_2 entering the spur is predicted to approach that within the main line.
	• Bends	Bends predicted to make only make a marginal difference to the mixing of the O_2 as it migrates along the spur. The greatest degree of turbulent mixing at bends occurs at high flow velocities, but this coincides with non-stratified flow when the O_2 concentration will already be fairly uniform. At low flow velocities, when the flow may be stratified and the O_2 concentration is non-uniform, the degree of turbulent mixing at bends will be much reduced[Note3].
viia	Square wave perturbation of O_2 concentration - Simple Pipe Model	Using OLGA for perturbation spikes lasting up to two days it was found that the spike was almost unchanged in sections of the network at normal flow. However, in spurs with very low velocity (0.02 m/s) the concentration spike was diluted by the pre/post spike gas, such that the change in concentration was significantly less extreme. The CFD work showed that much of this was due to numerical smearing, and that in reality true molecular diffusion will produce a somewhat similar effect, but of much smaller magnitude.
		In spurs with very low velocity (0.02 m/s) the concentration spike was diluted by the pre/post spike gas, such that the change in concentration was significantly less extreme. Much of this was due to numerical smearing, and that in reality turbulent diffusion will produce a somewhat similar effect, but of much less magnitude.
viib	Square wave perturbation of O_2 concentration – Complex Network Model	For all branches except one, the concentration spike went through as a bell curve within circa 2.5 days. However, in the longest continuous branch (and lowest flow) the concentration spike was shuttled back and fore in the pipe as part of the diurnal swing. Although this is not a concern when the oxygen is added outside the boundaries of the pipe, it might become a concern (for controlling O_2 below say an upper bound of 1000 PPM) if O_2 were added inside the branch boundaries, particularly at a low flow node within the pipe, such that the concentration could potentially accumulate over time if oxygen were added at a fixed rate rather than in relation to the flow to achieve a certain concentration.
viii	How long / far will the oxygen last within the pipeline and at what repeat distance must additional O_2 be added to maintain the minimum requirement for both steady state and during no flow conditions.	See above. For a 250 PPM margin between the injected (500 PPM) vs the minimum O_2 concentration (250 PPM). At normal network velocities (>1 m/s) it would require >> 1000 kilometres of residence time to reduce the O_2 concentration to 250 PPM. For low flow rate spurs a very small improvement was seen in the O_2 concentration when the diurnal pressure variation was included in the model. No flow spurs (i.e. dead legs) are covered by the same residence time constraints listed above i.e. if the combination of low and no flow results in an average gas residence time of 30 days or more then the O_2 concentration is predicted to fall below the minimum concentration of 250 PPM.
ix	Will stratification of oxygen occur where the concentration can then build up outside of the safe limits?	Not predicted. It is important to note that the two-layer stratification predicted by the full CFD model does not constitute reseparation of O_2 from a fully mixed mixture. When fluid within the spur is fully mixed, there is no evidence to suggest that O_2 can separate out of the mixture for the time and length scales of interest to the gas network.

Notes:

1. It is important to consider the oxygen concentration of any intermediate blends of O_2 with hydrogen so as to minimise or preferably eliminate mixtures within the flammability limits. However, this may lead to longer mixing lengths or higher differential pressures (if static mixers are employed).

#	Issue	Conclusion / Observation
	2.	In the absence of sources/sinks of O_2, the concentration is bounded by the concentration at the injection and the background concentration - 1000 ppm and 500 ppm respectively. There is a sink due to corrosion, so the concentration can fall below 500 ppm. Without a mechanism to act as a source (other than the injection itself), the concentration must be less than (or equal to) 1000 ppm. (The mixture will not unmix within the spur to form a higher concentration O_2 accumulation.)
	3.	Once mixed the mixture will not "unmix" to higher O_2 concentrations. Hence, not predicted to see O_2 concentration higher than that injected.

1.2 Suggested Further work

The suggestions for further work based on the modelling results and relative to the scope requirements are summarised in Table 1-2 below. It should be noted that this study was designed as an initial screening of the O_2 inhibition concept. This report provides a response to all questions raised by NGT based on the desk based engineering assessments conducted and information available. Later stages of engineering will require more detailed investigation.

Table 1-2 Suggestions for Further Work

#	Issue	Suggested Further Work
i	Can O_2 be controlled within the prescribed limits?	One of the fundamental assumptions of the work in this report was the rate of consumption of O_2 on the pipe wall. Experimental studies are required to quantify the rate of oxygen consumption on the pipe wall for all H_2 gas mixtures and pipe materials of interest. Work is also required to determine the order of reaction and to determine any other factors that impact the rate. At the start of the project Edinburgh University were contacted regarding potential experimental work, this or one of the other research establishments that study gas-surface interactions should be considered.
ii	Initial thoughts on adding O_2 to form the mixture.	O_2 monitors should be investigated since these are essential to ensure O_2 is well mixed and that confirm concentration is within acceptable limits.
iii	Where is a suitable location to inject and measure oxygen to maintain and manage the concentration?	One of the key uncertainties identified is understanding the lowest sustained gas velocity within the network, since this determines the residence time of the gas and the percentage of O_2 consumed. The complex model was based on a "worst case winter" scenario for a previous project on linepack. ROSEN recommend that NGT consider work to identify scenarios likely to give very low gas flows and velocities in the system and extract results from the SIMONE model.
iv	Define the positions / intervals.	See (i) and (iii) above.
v	Are these dependant on pipe condition or other factors?	
vi	Impact of key features of the model - branches / fittings.	
viia	Square wave perturbation of O_2 concentration - Simple Pipe Model	
viib	Square wave perturbation of O_2 concentration – Complex Network Model	
viii	How long / far will the oxygen last within the pipeline and at what repeat distance must additional O_2 be added to maintain the minimum requirement for both steady state and during no flow conditions.	
ix	Will stratification of oxygen occur where the concentration can then build up outside of the safe limits?	The CFD work identified that O_2+H_2 mixtures in particular could potentially give rise to density induced effects. This could be investigated visually using Schlieren optics/photography or similar.

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ABBREVIATIONS

Abbreviation	Details
CFD	Computational Fluid Dynamics
CV	Calorific Value
H_2	Hydrogen
HHV	Higher Heating Value
ID	Inner Diameter
LFL	Lower Flammability Limit
NGT	National Gas Transmission
NG	Natural Gas
NTS	National Transmission System
O_2	Oxygen
PPM	Parts Per Million (expressed on a mole/standard volume basis for this work)
UFL	Upper Flammability Limit
WP1 / 2 / 3	Work package 1 / 2 / 3

2 SCOPE OF WORK

2.1 WP1

The flow assurance methodology, which will be applied to meet the defined objectives listed in Work Package 1 in Section 2 is presented below. Blends from 5%, 20% H_2 / Natural Gas to 100% H_2 will be considered while maintaining a minimum Oxygen concentration of 250 ppm (by volume). The flows will be adjusted to have the same calorific value (i.e. the volumetric flow will increase with increasing H_2 concentration in the H_2 / NG blends) so that the blends can be compared on a similar basis with respect to gas usage.

For this work it will be assumed that an initial uniform concentration of uniform concentration of 500 ppm (or other values) can be achieved and is available at the inlet of the modelled system. The use of static mixers is well known and routine in many industries to facilitate more rapid mixing, otherwise it can take from 20 to 100 pipe diameters to achieve mixing in the gas stream. This report will include comments based on general literature, achieving a uniform concentration is not part of current SOW, but will be addressed in WP2.

2.1.1 Simplified Pipe System

Using OLGA (version 2024.1), flow assurance software marketed by Schlumberger, the initial work will aim to demonstrate if the required oxygen concentration can be controlled and maintained in the network within the required / prescribed limits. A range of simplified pipe systems will be used for the initial modelling (as shown in Figure 3-2), which will demonstrate the impact of key features in the gas network such as branches and loss of O_2 in the system. The results will also be used to determine if the required O_2 concentration can be maintained in various parts of the system.

Based on the analysis the following issues will be addressed:

- Where is a suitable location to inject and measure oxygen to maintain and manage the concentration?
- Flow reversals and their frequency in the vicinity of injection points is an operational issue. The system will need specific oxygen detection in the main line either side of the injection point to ensure that oxygen concentration does not exceed specified limits due to no flow or flow reversal in the main line. This will be discussed in WP2 work, but is not included in the SOW for the flow assurance studies, apart from a sensitivity to investigate the perturbation of the oxygen concentration to 1000 PPM. Issue will be addressed as part of WP2.
- Help to define the positions / intervals of injection points
- Confirmation whether the injection locations are dependant on pipe condition or other factors
- Pressure affects the molar concentration per unit volume of the oxygen, so if O_2 consumption per unit length is fixed, then increasing the pressure would also increase the number of moles of O_2 available per unit volume. Rate of diffusion is inversely proportional to pressure, so diffusion will reduce at higher pressures. Density is proportional to pressure so velocity and Reynolds number will both be affected. All the above are known quantifiable affects so a simple sensitivity in Excel will be performed rather than using OGLA.

As part of the initial tests square wave O_2 concentration variations will be added to the system while maintaining fixed volumetric flowrates and pressures. Simulations will also model the potential loss of oxygen in the system. The initial modelling performed in OLGA to determine the overall dynamics of the system will include:

- Straight pipe section with flow and no flow at steady state and over a transient shut-in (no flow) period.
- Bend pipe sections with flow and no flow will be studied using CFD only, since OLGA is pseudo one dimensional model that does not consider bends.
- Pipeline "T" to form "Dead Leg" i.e. no or limited flow at various ratios of flow Q1 / Q2 (as shown in Figure 3-2). The square wave O_2 concentration perturbation will be generated and followed through both L2 and L3 legs of the system of time period of three times that required for the perturbation to pass through the system.
- The size of the system must be sufficient to allow the streams to achieve a fully developed flow pattern; this typically 80 to 100 pipe diameters for a turbulent gas system. Hence, as a conservative estimate the L1, L2 and L3 legs will be at least 1000 pipe diameters.
- The primary variables to be studied are the flowrates Q1 and Q2 (and by difference Q3). The flowrates at a given pressure and temperature will define the Reynolds number in each section and hence the degree of turbulence.
- The pipe diameter is of secondary importance since it will predominately change the flowrate required to achieve a given Reynolds number. However, two diameters will be studied.
- The pressure and temperature of the system define the density and viscosity of the gas. Three pressures will studied after agreement with NGT.
- Studies will also be performed whereby oxygen is consumed by the pipework or lost in reactions with system components. A key aim will be to determine how long / far will the oxygen last within the pipeline and at what repeat distance must additional O_2 be added to maintain the minimum requirement for both steady state and during no flow conditions (in a branch).

2.1.2 CFD Modelling

Additional modelling will be performed using CFD to determine three dimensional (3D) aspects of flow that cannot be defined using the pseudo one dimensional OLGA model. Of particular concern is the potential for density based stratification of the gases and molecular diffusion.

- Impact of bends on mixing and flow distribution.
- Impact of diffusion in dead legs with complete cessation or very low flows.

Where possible the CFD models will also be used to infer the behaviour in previous ROSEN and SANDIA test set ups to help understand previous test results:

- Does stratification of gases occur?
- Could this be improved in future tests if the gases are flowed (i.e. continuous purge)?

2.1.3 Modelling A Subsection of the Network

A more complex geometry (i.e. a mini network or part of the NG gas network such as a specific city or region) will be studied at a minimum of three conditions determined from the matrix of cases for the simplified system described in Section 2.1.1 and any learnings from the CFD modelling described in Section 2.1.2. The extent / details of the complex geometry will be agreed with NG.

The network model will allow shippers and customers to have a variable supply / demand including periods of no flow. Worst case diurnal and seasonal cases will be used to explore the envelope of potential cases.

3 BASIS AND METHODOLOGY

3.1 Background

The high level requirements for a simplified and a more complex pipeline model were set out in §2.1.1 and §2.1.3 respectively. This study is predominantly interested in areas of the network with minimal or no flow since these regions are the most likely to show:

- The impact of loss of O_2 due to consumption on the walls of the pipeline (O_2 consumption has more time to take effect without arrival of fresh gas).
- The ratio of internal pipe area to volume of contained gas is larger for smaller pipelines, so the relative consumption of O_2 will be greater (particularly when stagnant).
- The impact of turbulence from bends and fittings and
- Potential stratification of the gas species due to molecular weight difference (when turbulence of gas is minimised).

In 2023 NGT commissioned ROSEN to investigate the impact of hydrogen and hydrogen blends on linepack capacity and assess the potential solutions to increase and manage linepack in the future (see Ref. [4] and [5]). In order to determine the linepack flexibility (i.e., the useable gas storage), static (steady state) and transient simulations were required to define the change of linepack over defined timeframes e.g. diurnal swings, cold snaps, seasonal changes etc.

A model was constructed using the transient pipeline modelling software OLGA of the North section of the National Transmission System (NTS) which includes the inlet gas supply at [redacted] with pressure boundaries at the southern end of the system ([redacted].

- The model also included all the known demands (such that gas left the system at these points) and the pressure boost due to compressor stations. The model was fast to run (less than 10 minutes) and fully compositional.
- OLGA model was built as a complement to NG's existing high fidelity SIMONE model, allowing fast prototyping of different scenarios.
- The data held in the OLGA model is useful for this current study.

Figure 3-1 Northern Section of the NTS

The [redacted] are a good example of a region of the UK where demand for gas to smaller diameter offtakes along the gas transmission pipes may be very low during parts of the diurnal or seasonal swings, since the housing and industrial density is low in this area. For the [redacted] section of the NTS the maximum and minimum pipe inner diameter (ID) size was 1.12 m and 0.586 m respectively.

The various aspects of the scope will be investigated using the three main techniques i.e. the simple pipe model, CFD and the more complex network pipe model as shown in Table 3-1 and described in the following sections. The main objective of studying a section of the network will be to investigate how the impact of O_2 concentration changes in the main line affect the multiple demand points on the smaller branches as opposed to very short spurs with a single demand at the terminus.

Table 3-1 Methodology Matrix

Issue	Simple Pipe Model	CFD	Complex Geometry / Section of Network
Straight Pipe	Straight parts of "T"		Network is essentially collection of straight pipes
Bend	*Physics not in OLGA*	Turbulence factor of bend	*Physics not in OLGA*
Dead Leg	Will look at "T" system		
Consumption of O_2	Based on corrosion rate at wall of pipe	*Too complicated for CFD and Complex Geometry*	
Perturbation of O_2 Concentration (square-wave) + Blends	Follow square wave of concentration change as profile plot and trend. + blends	Used to show diffusion component	Follow square wave of concentration change, Impact on demand points and boundary. + blends
Stratification / Diffusion of O_2	*Physics for Stratification and diffusion not in OLGA*	Based on Fick's law and Literature values	*Physics for stratification and diffusion not in OLGA*
Pressure		Impact on diffusion. & stratification.	

Notes:

Cells with grey shading indicate that simulations will be excluded for these modelling techniques for that particular issue.

3.1.1 General Assumptions

General assumptions are defined in this section. Other assumptions are given in the specific sections below:

- ROSEN and SANDIA test setups will not be modelled explicitly, but behaviour will be inferred from general CFD results.
- Consumption of O_2 will be considered as proportional to the rate of corrosion at the pipe wall (ROSEN will assume 10 μm/yr as base case)

- The pipe diameter is of secondary importance as a sensitivity since it will predominately just change the flowrate required to achieve a given Reynolds number. However, two diameters will be studied for simple pipe system.
- No valve closures – flow in side branch can decline to zero (dead leg) but no valve separation from main pipeline.
- The rate of consumption of O_2 by the pipe wall will be some currently unknown function of concentration. For this study as a conservative base case assumption the O_2 consumption rate will be assumed to be independent of O_2 concentration (i.e. 0^{th} order reaction). NGT requested at the kick off meeting that 5% gas mixture (of Hydrogen in NG) should be included, but that the 2 % mixture could be removed. Similarly to concentrate on 500 ppm O_2 as the base case rather than 250 ppm.

3.2 Simple Pipe Model

The simple pipework model illustrated in Figure 3-2 consists of a trunk line with a smaller spur line connected via a T-branch. The details of the spur are set out below.

- Based on analysis in Ref. [5] for a winter case the average absolute speed ranged from 0.1 to 7.2 m/s with an overall average of 2.4 m/s. The nominal maximum velocity in the NTS is 20 m/s. It is proposed that the flow in the main branch is set at 10 % of this value (i.e. 2 m/s) as a typical velocity, which is sufficiently large that no issues with stratification or poor diffusion are expected. The smaller line section from the branch of the "Tee" is where we will mainly investigate stratification / diffusion and this is at far lower velocity. These values could be adjusted later based on future findings, but investigating other velocities in main branch is not part of this phase of the work.
- Based on a review of spurs ([redacted] that cannot be ILI inspected Ref. [6], the average ID was 0.5281 m with a minimum ID of 0.1 m and a maximum length of [redacted] m.
- By coincidence in the [redacted] part of the network, there is an 18.1 km section from [redacted] with a diameter of 0.5858 m.
- Hence, the [redacted] will be used as the basis of the simple pipe model (i.e. L2). The main branch (L1 and L3) will be modelled as 0.889 m ID 18.1 km stubs either side of the small ID T-branch.

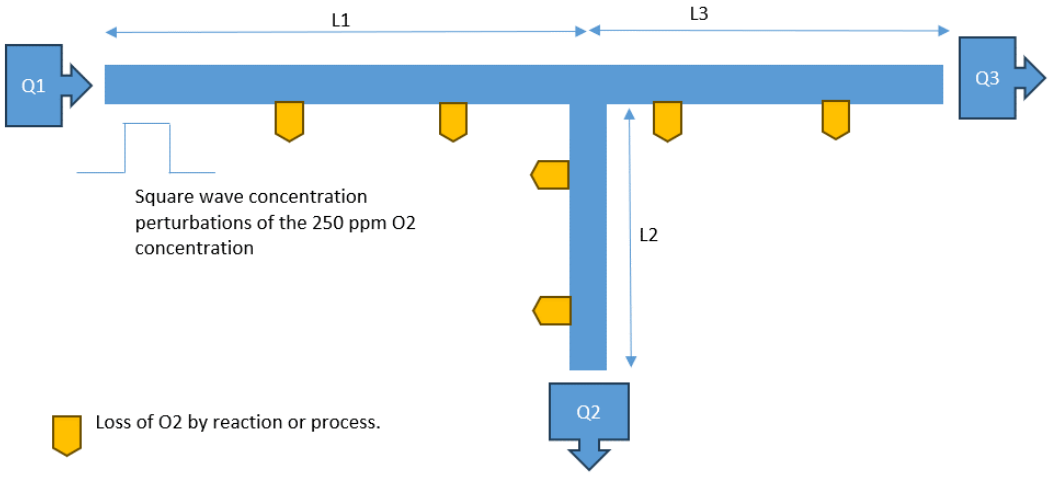


Figure 3-2 Schematic of Pipeline Test System

3.2.1 Thermal Modelling

Thermal effects will be simplified to a uniform temperature across the model (i.e. adiabatic). The only exception will be compressor stations (if required), where the temperature will rise due to pressure boosting. However, the temperature will be restored immediately downstream of the compressor using an aftercooler. As noted previously stratification is more likely to occur at low temperature, so the base case temperature will be assumed to be 0 ^{o}C (winter) with summer (25 ^{o}C) and average (15 ^{o}C) as potential sensitivities.

3.2.2 Gas Composition, Properties and Heating Values

A natural gas composition was supplied as part of the work described in the previous ROSEN Linepack Flexibility report, Ref. [5] and will be used as the basis for this work (see Table 9-2). The following reference conditions will be used for conversion between mass and volume:

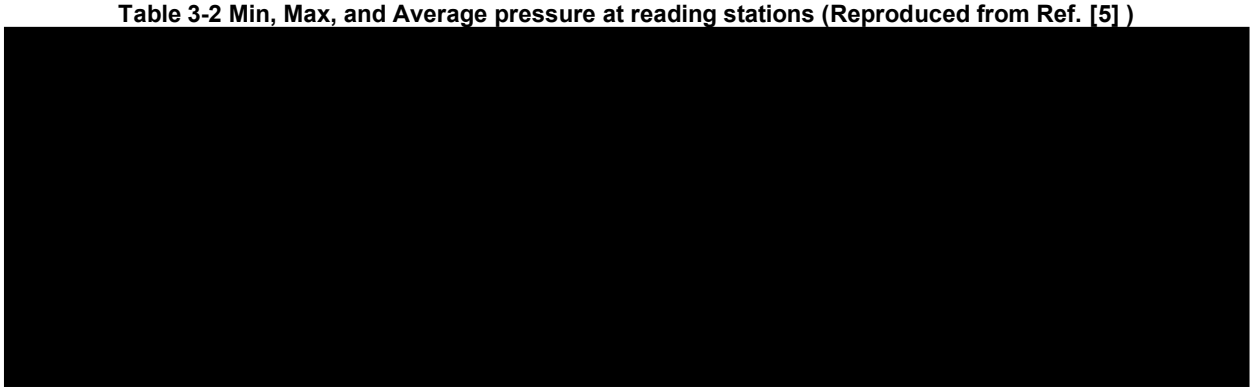
- Standard Molar Volume of an ideal gas at 273.15 K and 101.325 kPa is 2.241383 x 10^{-2} m^3/mol.
- Gross (higher) calorific value (CV) / Higher Heating Value (HHV) expressed in MJ/m^3 at metering and combustion reference conditions of 15 °C and 101.325 kPa. Hence, volume corrected to this temperature is 2.3645 x 10^{-2} m^3/mol.
- The density (relative to air) is given by dividing the average molecular weight to the fluid by the molecular weight of air (28.97).
- The Wobbe number is given by dividing the HHV by the square root of the relative density.

The CV was based on Higher Heating Values shown in Table 9-1. It should be noted that the CV supplied by NGT as part of the previous linepack study Ref. [5] , by averaging the CV across multiple testing stations was within 1 % of the value calculated by averaging the compositions across the same stations and using the HHV values from Table 9-1. The increase in volumetric flow of gas required to provide the same heating value as natural gas for various H_2 blends is shown in Table 9-4.

3.2.3 Pressure Boundaries

The previous linepack study reviewed the pressures across the network for the PEAK case, Ref. [5]. Based on the average pressures a value of 60 bar will be used for the arrival pressure of the simple pipe model.

Table 3-2 Min, Max, and Average pressure at reading stations (Reproduced from Ref. [5])



3.2.4 Simulation cases

The base case conditions and that of the sensitivities are shown in Table 3-3. The base case is shown with a green background. Each sensitivity will be achieved by varying only one of the other variables at a time (i.e. those with a yellow background) all other variables will stay at the base case condition. Sensitivities will be investigated using either the OLGA model or with Excel spreadsheet models if appropriate. The flow in this smaller T-branch will be studied over two orders of magnitude i.e. 0.2, 0.02, 0.002 m/s as well as a stationary (i.e. zero flow) flow case[b].

3.3 Complex – Network Model

The section of the NTS from [redacted] is approximately 190 km with an ID of 0.586 m and will be taken as the representative a larger scale "T" from a higher flow branch (i.e. from [redacted]. The main objective of studying a section of the network will be to investigate how the impact of O_2 concentration changes in the main line affect the multiple demand points on the smaller branches as opposed to very short spurs with a single demand at the terminus.

Figure 3-3 shows a comparison of the pipes used for the Simple model ([redacted]) and Complex model ([redacted] in the form of a high level schematic. The pipe details (internal diameter and length) are shown in Figure 3-4 (a more complete view of the entire north section is shown in Figure 9-1). The customer demand points relative to the start ([redacted]) and end ([redacted]) are from the linepack OLGA model from earlier work, Ref. [5] are shown in Figure 3-5 and Table 9-6. For the modelling in this work the flow out of respective demand points will be made relative to the total flow into the pipe at the ratios defined by Table 9-6 so as to achieve the inlet velocities required.

[b] Zero flow in the "T" section only.

Table 3-3: WP1 Base Case and Sensitivities for Simple Pipe Model

Main Branch (L1) Flow		Side Branch (L2) Flow		Arrival/Min Pressure (barg)	Ambient Temperature (oC)	Gas (H2/NG)	O2 Conc. (ppm)	Consumption of O2 based on corrosion rate (mm/year)	L2 - ID pipe (mm)
Flowrate (kg/hr)	Gas Velocity (m/s)	Flowrate (kg/hr)	Gas Velocity (m/s)						
Based on vel.	2 m/s	Based on vel.	0.2	60	0 (Winter)	100% H2	500	10	586
Square Wave[Note2]		Shut-in L2	0.02	+20%?	15 (Average)	2%	250	1	100
		Note-1	0.002	-20%?	25 Summer	5%	1000	0.1	
						20%			

Base Case
Sensitivity Case
Unlikely Sensitivity Case
Case Excluded

Notes:

1. Flowrate such at which 10 % or 1 % of O_2 concentration is consumed at exit of pipe.
2. Square wave 500-0-500 ppm, with zero flow over period of 4 hours.

Figure 3-3 Schematic of Pipes: Simple ([redacted]) and Complex ([redacted])

Figure 3-4 Pipe Details [redacted]

Figure 3-5 Section of OLGA Linepack Model from [redacted]

3.3.1 CV monitoring Points

In order to define the suitable locations to inject and measure oxygen to maintain and manage concentration, the starting point will be to consider the current CV monitoring points since adding additional equipment to an existing measurement site is likely to be with considerably lower CAPEX and OPEX compared with a new location. In addition to this, the impact of injected oxygen on the CV of the gas must also be considered. Hence, CV will be reduced slightly in proportion to the concentration of oxygen in the gas (i.e. 0.05%). A comment will be added in the final report.

NGT are correct to point out that many of the concentrations of the hydrocarbon gases will be analysed using a flame ionisation detector or similar. This will not detect nitrogen or oxygen. Non-combustible gases can be detected using a thermal conductivity detector, but the difference in thermal conductivity between nitrogen and oxygen is very small so a specialist technique may be required for oxygen concentration.

Figure 3-6 shows the existing CV monitoring points in the north of the NTS, such that the complex system modelled in this work has monitoring at [redacted]

Figure 3-6: CV Monitoring points

4 SIMPLE PIPE MODEL BUILD AND RESULTS

4.1 Oxygen consumption and Order of reaction

Many corrosion mechanisms require liquid water in order for any significant reaction to occur. For transmission quality gas the water content will be circa 60[c] PPM (i.e. all water is vapour phase, with no liquid water phase), so rapid corrosion should not be possible unless out of specification gas enters the system. Similarly CO_2 and H_2S / Sulfides should be tightly controlled and not contribute to a significant corrosion risk; only pure oxides of iron will be considered for this work.

However, there is evidence that oxygen can react at the pipe inner surface. Black powder is the name given to the mixture of iron oxides, carbonates and sulfides found in gas pipelines, and can also include salt, sand, clay, mineral scales such as calcium carbonates and gypsum, strontium and barium sulfate etc. The variability of black powder is illustrated by reports of the powder being completely iron sulfide (l) to completely iron oxide.

The basic hypothesis for this work is that the consumption of oxygen by some form of corrosion at the pipe wall is possible. The iron component of steel can undergo a number of potential reactions with oxygen. However, it is not within the scope of this work to determine the exact nature of the corrosion products formed, the specifics of the reaction pathway, temperature/pressure dependence of corrosion rate or the reaction kinetics. Some of the potential iron oxides are listed in Table 4-1.

Table 4-1 Some of the Oxides of Iron, Ref. [7]

Name	Iron Oxidation State	Formula	Stoichiometry Ratio O_2/Fe
Magnetite	II/III	Fe_3O_4	0.667
Iron(ii) Oxide	II	FeO	0.5
Hermatite	III	Fe_2O_3	0.75
Iron(iii) Oxide	III	Fe_3O_2	0.333

The basic reaction kinetics for metal wall reaction with oxygen is discussed in Appendix B (see §10). The rate of consumption of O_2 by the pipe wall will be some currently unknown function of concentration. For this study as a conservative base case assumption the O_2 consumption rate will be assumed to be independent of O_2 concentration (i.e. 0^{th} order reaction).

$$For\ A \overset{k}{\Rightarrow} Products, \qquad {\partial a}/{\partial t} = k$$

Hence, for the base case modelling the rate of rection of oxygen consumption was only dependent on k, it was independent of the concentration of oxygen.

As shown above various oxides of iron are possible as a conservative treatment the basic formula used was the one that gave the highest consumption of O_2 (i.e. highest O_2/Fe ratio)

$$4Fe + 3O_2 \rightarrow 2Fe_2O_3.\ Hence\ 0.75\ moles\ of\ O_2\ consumed\ for\ every\ mole\ of\ Fe\ corroded.$$

[c] 50 mg/sm^3

The moles of O_2 consumed for the base case were calculated depending on a loss of 10 μm/year of iron (density of iron 7850 kg/m^3 and molecular weight of 55.85 kg/kmol).

4.2 Excel Modelling

4.2.1 Excel Model Build

A simple matrix / table form Excel model[d] was constructed for the base case velocity of 0.02 m/s. For the L2 spur (see Figure 3-2) the gas travels 1728 m over the course of day and the gas has a total residence time in the 18 km pipe of 10.41 days. The L2 distance and the time were each divided into 10 intervals. A schematic is shown in Figure 4-1, it can be seen that for the first length section, the gas is always coming in from the left at approx. 500 ppm, so it only changes by a single loss of oxygen consumption i.e. it does not lose further oxygen over time. For the subsequent length sections the gas enters from the section to the left, so will have already lost oxygen in that previous section then continues to lose further oxygen as it is consumed in that new section. The diagram shows how the gas concentration information is transferred with respect of distance (left to right) and in regards to time (from top to bottom). After approximately 10 days the system reaches steady state with no further change in the oxygen concentration in terms of distance or time. A simple overview of the method can be understood by considering a small sample of gas of length $\delta\iota$ as it enters L2 and emerges from the far end of L2 10.4 days later.

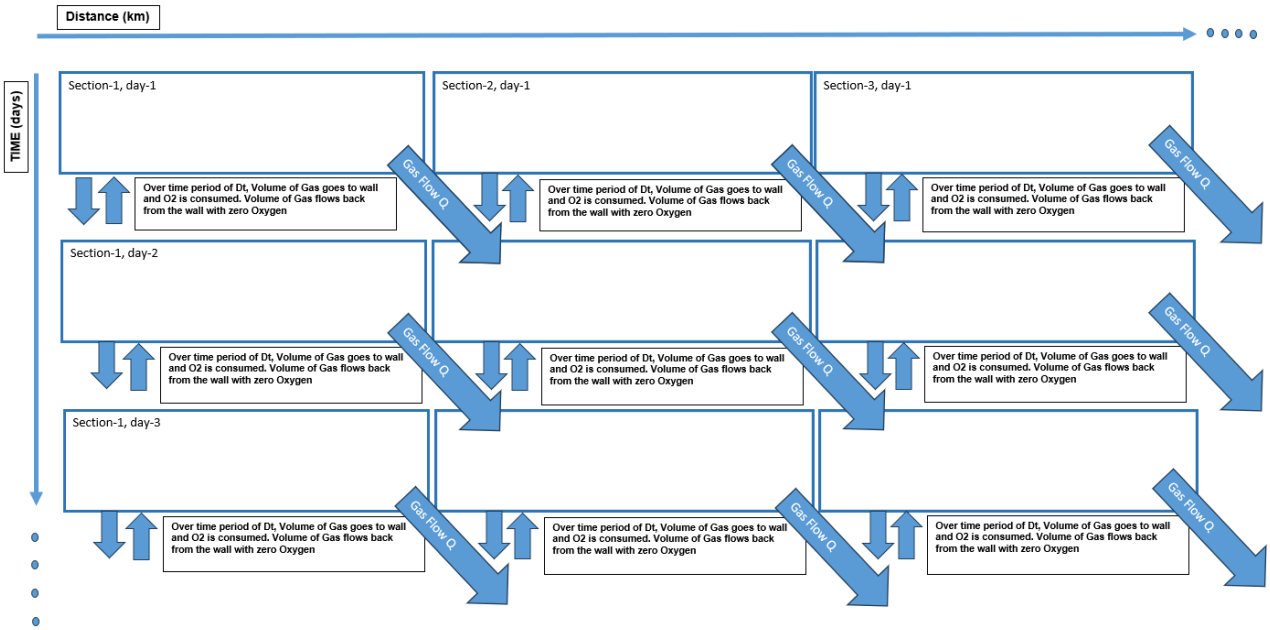


Figure 4-1 Schematic Diagram of Excel model

[d] Only the L2 section of the system was modelled in Excel.

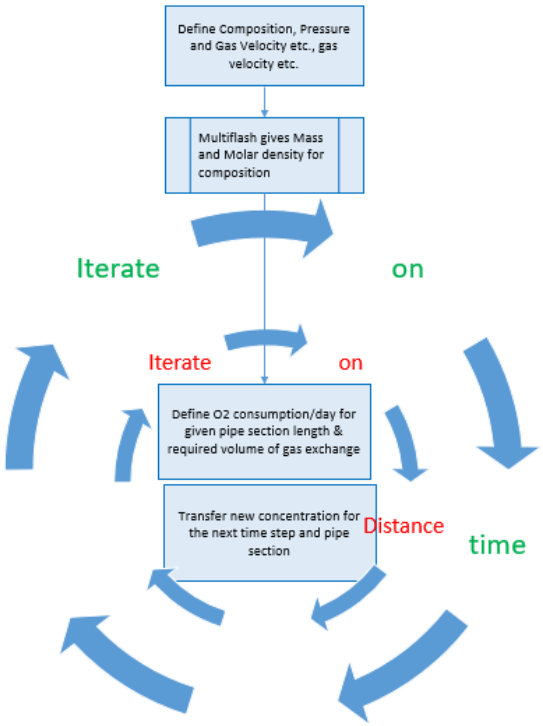


Figure 4-2 Flow Diagram of Excel Model

4.2.2 Excel Model Base Case

The base case data shown in Table 4-2 was used in the Excel model described above with ten 1728 m sections over 10 days the output from the Excel model for a single day is summarised in Table 4-3. It is also shown graphically for the 10 day period as trend and profile plots of the O_2 concentration in Figure 4-3 and Figure 4-4 respectively. Extrapolating the data to the full 10.4 days of residence time (for a pipe length of 18 km, based on a gas velocity of 0.02 m/s) gives a final O_2 concentration of 421 PPM.

Table 4-2 Base Case Data Summary

Parameter	Value	Units	Comments
Density Steel	7850.00	kg/m3	
MW O_2	32.00	g/mol	
MW Iron	55.85	g/mol	
MW H2	2.02	g/mol	
Concentration of O_2	500.00	ppm	
Velocity of Gas	0.02	m/s	See Figure 4-1 and Figure 4-2
Pipe length	1000	m	Values in Table 4-3 are based on first 1 km section of the total 18 km spur
Pipe ID	0.59	m	
Pressure	[redacted]	bar	
Temperature	0.00	^oC	
Stoichiometry	0.75	(-)	Moles of O_2 consumed relative to Fe corroded
Corrosion rate	10.00	micron/year	
Notes:			

Table 4-3 Base Case Calculated Values (1st Kilometre, 1st Day)

Parameter	Units	Value	Comments
Multiflash Calculations			
Gas Density	5.26	kg/m^3	
Molar Density (All Gases)	2.59	kmol/m^3	
Ave. Mol Wt.	2.03	kg/kmol	
Calculation of O_2 Consumed at wall Relative to O_2 in gas phase			
Steel Corrosion	0.0184	m3/year	Volume iron corroded (1 km of pipe/year)
O_2 consumed	5.32E-0^3	kmol/day	O_2 corroded per day (1 km of pipe)
	1.97E-0^5	kmol/m^3	O_2 consumed per m^3 (of gas volume)
Initial O_2 Conc.	1.30E-0^3	kmol/m^3	Initial Concentration of O_2
Final O_2 Conc.	1.28E-0^3	kmol/m^3	O_2 Concentration at end first day
	493	PPM	Concentration of gas after 1 day

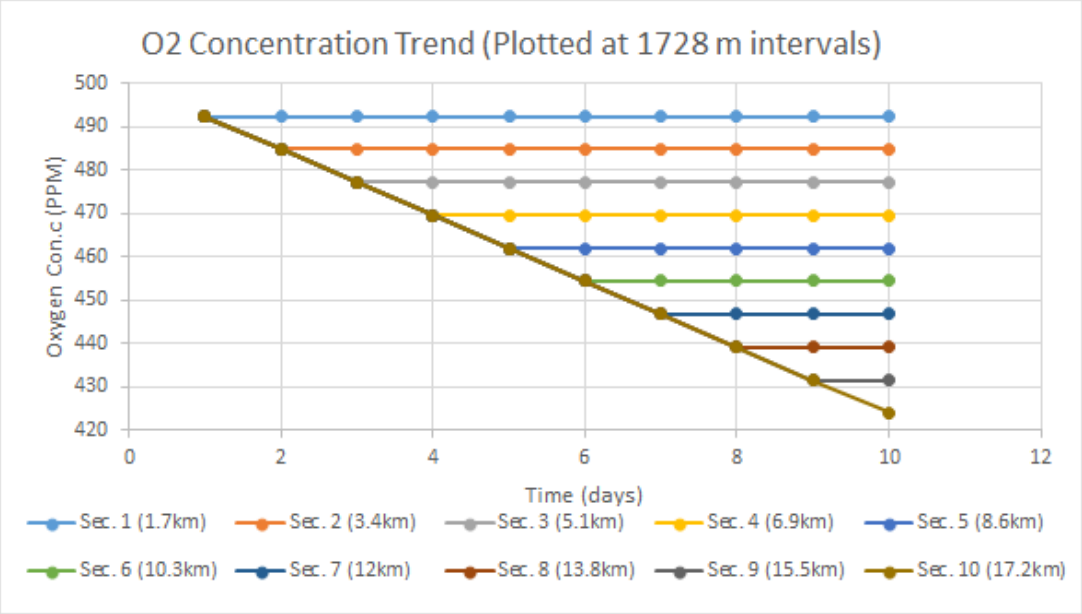


Figure 4-3 Excel Model - Base Case, O_2 Concentration Trend Plot (for each Section)

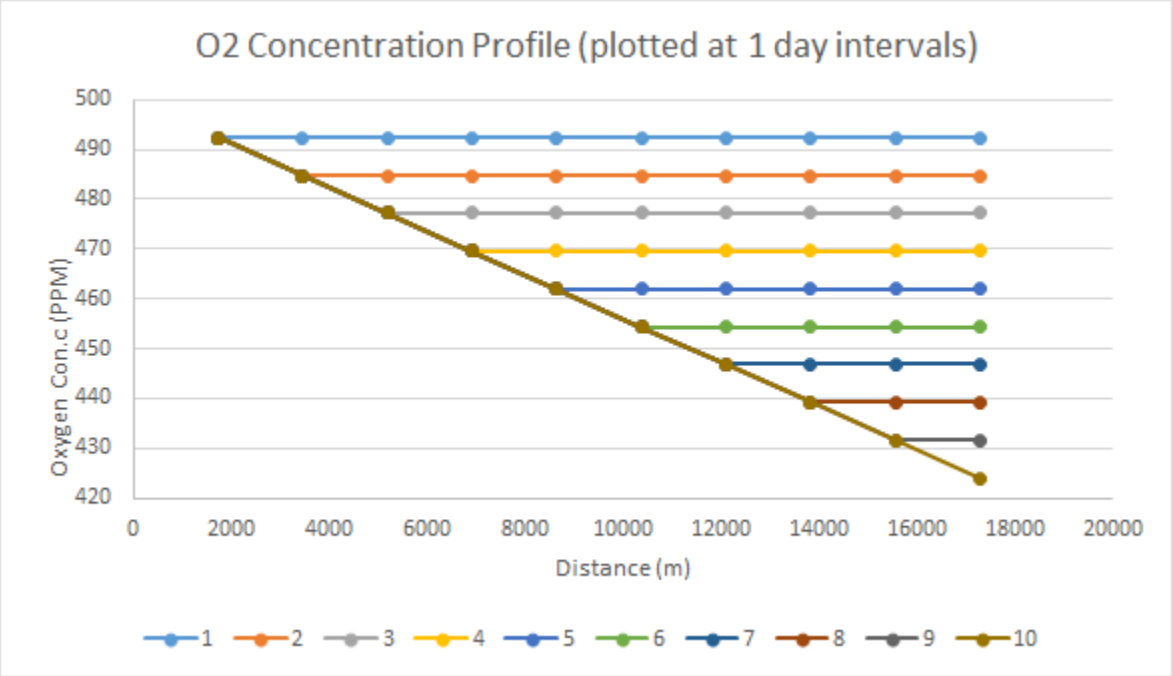


Figure 4-4 Excel Model – Base Case O_2 Concentration Profile Plot (for each Day)

4.2.3 Excel Model Sensitivities

As discussed above the key dependence for a 0th order reaction is the residence time in the pipe. The sensitivities are described below and summarised in Table 4-4.

4.2.3.1 ES1 - Oxygen concentration (1000 PPM)

Based on the simple 0th order reaction kinetics discussed above, increasing the oxygen concentration (500 to 1000 PPM) leads to the same absolute loss of oxygen in PPM, but from a higher base, i.e. the percentage change is lower, but the differential change is the same. If the reaction was taken as higher order (i.e. 1st of 2nd rather than 0th) then the rate of reaction would increase at higher concentrations of oxygen.

4.2.3.2 ES2 - Order of Reaction (1st Order)

An assessment was made of the impact of a 1st order reaction[e] compared with the 0th order used in the base case Excel model (and all the OLGA models). As shown in Appendix B (see §10) the integrated form of the rate equation for 1st order reaction is:

$$k.t = Ln\left[{}^{a_0}/_{a}\right]$$

[e] At the current time there is no detailed understanding of either the rate or order of the reaction. Better understanding of both may lead to significant savings regarding the amount of oxygen required and the complexity of the instrumentations systems required to ensure minimum concentration levels.

Hence, the k factor was calculated based on the initial slope of the reaction rate (1.77 e-7 s^{-1}).

As expected the 1st order reaction showed a slower rate of loss (0th order reaction is conservative (i.e. more O_2 consumed over time). For example after 10 and 40 days residence time with a 0th order reaction 15.2% and 60.9% of O_2 was consumed, whereas with 1st order reaction only 14.2% and 45.8% was consumed respectively.

The approximation of a 0th order reaction simplifies the calculation and does not lead to a significant degree of inaccuracy when the reduction of oxygen concentration is relatively low (circa 15%).

4.2.3.3 ES3 - Corrosion Rate (1 μm/year)

This Sensitivity lowered the corrosion rate by an order of magnitude relative to the base case (1 μm compared with 10 μm for base case). For the 0th order reaction loss of oxygen concentration with (residence) time is directly proportional to the reaction rate i.e. loss of oxygen concentration is one tenth that of the base case.

4.2.3.4 ES4 - Pressure ([redacted] bar)

On increasing the pressure from [redacted] bar the mass density increased from 5.264 to 6.118 kg/m^3 and the molar density increased from 2.592 to 3.013 kmol/m^3. Hence, the initial oxygen concentration increased from 0.001296 to 0.001506 kmol/m^3. It can be seen in Table 4-4 that although the residence time has increased from 10.4 to 12.1 days[f], the increased molar concentration ensures that the overall loss of oxygen at the end of L2 is not significantly different to the base case. However, this may well vary to some extent for reaction rates at orders higher than 0th.

The change in viscosity with pressure was found to be very small, and remains effectively unchanged from the base case for the purpose of the ES4 sensitivity. A small reduction in the Reynolds number was observed relative to the base case (7219 to 7216) predominantly driven by velocity change.

4.2.3.5 ES5 - Temperature (Summer, 25 °C)

At 25 °C the mass density decreases from 5.264 to 4.822 and the molar density decreased from 2.592 to 2.374 kmol/m^3. It can be seen in Table 4-4 that although the residence time has decreased from 10.4 to 9.5 days, the decreased molar concentration ensures that the overall loss of oxygen at the end of L2 is not significantly different to the base case. However, this may will vary to some extent for reaction rates at orders higher than 0th.

A small reduction in the Reynolds number was observed relative to the base case (7219 to 6802) predominantly driven by density and viscosity change.

4.3 OLGA Modelling

4.3.1 OLGA Model Build

Figure 4-5 shows the simple (compositional) OLGA model defined in §3.2. The model has three external boundaries with one internal node to form a "Tee" pipe system. The mass was injected at the Inlet of

[f] i.e. higher density leads to a longer residence time (if we keep same energy at burner tip).

branch-1 (L1) and initially flows to pressure boundaries of ■ bar at the outlet of branch-2 (L2) and branch-3 (L3). A negative source at end of L2 (Pipe-7-1) extracts the required flow[g]. Hence, the pressure settles to the required value to maintain the flow in L2. Fluids were defined within Multiflash and OLGA FEED blocks with 500 PPM and 0 PPM O_2 compositions. Additional FEED blocks were added for the 5%, and 20% H_2 in NG (again with 500 PPM and 0 PPM O_2) to be used in later sensitivities described below. The L2 spur is connected to the L1-L3 main branch using an internal node[h]. Each branch was made up of six[i] pipes (with each pipe consisting of three sections) undulating in a sawtooth pattern of ± 50 m elevation change[j].

Similar to the Excel model discussed above, the consumption of O_2 by the pipeline due to corrosion is modelled in OLGA as a 0^{th} order reaction using a Pull (O_2 consumed from the gas by the pipe wall section) and Push (O_2 depleted gas returned to the pipe section). Figure 4-6 shows how a small purge stream volume of gas is taken out using a negative mass source at the original O_2 PPM concentration, the O_2 is removed from the gas and a slightly depleted volume of gas is injected back into the pipe section as gas with zero oxygen content.

Within OLGA, each section (for a given ID) has the same mass of oxygen removed, regardless of flowrate[k] or distance along the pipeline (i.e. 0^{th} order reaction). However, OLGA does take account of the flowrate of gas since the O_2 removed is fixed, but the gas flowing from section to section can be varied. The schematic of the OLGA model (Figure 4-5) shows the separate Pull / Push gas sources in each section of the model.

[g] Starting at three hours ramping up over 1 hour. A the same time valve is closed at the outlet of L2 and thereafter approaches steady state.

[h] The node plays no other active part in the modelling.

[i] Branch-2 (L2) had a 7^{th} pipe, but this was purely to hold the additional negative mass source and valve associated with the flow/velocity control.

[j] Equivalent to a slope of 1.6%.

[k] However, the oxygen consumption does depend on the internal surface area of the pipe so actual moles of oxygen consumed vary with internal diameter for a given gas velocity.

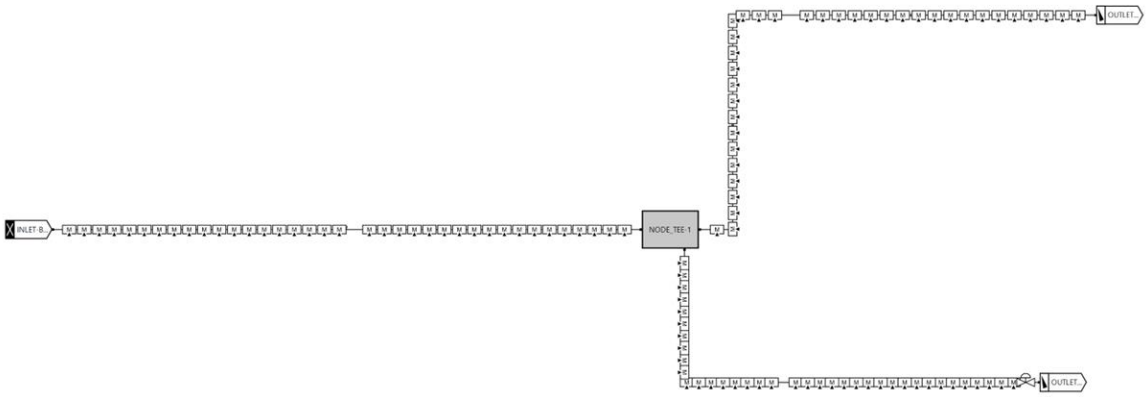


Figure 4-5 OLGA Model of the Simplified Pipe Base Case

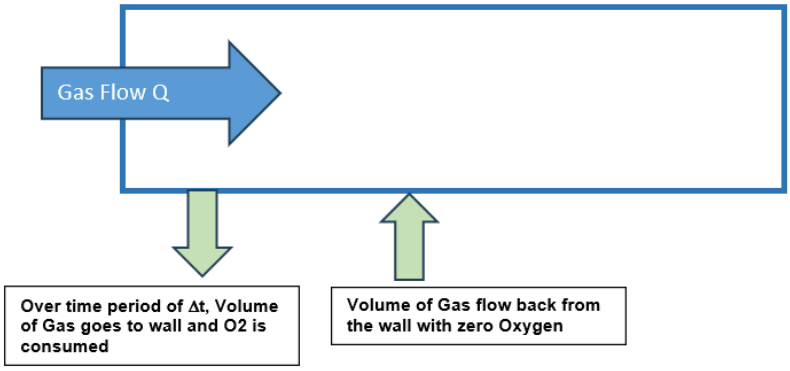


Figure 4-6 Consumption of O_2 at the Pipeline Wall Schematic

4.3.2 OLGA Model Base Case

The initial conditions of the OLGA model were set using the Steady State solver. Hence, at time zero all three branches of the model were filled by hydrogen with 500 ppm of O_2. The impact of the consumption of O_2 at the walls starts at time zero, such that it takes the full residence time of the gas (flowing from left to right) in each of the sections before steady state is achieved. This is effectively the same approach as the Excel model, but executed at far smaller time steps.

Figure 4-7 shows that pressure varies very little over the main branch (L1 and L3) before and after the 'TEE' to form the L2 spur. As defined in by the base case model (see §3.2.4), the velocity in L1 and L3 was set as 2 m/s and in L2 as 0.02 m/s. The main impact on the pressure profile is caused by the undulations in topography (± 50 m). Figure 4-8 shows the O_2 concentration profile at various times up to 30 days. It can be seen that the system does not come to a steady state equilibrium until shortly after

the gas residence time of 10.4 days. As with the excel based model the decline in O_2 concentration is directly proportional to distance (which equates to residence time, see Figure 4-9[l]).

Figure 4-7 Pressure Profile – Base Case

[l] It should be noted that the pipe position is shown in the from branch#-Pipe#-Section# e.g. BRCH2-P2-S3.

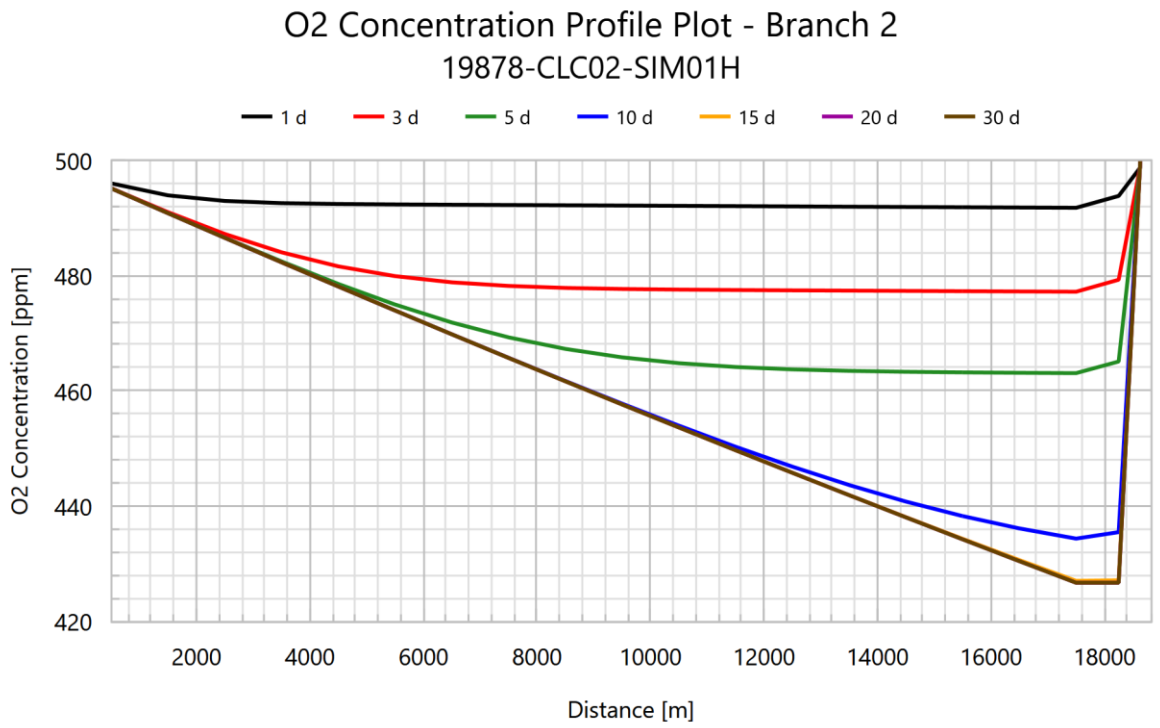


Figure 4-8 O_2 Concentration Profile – Base Case

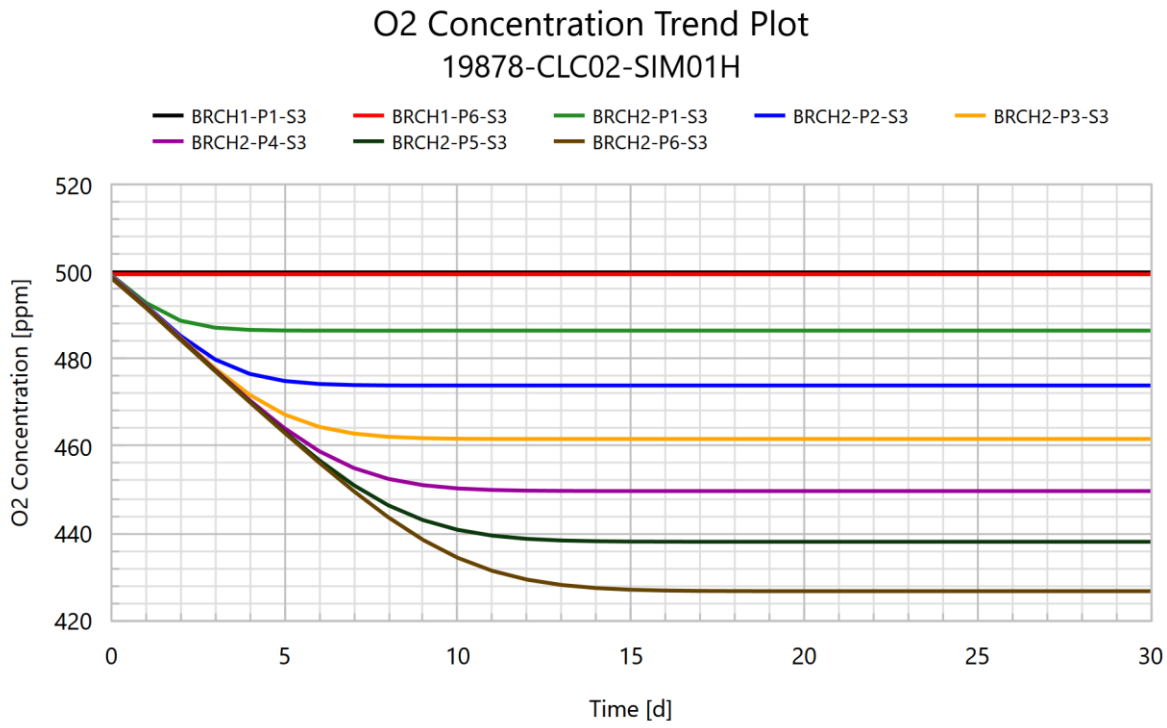


Figure 4-9 O_2 Concentration Trend – Base Case

4.3.3 OLGA Model Sensitivities

It should be noted that most of the sensitivities were conducted at the same thermal flow (i.e. on combustion) as the base case. Hence, for OS4 (5% H_2 in NG), OS5 (20% H_2 in NG) the gas velocity was reduced, because on a volume basis the gases have a larger HHV than 100% H_2. By contrast for OS6 (L2 diameter reduced to 100 mm) the velocity goes up since the same gas volume is forced to flow through a considerably reduced cross sectional pipe area.

Sensitivities OS2 and OS3 are at higher (0.2 m/s) and lower (0.002 m/s) velocities. Hence, the thermal flow on combustion is also a factor of ten higher / lower than the base case respectively.

The key results for each of the OLGA sensitivities are summarised in Table 4-5

4.3.3.1 OS1 - Square Wave Composition Perturbations

Following a Restart from the base case steady state condition (at 30 days) the OLGA model was adapted to allow square wave perturbations of O_2 concentration (starting at the entrance of L1) to be investigated (both starting at 35 days):

- OS1-A: the first was a two day reduction from 500 down to 250 then back up to 500 PPM. This represents a temporary loss of O_2 generation/supply e.g. one train of a two train supply was lost or suffered a reduction in output.
- OS1-B: the second was a two day increase from 500 up to 1000 then back up to 500 PPM. This represents a temporary increase of O_2 either through a fault in generation / supply or due to a period of low flow (and or flow reversals) in the gas branch such that a local plug of higher concentration O_2 built up (at inlet of L1) before being swept forward on resumption of normal flow.

Figure 4-10 shows that the minimum O_2 concentration seen in OS1-A was at the start of branch-2 (BRCH2-P1-S3 of the L2 spur, approximately 3 km from the “Tee”) shortly after end of the perturbation. However, the perturbation is now seen at the end of L2 but not until 11 days later. Obviously at the “Tee” separating L2 from L1 and L3, the concentration keeps in line with the concentration in branch-1 (L1), but to reach 3 km (i.e. end of the first pipe) takes approximately 1.7 days, such that the concentration perturbation “bleeds out” into the 500 PPM gas either side of it due to numerical smearing/diffusion, such that the minima gets smaller as it passes through L2. This is discussed in more detail in the CFD work (§6).

Similarly Figure 4-11 shows that the maximum PPM observed in L2 for OS1-B (Pipe 1 - Section 3) was 850 PPM was seen at start of L2 shortly after end of the perturbation, but not until 11 days later at the end of L2. Once again the maximum in the concentration perturbation “bleeds out” into the 500 PPM gas either side of it, such that the maxima gets smaller as it passes through L2.

It is noted that for OS1-A the consumption of O_2 at the pipe wall acts in the same direction as the O_2 perturbation such that the concentration minimum is initially weakened by dilution, but then starts to be strengthened at the back end of L2 as the consumption of O_2 forces the minima to lower values once more. For OS1-B the dilution effect and consumption at the wall operate in unison both reducing the maxima as it passes through the pipeline.

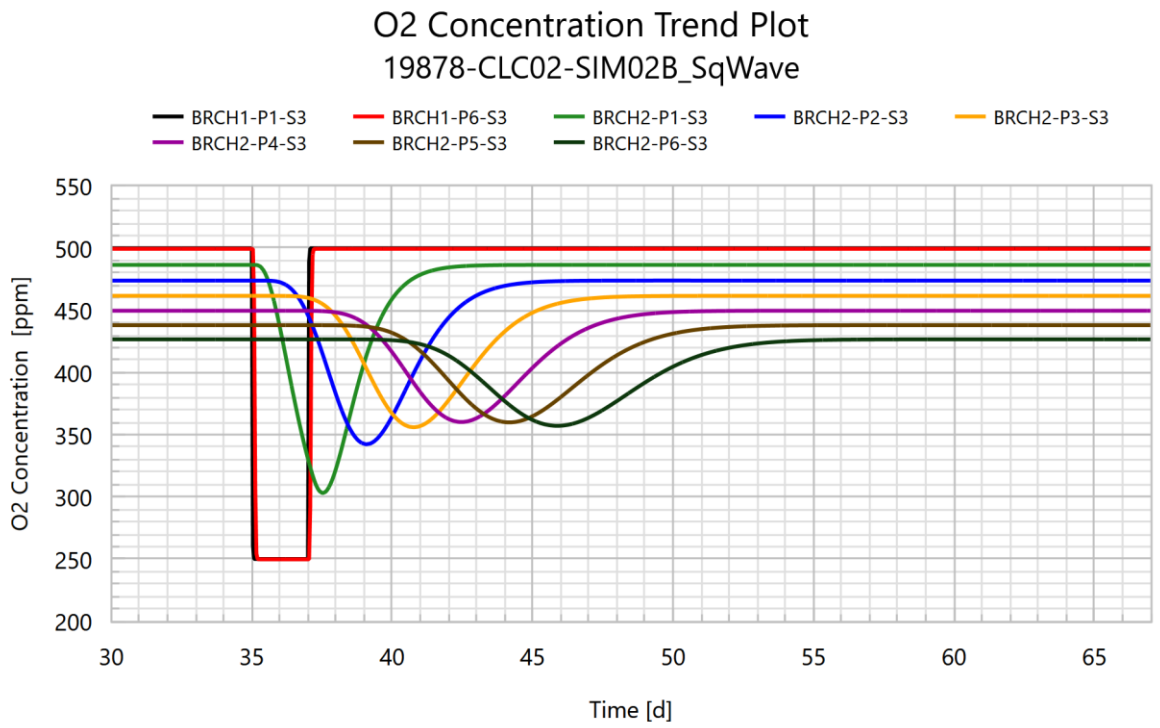


Figure 4-10 O_2 Concentration Trend – OS1-A, Square wave Perturbation (500-250-500)

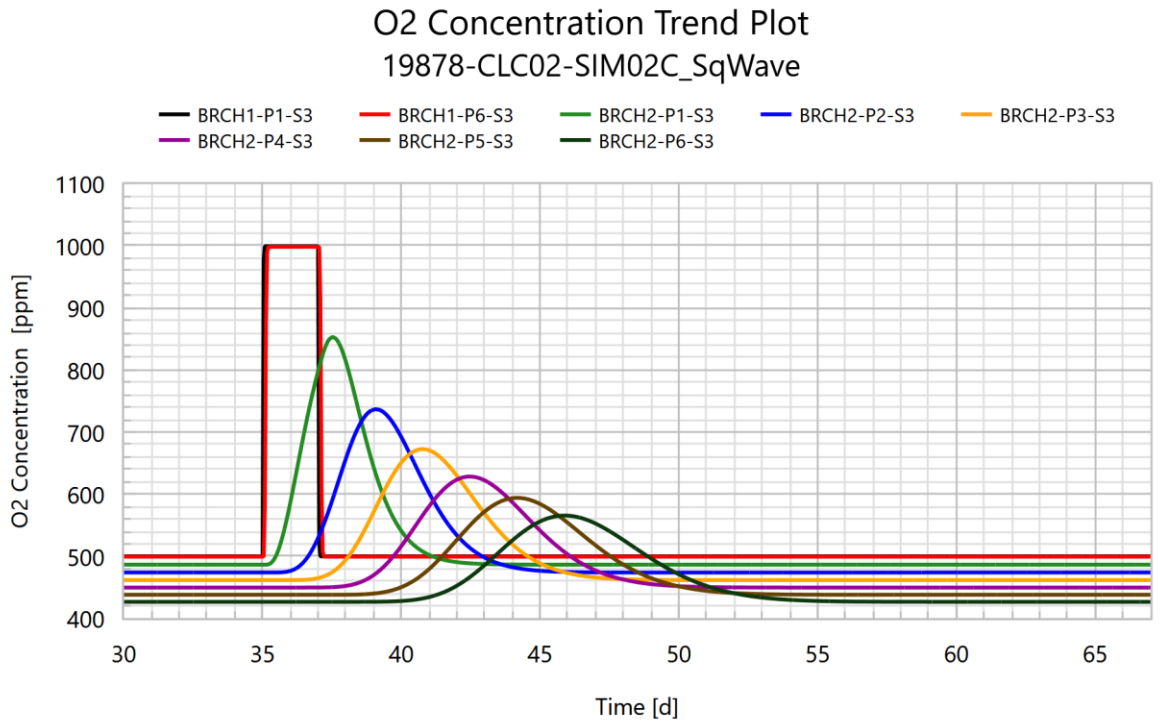


Figure 4-11 O_2 Concentration Trend – OS1-B, Square wave Perturbation (500-1000-500)

4.3.3.2 OS2 - Gas Velocity L2 (0.2 m/s)

The larger gas velocity leads to a higher thermal flow. Residence time was reduced by factor of 10. Hence, the final O_2 concentration at end of L2 is reduced by 7.7 PPM compared with a reduction of 68 PPM for the base case. The larger flow also gave a far larger Reynolds number pushing it further into the turbulent[m] region.

4.3.3.3 OS3 - Gas Velocity L2 (0.002 m/s)

The smaller gas velocity leads to a lower thermal flow. The residence time and hence O_2 consumption increased by factor of 10. Hence, final O_2 concentration at end of L2 reduced by 388 PPM compared with a reduction of only 68 PPM for the base case. The lower velocity also gave a far smaller Reynolds number, such that the flow in L2 was predicted to be laminar.

4.3.3.4 OS4 - Composition (5% mol H_2)

As discussed above, this sensitivity at 5% H2 in NG was at the same thermal flow at the burner tip, so the velocity was reduced, and the residence time increased by approximately a factor of 4. Hence, the final O_2 concentration is lower (i.e. more consumed, because residence is longer). The gas density is a factor of 10 higher than the base case. The Reynolds number doubled (more turbulent).

4.3.3.5 OS5 – Composition (20% mol H_2)

Similar to OS4, but magnitude of change was reduced.

4.3.3.6 OS6 - L2 Diameter (ID = 100 mm)

Once again this sensitivity was at the same thermal flow as the base case, with the L2 diameter reduced to 100 mm the velocity in L2 increased substantially from 0.02 to 0.68 m/s. The consequence was a far shorter residence time (down from 10.4 to 0.3 days), so final O_2 concentration was far larger than the base case (gas O_2 concentration was only reduced by 11 PPM). The higher velocity also gave a far higher Reynolds number (6x higher, so significantly more turbulent).

It should be noted that if different diameter pipes are compared at the same velocity, then smaller pipes display a higher rate of O_2 loss per day. This can be attributed to the greater inner metal surface for a given flow cross section area. Figure 4-12 shows the rate of decline of O_2 based on the diameter of the pipe.

[m] The Laminar flow regime was taken as Re ≤2000, The turbulent regime as Re > 4000 and the transition region as between 2000 – 4000.

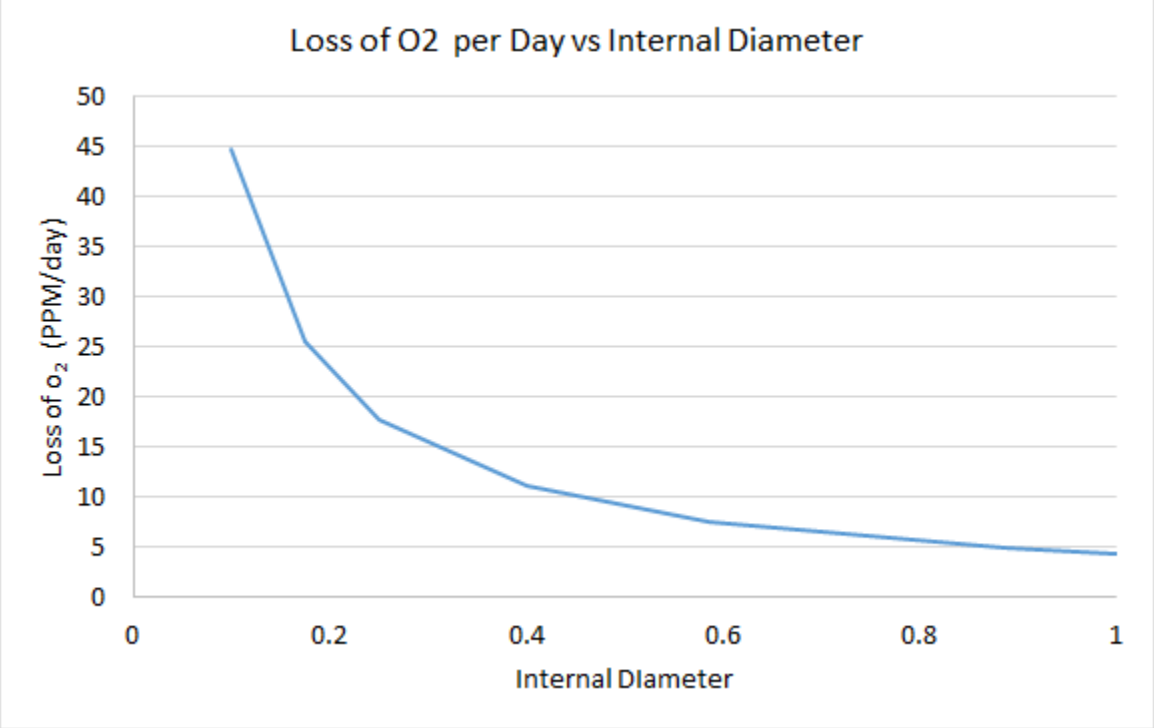


Figure 4-12 Loss of O_2 Per Day of Residence Time vs Internal Diameter

4.3.3.7 OS7 Shut-in from Steady State (after 35 days)

Following a Restart from the base case steady state condition the OLGA model was adapted (additional valve at the end of branch-3) to allow the system to be shut-in (at 35 days). The pressure settled out as the outlet valves on branch-2 and branch-3 were closed and the entry mass source was ramped to zero such that new gas no longer flowed into the model. After shut-in (see Figure 4-13) the gas velocity also declined to zero (apart from any thermally driven natural convection) see Figure 4-14. O_2 was then consumed at the pipe wall based purely on residence time[n].

It can be seen that if the minimum required O_2 concentration is taken as 250 PPM, then it would take approximately 35, 45 and 70 days of shut-in at the end of the L2 spur (Pipe-6-3), start of the spur (Pipe-1-1), and in the main pipeline (branches 1 and 3) respectively. As shown in Figure 4-12 the rate of decline of the O_2 is lower in L1/L3 than L2 because of the difference in diameters.

Using the simple relationship between residence time and O_2 concentration these are plotted against the reciprocal of gas velocity in Figure 4-15 (actual velocities in m/s are shown as labels against the residence time data). The plot is shown for a 0.5858 m ID pipe with a length of 1000 km (610 miles) such that most of the UK NTS would be covered within this size of system. As shown in Figure 4-12, the rate of loss of O_2 depends on the internal diameter, so for other pipe sizes sightly different gradients would apply.

[n] Such that the O_2 concentration fell (almost) linearly from the local steady state defined by the original local velocity (0.02 m/s for base case) and the distance from the 500 PPM gas source maintained in the main branch.

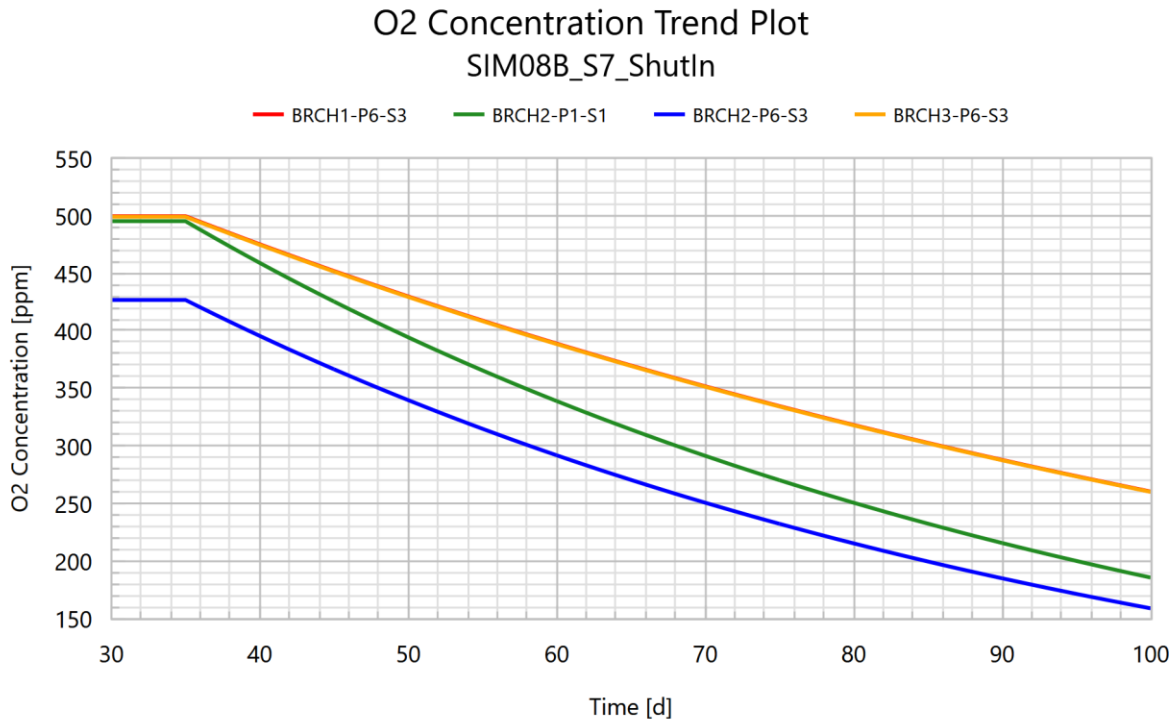


Figure 4-13 O_2 Concentration Trend – OS7 – Shutin of System from Steady State at 35 days

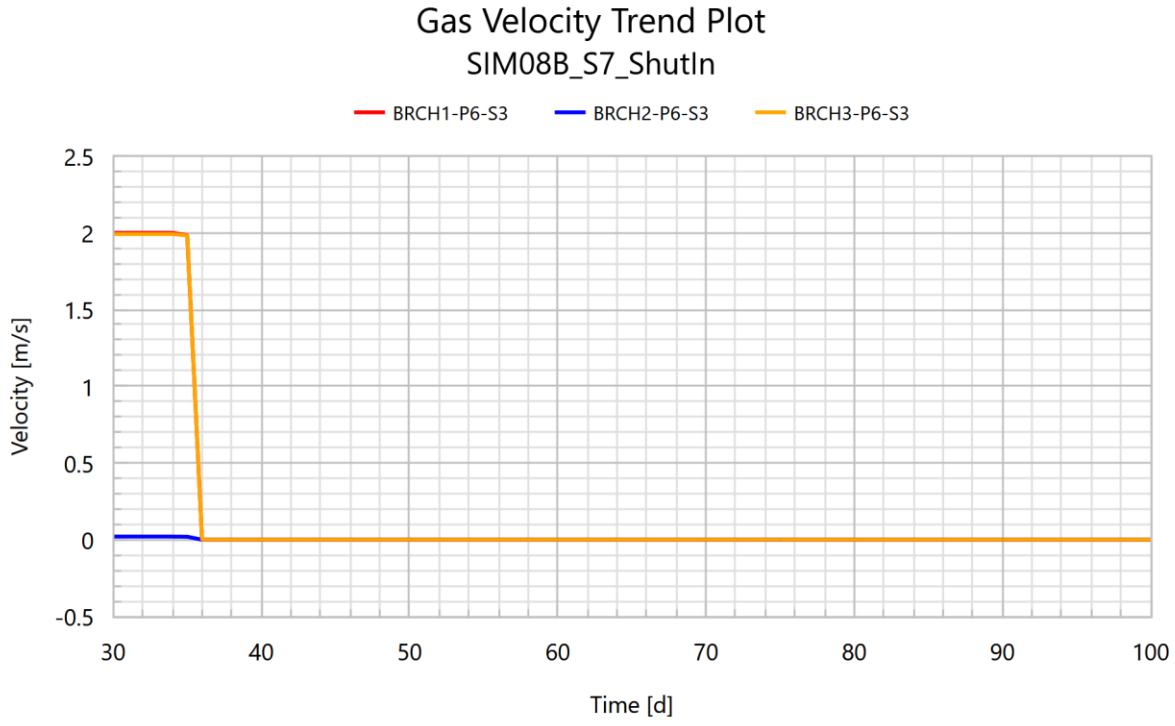


Figure 4-14 Gas Velocity Trend – OS7 – Shutin of System from Steady State at 35 days

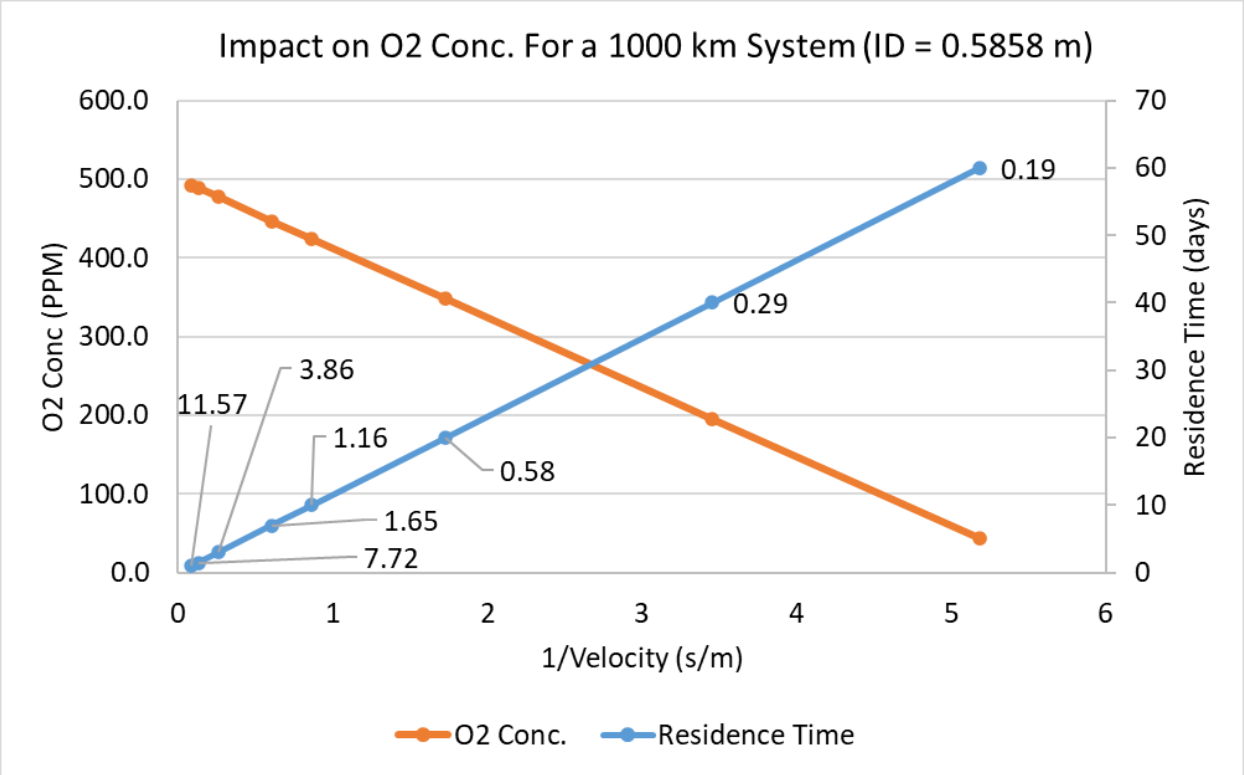


Figure 4-15 Oxygen Concentration and Residence Time vs Inverse Velocity (actual velocity shown as labels)

Table 4-4 Summary of Excel Sensitivity Results Relative to Base Case

Sens. #	Description	Sensitivity Departure from Base Case	Gas Density	Gas Viscosity	Outlet O_2, L2	Velocity / Residence Time L1&3	Velocity (m/s) / Residence Time L2	Quantification of Sensitivity
			(kg/m^3) / ($kmol/m^3$)	(Ns/m)	[PPM / ΔPPM / % Loss]	(m/s) / (d)	(m/s) / (d)	
Base Case			5.264 / 2.592	$8.56E^{-06}$	421 / -79 / -15.8%	2 / 0.104	0.02 / 10.4	Excel model gives similar but lower fidelity results than OLGA
ES1	O_2 conc. 1000 PPM	1000 ppm starting O_2 concentration spec instead of base spec of 500 ppm.			921 / -79 / -7.9%			Same loss of oxygen in ΔPPM, but from higher base.
ES2	Order of Reaction	First order reaction model used instead of zeroth order.			425 / -75 / -15%			Rate of oxygen consumption declines with falling O_2 concentration
ES3	Corrosion Rate	Corrosion rate of 1 um/yr used instead of 10 um/yr base case value.			492 / -8 / -1.6%			Rate is order of magnitude smaller, which is reflected in % loss.
ES4 Note-1	Pressure	[redacted]	6.119 / 3.013	$8.56E^{-06}$	421 / -79 / -15.8%	1.72 / 0.121	0.0172 / 12.1	Both residence time and oxygen molar density have increased. Hence, result is similar to base case.
ES5 Note-2	Temperature - Summer	25 °C instead of 0 °C	4.822 / 2.374	$9.07E^{-06}$	421 / -79 / 15.8%	2.18 / 0.09	0.0218 / 9.54	Density, residence time and oxygen molar density have decreased. Hence, result is similar to base case.

Notes:

(1) The change in viscosity with pressure was found to be very small, and remains effectively unchanged from the base case for the purpose of the ES4 sensitivity. Small reduction in Reynolds number from base case (7219 to 7216) predominantly driven by velocity change.
(2) Small reduction in Reynolds number from base case (7219 to 6802) predominantly driven by density and viscosity change.

Table 4-5 Summary of OLGA Sensitivity Results Relative to Base Case

5 COMPLEX NETWORK MODELLING

As discussed in §2.1.3, §3.1.1 and §3.3 an OLGA model was constructed of the North section of the National Transmission System (NTS) for a previous project (Ref. [5]) which includes the inlet gas supply at [redacted] with pressure boundaries at the southern end of the system ([redacted]

The aim was to study a more complex geometry at three conditions determined from the matrix of cases for the simplified pipe system and any learnings from the CFD modelling (§6). The main objective was to investigate how the impact of O_2 concentration changes in the main line affect the multiple demand points though the system as opposed to very short spurs with a single demand at the terminus (described in the simple pipe model). As discussed in §4, for the 0th order reaction considered the consumption is principally controlled by residence time. It was considered impractical to add the impact of O_2 consumption explicitly to the complex model, so the study is based solely on identifying regions of the system that experience periods of low gas velocity.

The lines from [redacted] supply major cities ([redacted]). Similarly the line from [redacted], serves [redacted] and the line from [redacted] contains the Irish interconnector. Hence, for this work the investigation concentrated on: [redacted] for the study of lines that are likely to give low velocity. As for the simple pipe model (§4.3.3) the cases for the complex model flows were maintained at the same calorific value (i.e. the volumetric flow was increased with increasing H2 concentration in the H2/NG blends). The cases shown below are described over the following sections:

- CASE-1 Investigate the current “North” network and the way it is operated. Does the system have consistently low periods of velocity for NG.
- CASE-2 As for CASE-1, but with 20% H_2
- CASE-3 As for CASE-1, but with 100% H_2
- CASE-4 500-1000-500 PPM square wave O_2 concentration perturbation

5.1 CASE-1, NG

Simulation results from Ref. [5] for CASE-1 are reproduced as Table 5-1 and Figure 5-1. These show the gas steady state velocity and pressure profiles (i.e. inlet flowrates, demand outflows and pressure boundaries were held constant). It can be seen that for some of the branches the flowed in to the system from one of the pressure boundaries rather than flowing out of it so the gas velocity was shown as negative ([redacted]). Hence, the minimum gas velocity was not the same as the minimum gas speed (i.e. absolute value of velocity). On re-examination of the original data set as gas speed values the difference is not significant for any of this CASE-1 apart from [redacted]. With this correction the lowest minimum gas speeds are seen in (decreasing values): [redacted]

However, the steady state results do not capture the change in gas velocity/speed, and pressure during the normal diurnal swing where the inlet flows, demand outflows across the network and the boundary pressures all vary with time. Hence, in order to capture the time variation of the gas velocity/speed a transient case from Ref. [5] was also considered. Figure 5-2 shows a contour plot with colour bands representing gas speed as a two dimensional plot of time against distance for [redacted] (plots for [redacted] are shown in Appendix D (§10).

Table 5-1 Steady State Pressure and Velocity (NG, Ref. [5])

[redacted]

Figure 5-1 Steady State Velocity Profiles (NG, Ref. [5])

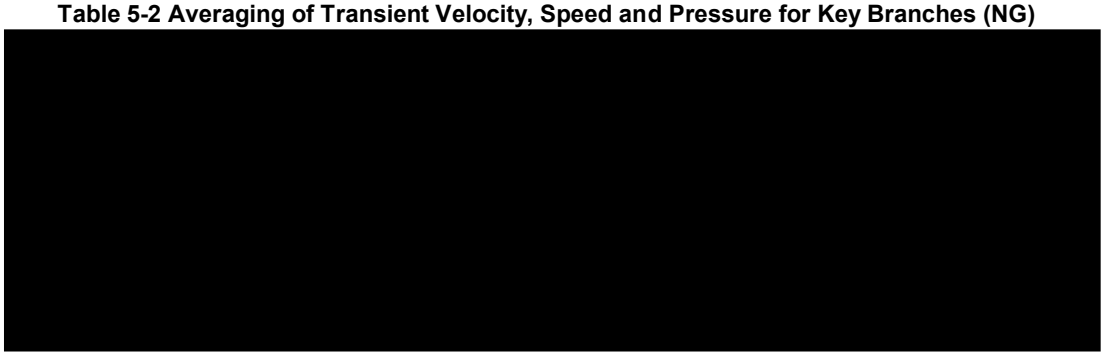
Table 5-2 shows a summary of the gas velocities, speed and pressure for the transient results. It can be seen that although a minimum and maximum gas speed of 0.002 and 2.71 were recorded these were only for relatively brief periods. When the speed and velocity were averaged over the entire [redacted] branch and time duration of the diurnal swings they were found to be 1.384 and 1.380 m/s respectively[o]. The [redacted] branch is far longer (372 km, as a continuous run, a residence time of

[o] For the network model the component pipes and underlying sections lengths are not equal, such that shorter sections will prejudice the mean values. However, for the purpose this study they still give a reasonable approximation to the true mean.

3.1 days) than the other branches considered. By contrast the [redacted] branch is 189 km, with a mean velocity of 2.58 m/s and a residence time of less than one day (20.3 hours).

Figure 5-2 Gas Speed Contour Plot (Time vs Distance, [redacted], NG)

Table 5-2 Averaging of Transient Velocity, Speed and Pressure for Key Branches (NG)



5.2 CASE-2, 20% H_2 in NG

CASE-2 is similar to CASE-1, but with 20% H_2 (in NG) instead of only NG. As discussed previously the 20% H_2 (in NG) case was at the same thermal flow at the burner tip as the NG case, so overall the gas flowrates and velocities increased relative to CASE-1.

Simulation results from Ref. [5] for CASE-2 are reproduced as Table 5-3 and Figure 5-3. These show the gas steady state velocity and pressure. In general the positive and negative velocities have increased. However, there are a few exceptions as gas flow balances around the system.

Table 5-3 Steady State Pressure and Velocity (20% H_2 in NG)

[redacted]

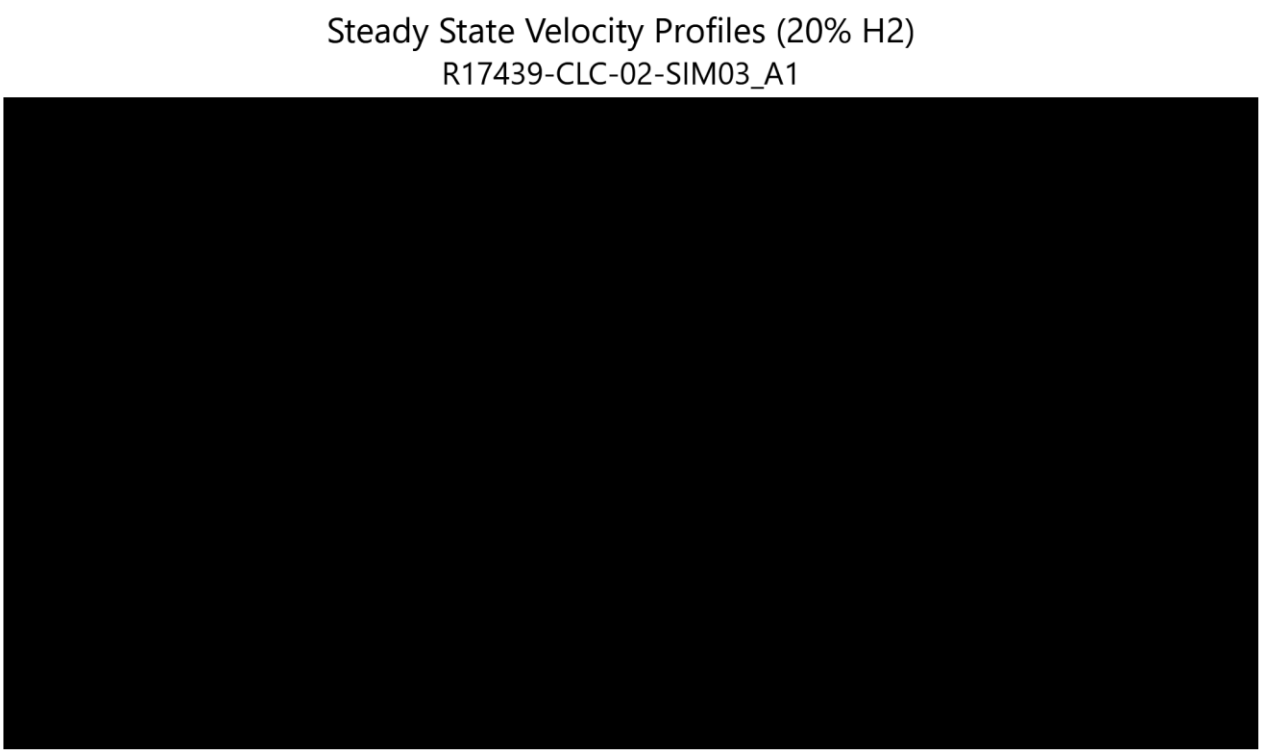


Figure 5-3 Steady State Velocity Profiles (20% H2)

Figure 5-4 shows a summary of the gas velocities, speed and pressure for the transient results at 20% H_2. It can be seen that for [redacted] although a minimum and maximum gas speed of 0.002 and 2.4 m/s are recorded these are only for relatively brief periods. When the speed and velocity were averaged over the entire branch and time duration of the diurnal swings, they were found to be 1.03 and 0.446

m/s respectively. Hence, the average speed/velocity has increased relative to CASE-1 for all branches excluding [redacted].

Figure 5-4 Gas Speed Contour Plot (Time vs Distance, [redacted], 20% H2)

Table 5-4 Averaging of Transient Pressure and Velocity for Key Branches (20% H2 in NG)

5.3 CASE-3, 100% H2

CASE-3 is similar to CASE-1, but with 100% H_2 instead of NG. As discussed previously the 100% H_2 case was at the same thermal flow at the burner tip as the NG case, so overall the gas flowrates and velocities increase dramatically (approximately a factor of three) relative to CASE-1.

[p] The boundary pressures were held constant, so it simply reflects re-balancing of the system at the higher volume flow required for the H_2 blend.

Simulation results from Ref. [5] for CASE-3 are reproduced as Table 5-5 and Figure 5-5. These show the gas steady state velocity and pressure. The positive and negative velocities have increased significantly. The pressures at the inlet of the system have increased[q], but not as much as one might initially expect owing to the decrease in fluid viscosity with increasing hydrogen concentration.

A transient simulation was not performed in Ref. [5] for 100% hydrogen. However, from the steady state results it can be seen that the velocities are significantly greater than for CASE-1 or CASE-2.

Table 5-5 Steady State Pressure and Velocity (100% H2)

[redacted]

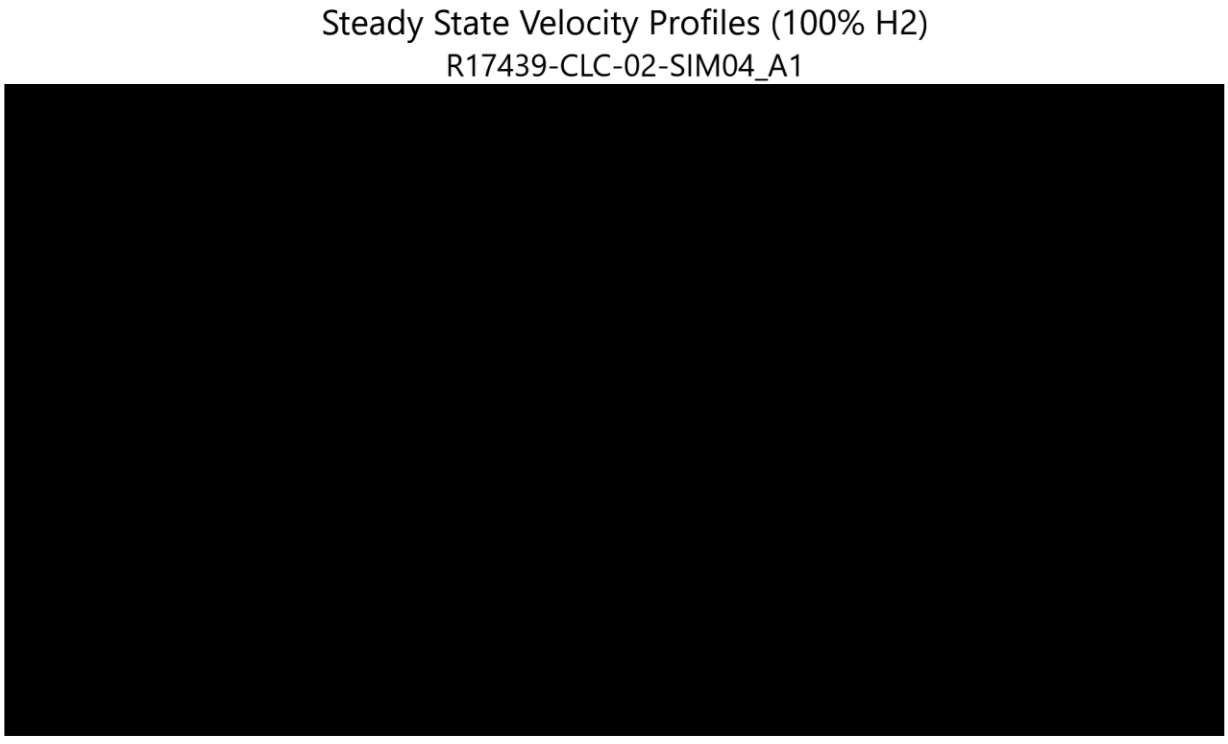


Figure 5-5 Steady State Velocity Profiles (100% H2)

[q] Pressures at the outlet boundaries were fixed to be the same as CASE-1.

5.4 Impact of Diurnal Pressure Variation on Spurs

The work in §5.1 to §5.3 showed that even though sections of the "North" network exist at very low flowrate conditions for brief periods, when considered over the normal diurnal swings the average velocities are all greater than 1 m/s (NG, 20% H_2 and 100% H_2). Hence, from Figure 4-15 it can be seen that even for a 1000 km pipe system the residence time is under twelve days, so the loss of O_2 across the line would be circa 100 PPM[r].

Although the short spurs discussed in §3 may not be subject to the same diurnal changes in flowrate as CASE 1 to 3, they will still be subjected to the diurnal pressure swings at their connection points to the NTS.

The base case simple pipe model described in §4.3.2 (100% H_2 with 500 PPM oxygen) was used to demonstrate the impact of diurnal pressure variation on short spurs at their connection point to the network while maintaining the same very low flowrates through the spur (i.e. mass flowrate boundary at the exit). Hence, the pressure estimates taken from the sections above based on data from Ref. [5] were used such that gas was pushed into and pulled out of the spur depending on the pressure variations seen in the network (see Figure 5-6). The OLGA results in Figure 5-7 (trends) and Figure 5-8 (profiles) show the pressure and O_2 concentration.

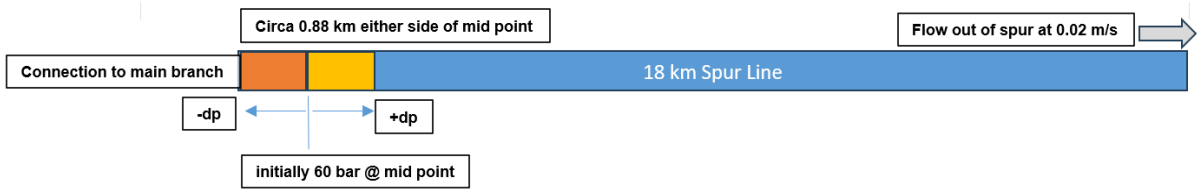


Figure 5-6 Schematic of "Gas Piston" Effect in the Spur Line owing to Diurnal Pressure swings

It can be seen that when +/- 3 bar pressure cycling (i.e. 6 bar peak to peak) was added as a diurnal swing the mean O_2 concentration were observed to cycle by about 7 PPM at the exit of the spur for each oscillation in pressure. A simple analysis based on compressibility of gas can be used to explain the oscillation of O_2 concentration with changes in pressure. From the base case results the total decline in O_2 concentration across branch-2 is circa 70 PPM i.e. 3.9 PPM/km. So if we consider the pressurisation / depressurisation of [redacted] around the midpoint of [redacted], it corresponds to a piston of gas (0.9 km) being displaced into and back out of the midpoint i.e. a concentration change of 7.74 PPM in total (the gas displacement is shown schematically in Figure 5-6).

It can also be seen that the steady state O_2 concentration at the end of the spur (branch-2) moved from a midpoint of circa 429 PPM to a new higher midpoint of 431 PPM (i.e. 1.4 PPM higher O_2 at the end of the spur when pressure fluctuations were included). As for the earlier work this change is on the same

[r] If we consider Figure 4-15, at a gas velocity of 1 m/s, the residence time is 11.6 days (blue line) and the O_2 is reduced to 400 PPM (orange line).

timescale as the residence time in the 18 km spur (at 0.02 m/s i.e. 10.4 days). A further small change occurs after this, but at a far shallower gradient and of far smaller magnitude[s].

Hence, we can conclude that for the pressure fluctuations likely to be seen in the NTS over a diurnal swing (typically greater than [redacted] peak to peak) should have a small beneficial effect regarding the loss of O_2 in spurs of the main network. The benefit is expected to be directly proportional to the size of the pressure fluctuations in the main network.

Figure 5-7 Pressure and O_2 Concentration Trend at Outlet of Spur Line

[s] The author cannot give an explanation of this later change, but it is thought to be the result of second order effects as the system establishes equilibrium.

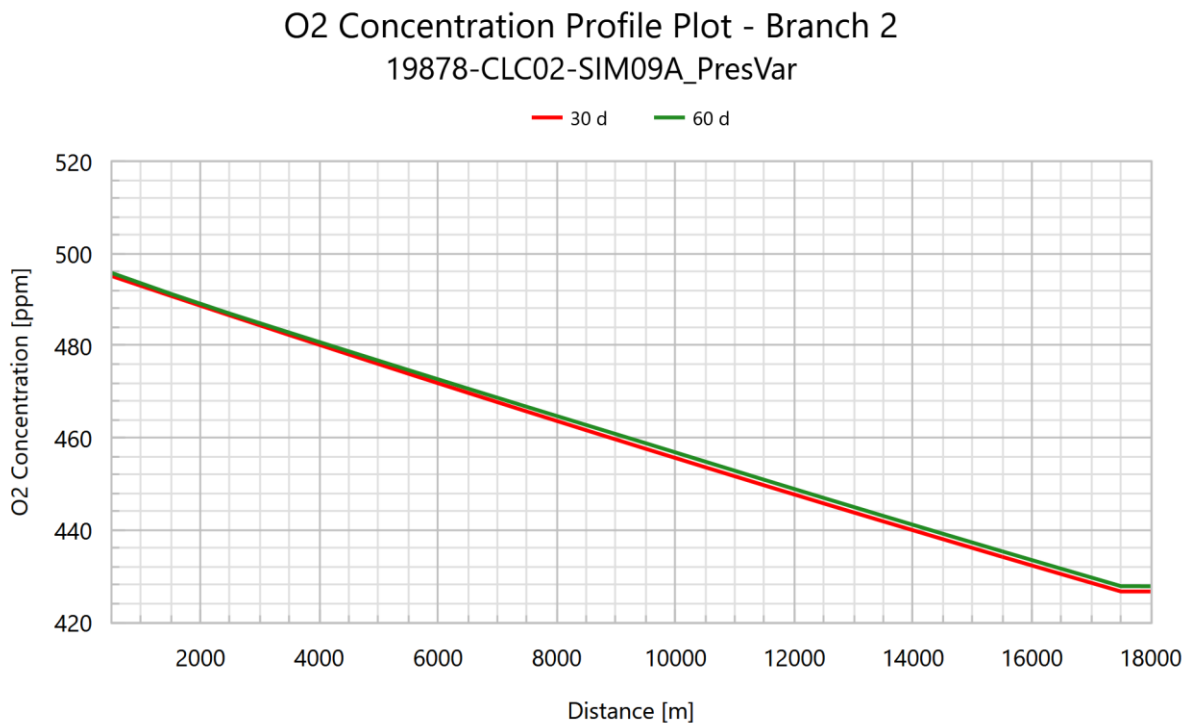


Figure 5-8 Oxygen Concentration Profile at Outlet of Spur Line

5.5 CASE-4, 500-1000-500 PPM Square Wave Concentration Perturbation in Complex Model, NG

The objective of this case was to investigate how a high oxygen concentration flow scenario at the inlet ([redacted]) will impact the rest of the system. This will be used to inform potential safety conditions from a build-up of O_2 concentration in the system. The model is relatively complicated, so the changes made to the model were restricted to a 500-1000-500 PPM O_2 concentration spike (in NG) for eight hours. The total duration of the simulation was 3 days (i.e. the supplied "Peak" case repeated three times to create three diurnal cycles. Although the physical properties of hydrogen and flow rates are likely to be significantly different to NG; ROSEN believes this case gives useful Insite into the movement of a concentration spike through the system.

Figure 5-9 shows the O_2 concentration at the end of each branch of the model. As gas emerges from [redacted] section ([redacted]) the initial 8 hour square wave of 1000 PPM O_2 arrives largely unchanged, except for some rounding (i.e. from square wave to bell shaped curve with peak at 9.7 hours). As the gas emerges near [redacted] ([redacted] the rounding of the bell curve is more advanced and the maxima has reduced to 960 PPM (at 19.4 hours). Hence, by the time the concentration spike passes into the pipes south of [redacted] a full diurnal oscillation in conditions has occurred, such that the concentration spike further into the system splits into multiple peaks at reduced concentrations. For example with gas emerging at [redacted] ([redacted]) shows two peaks of similar concentration (770 PPM) at 1.5 and 1.7 days respectively. After 2.3 days (with the exception of [redacted]) the oxygen spike had predominantly passed out of the system.

If we look at [redacted] in more detail (Figure 4-10), we can see that the concentration falls dramatically as it passes down the pipeline, but because of the very low flowrates highlighted in §5.1, the diurnal swings tend to push the gas back and fore in the pipe such that the unlike all the other pipes,

the gas is still significantly above the 500 PPM level after 3 days. For this case the 1000 concentration spike is seen to be broken up by the diurnal swings. The concentration spike is shuttled back and fore in the pipe as part of the diurnal swing. Although this is not a concern when the oxygen is added outside the boundaries of the pipe, it might become a concern if O_2 were added inside the [redacted] pipe boundaries, particularly at a low flow node within the pipe, such that the concentration could potentially accumulate over time if oxygen were added at a fixed rate rather that in proportion to the flowrate (i.e. to achieve a certain concentration).

Figure 5-9 O_2 Concentration Trend at the Exit of Pipeline Branches (500-1000-500 PPM Square Wave)

Figure 5-10 O_2 Concentration Trend within [redacted] Pipeline (500-1000-500 PPM Square Wave)

6 CFD MODELLING

The possibility of gas-gas unmixing was first discussed by Van der Waals and Korteweg at the start of the 20th century (see Ref. [8]). It was shown that the mixture critical line could move to temperatures higher than the critical temperatures of the two components (i.e. gas-gas unmixing). Thus, certain fluid mixture with very weak attraction between unlike components can unmix at temperatures well above the critical temperatures of the individual components. Although discussed at the start of the 20th century, it took a further forty years till, Krichevskii and Tsiklis measured binary mixture phase separation above the critical temperatures of both components in the system ammonia-nitrogen. Several other systems have since been found to exhibit gas-gas unmixing, but they do not include the pairs of components under consideration for this study. Hence, it was concluded that this phenomenon could be ignored for this work.

6.1 CFD Studies from the Literature Related to Mixing and Stratification of H2 in Pipelines

6.1.1 Hydrogen - Methane Mixtures : Dispersion And Stratification Studies, Marangon, Ref. [9]

The aim of the work was the investigation of the dispersion and stratification properties of hydrogen and methane mixtures. Experimental activities were carried out in a large scale closed apparatus[t], characterized by a volume of 25 m^3, both with and without natural ventilation. Mixtures of 10% vol.

[t] At a pressure close to atmospheric.

hydrogen – 90%vol. methane and 30%vol. hydrogen – 70%vol. methane were studied with the help of oxygen sensors and gas chromatography.

In all the experiments a non-homogeneous mixture concentration within the apparatus was observed, both with and without natural ventilation and independently of the natural ventilation openings position. Moreover for long residence time and no ventilation a tendency to homogenization was also observed. For test carried out with a higher mixture release flow rate, the gas concentration measured at the centre of the ceiling, was higher than the concentration measured from sensors located at the same height but not directly above the release. Instead for a smaller release flow rate and no natural ventilation, the concentration within the apparatus was well stratified with same values in the horizontal planes.

For a test carried out with natural ventilation realized with openings on opposite sides of the apparatus (in the upper part on one side and the bottom part in the other side), the gas concentration was not homogeneous in the horizontal planes of the apparatus. This non uniform gas concentration was due to the air flow through the ventilation openings that created different zones, characterized by different concentration's values, even in the horizontal direction.

For experiments carried out with only one opening located or in the bottom or in the upper part of the apparatus, the results were dependent on the difference in temperature between the internal volume of the apparatus and the external ambient air. When the differences in temperature between the internal volume and the outside ambient air were smaller, a stratification was found within the apparatus. Instead for higher temperature's differences, the measured gas concentration was not uniform in the horizontal planes of the apparatus and the concentration measured by the sensor located in the opposite side, with respect to the opening location, was higher.

In the test carried out with only one opening in the bottom port, it was demonstrated that it was not efficient in diluting the mixture's concentration. Moreover with only one opening in the lower part of the apparatus and a difference in temperature, between the internal volume and external ambient air, of about 3°C, the stratification was well evident with homogeneous concentration's values in the horizontal planes of the experimental facility.

Finally, sample analysis with gas chromatograph technique, showed, for the presented experiment configurations and mixture's residence time within the apparatus, that the constituent gases in the mixture (hydrogen and methane) do not separate.

6.1.2 Equilibrium Distribution and Diffusion of Mixed Hydrogen-Methane gas in gravity field, Peng et al. 2024, Ref. [10]

This study systematically examined the equilibrium distribution of hydrogen-methane mixtures in a gravity fields:

- The molecular dynamic simulations of H_2 and CH_4 gases in a gravity field show that gravitational stratification of these gases requires either an extremely strong gravity field or very large drops in altitude (on the order of 100 km), in agreement with Boltzmann distribution theory predictions.
- Large pipe height and low temperature promote the stratification. However, even with a low temperature of 150 K and a large height of 1500 m, the stratification is insignificant and will not significantly affect the risk of hydrogen embrittlement.
- The diffusion time required to reach thermodynamic equilibrium increases linearly with pressure and the square of pipe height. It takes approximately 300 years to reach equilibrium in a 1500 m high pipe, and temporary interruptions in pipeline gas transportation will not cause significant

stratification. However, if gases are not well blended initially, it can lead to the misleading conclusion that gas can stratify in a gravity field.

6.1.3 Masters Thesis: Simulation of flow conditions for natural gas and hydrogen blends for different points of the distribution natural gas network. Fernandes, Ref. [11]

The objective of this work was to explore the issues of mixing hydrogen with natural. Hydrogen is nine times less dense than natural gas, such that (temporary) stratification phenomenon often occur, such and the effective mixing of the two gases is delayed for a considerable distance, depending on the flow characteristics.

A possible strategy to prevent this is the introduction of a static mixer in the gas pipeline to provide an efficient mixing within a short distance without causing a significant flow pressure loss. Using Ansys Fluent, three different cases were simulated to test the mixing of hydrogen with methane. The performance of an helicoidal mixer (KM) and a KVM mixer were analysed and compared to the standard T-junction hydrogen injection without static mixer. The necessary distance needed to achieve a homogeneous mixture, using the Coefficient of Variation COV[u] as the measure criteria, in the different cases was calculated and compared with the consequent pressure loss associated. The three cases were analysed for hydrogen injection percentages to 20% and for a (realistic size dimension) gas pipeline connecting the transmission line to the distribution line (pressures around [redacted]). A faster homogenization of the mixture was achieved with the use of static mixers, with the KVM mixer, being the most efficient mixer, since it is the mixer with the lowest distance needed to obtain the homogeneity of the mixture and with the lowest pressure loss, when compared with the helicoidal mixer. The T-junction without the T-mixer is, as expected, the case with the lowest pressure loss, but to achieve homogenization of the mixture required circa 30 diameters of distance from the exit of the T-junction. By contrast the mixers KVM and KMS were, for all the conditions tested, able to obtain a homogeneous mixture in a maximum distance of 7 and 12 diameters, respectively, from the exit of the static mixer.

Author's key conclusions:

- The Portuguese natural gas grid was considered. It was concluded that there were many potential hydrogen injecting locations.
- Despite the superior homogenization performances of the static mixer, they induce an increased pressure loss. The T-junction case gave least pressure loss, followed by the KVM static mixer and the helicoidal static mixer.
- The lack of experimental results to validate the CFD work was identified as a significant issue.

6.2 Specific CFD Simulations Conducted for this Study

The CFD work conducted for this study is reported in full in Appendix E (§13) and summarised below:

[u] The coefficient of variation is defined as the ratio of the standard deviation to the mean. It shows the extent of variability in relation to the mean of the population.

6.3 Discussion of CFD Results

It is important to note that the two-layer stratification predicted by the full CFD model does not constitute reseparation of O_2 from a fully mixed mixture. When fluid within the spur is fully mixed, there is no evidence to suggest that O_2 can separate out of the mixture for the time and length scales of interest to the gas network.

The two-layer stratification presented within this document is strictly related to an increase in the concentration of O_2 at the entrance of the spur; this incoming O_2 is not mixed with the fluid already within the spur and the stratification is not related to separating of the mixture. Once mixed into a homogeneous fluid the O_2 will not separate out into stratified layers from either hydrogen or its mixtures with NG[v].

It was shown in the OLGA simulations that all the cases are well into the turbulent region - the only exception is if we drop the flowrate from 0.02 to 0.002 m/s. With CFD, the code has to be instructed to enable a turbulence model[w]. For all cases considered (0.02 m/s or more), the flow is turbulent. The CFD shows that bends will only make a marginal difference to the mixing of the O_2 as it migrates along the spur. The greatest degree of turbulent mixing at bends occurs at high flow velocities, but this coincides with non-stratified flow when the O_2 concentration is fairly uniform, and mixing an already uniform concentration does not affect the O_2 concentration. At low flow velocities, when the flow may be stratified and the O_2 concentration is non-uniform, the degree of turbulent mixing at bends is much reduced, so a longer total mixing length will be required.

It was shown in the excel modelling that the viscosity was largely unaffected by pressure ([redacted] increase) and hence diffusion is not likely to change much (diffusion inversely proportional to viscosity). However, viscosity is affected by temperature, so as temperature goes up, viscosity increases and diffusion rate would go down.

For the CFD work a [redacted] change in pressure is unlikely to affect the mixing behaviour. The pressure will change the density. However, the buoyancy effect is proportional to $\Delta\rho/\rho$, so density cancels out and should not be significantly affected by pressure-induced density changes. For the cases considered the flow is turbulent, turbulent mixing will dominate over molecular diffusion.

At very low non-turbulent flow (i.e. below 0.02 m/s), it is expected that the behaviour will depend upon the gradient of the spur. For cases C3 (horizontal) and C9 (downhill, 10%) which are nominally zero velocity (dead leg), a buoyancy-driven two-layer stratified recirculation becomes established with each layer travelling at around 0.05 m/s in opposing directions (so 0.1 m/s relative to each other). The interface between the two layers is therefore likely to be turbulent, and the O_2 concentration is predicted to fall along the spur in the CFD model. Case C6 (uphill, 10%) is also nominally zero velocity, but there is no two-layer stratification for this uphill case. Instead, the migration of O_2 along the spur is much slower and it is likely limited by molecular diffusion. The concentration of O_2 is maintained close to 1000 ppm as it migrates along the spur.

[v] A high level HAZID is planned as part of WP2, where safety issues such as this will be discussed.

[w] i.e. the CFD model does not calculate that a turbulence model is needed internally within the code.

6.3.1 Study A – Passive transport of O_2 (like-for-like with OLGA), 3 Cases

- When stratification effects were ignored, the predicted arrival time from the CFD model at the downstream locations considered was in close agreement with the expected arrival time[x].
- This was not the case for the OLGA model. This discrepancy is likely due to numerical diffusion within the OLGA model caused by the long discretisation of the spur (segments are 1 km each) [Ref. 4]. (the long segments in the OLGA model were related to the practicality of programming the O_2 consumption within OLGA).

6.3.2 4.2 Study B – Full CFD (including stratification), 3 Cases

- An O_2 concentration variation of 500 ppm is not insignificant, while this may only be 0.05% on a volumetric basis, it is around 0.8% on a density basis.
- For the base case (Case B1: gas velocity at entrance = 0.02 m/s), an 0.8% density difference was sufficient to quickly establish a two-layer stratified flow, with dense O_2 rich fluid propagating quickly along the spur in the lower part of the section and a counterflow with O_2 at 500 ppm in the upper part of the section.
- For the first sensitivity case considered (Case B2: gas velocity at entrance = 0.2 m/s), the higher gas velocity was relatively more important than the buoyancy effect and was sufficient to overcome the counterflow in the upper part of the spur.
- At the base case gas velocity of 0.02 m/s, a two-layer stratified flow was established; it was inferred that terrain effects may be an important additional consideration.
- For the second sensitivity case considered (Case B3: gas velocity at entrance = 0.02 m/s with a 1% uphill slope), the arrival time is delayed when compared to the base case (Case B1) which is perfectly horizontal.

7 IMPLICATIONS FOR WP2

The conclusions from this report and recommended further work relevant to WP2 are summarised against the original scope of work in and. If an intermediate concentration (before mixing into the main network stream) was used to help formation of the final O_2 concentration (as discussed in Table 1-1 and Table 1-2). However, the UFL of hydrogen in Oxygen is 94% hydrogen (i.e. 6% oxygen) so even with 5000 PPM oxygen it would be 12 times lower than this limit.

[x] i.e. distance divided by gas velocity.

8 REFERENCES

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[12] M.J. Pilling , Reaction Kinetics, Oxford: Clarendon Press, 1975.

9 APPENDIX A - ADDITIONAL DATA FROM LINEPACK MODEL

Table 9-1 HHV Values for Natural Gas Mixtures

Component	HHV (MJ/kg)	HHV (kJ/mol)
Hydrogen	141.79	285.8
Methane	55.50	890.4
Nitrogen	0.00	0.0
Carbon Dioxide	0.00	0.0
Ethane	51.88	1560.0
Propane	50.35	2220.2
Isobutane	49.53	2878.7
Butane	49.41	2871.8
iso-Pentane	48.90	3528.5
Pentane	49.01	3536.4
n-Hexane	48.68	4195.0
n-heptane	48.44	4853.8
n-octane	48.26	5512.6

Table 9-2 Natural Gas Composition

Component	Mol%
Hydrogen	0
Methane	89.76105263
Nitrogen	1.374078947
Carbon Dioxide	1.290131579
Ethane	5.513947368
Propane	1.519342105
Isobutane	0
Butane	0.406710526
iso-Pentane	0.001447368
Pentane	0.084473684
n-Hexane	0.045657895
n-heptane	0.000789474
n-octane	0.000394737

Notes:
1. For brevity other components in the original composition that had a value of zero were left out of this table.

Table 9-3 HHV Molar Contribution Values for different Hydrogen Blends

Comp.	H_2 Blends (Mol)			
	Nat. Gas	2% Mol H_2	20% Mol H_2	100% Mol H_2
	Mol%	Mol%	Mol%	Mol%
Hydrogen	0	2	20	100
Methane	89.761	87.966	71.809	0
Nitrogen	1.374	1.3466	1.0999	0
Carbon Dioxide	1.290	1.2646	1.0329	0
Ethane	5.514	5.4037	4.4119	0
Propane	1.519	1.4890	1.2154	0
Isobutane	0	0	0	0
Butane	0.4067	0.3986	0.3254	0
iso-Pentane	0.00145	0.00142	0.00115	0
Pentane	0.08447	0.08278	0.06757	0
n-Hexane	0.04565	0.04474	0.03652	0
n-heptane	0.00079	0.00077	0.00063	0
n-octane	0.00039	0.00038	0.00032	0
Total	100.0	100.0	100.0	100.0
HHV (kJ/mol)	935.7	922.6	805.6	285.9
HHV (MJ/kg)	51.92	52.12	54.36	141.8
HHV (MJ/m^3)	39.57	39.02	34.07	12.09
Relative Density	0.6220	0.6110	0.5115	0.06959
Wobbe Number (MJ/m^3)	50.18	49.92	47.64	45.83

Table 9-4 Heating Values and Densities of NG + H_2 Mixtures

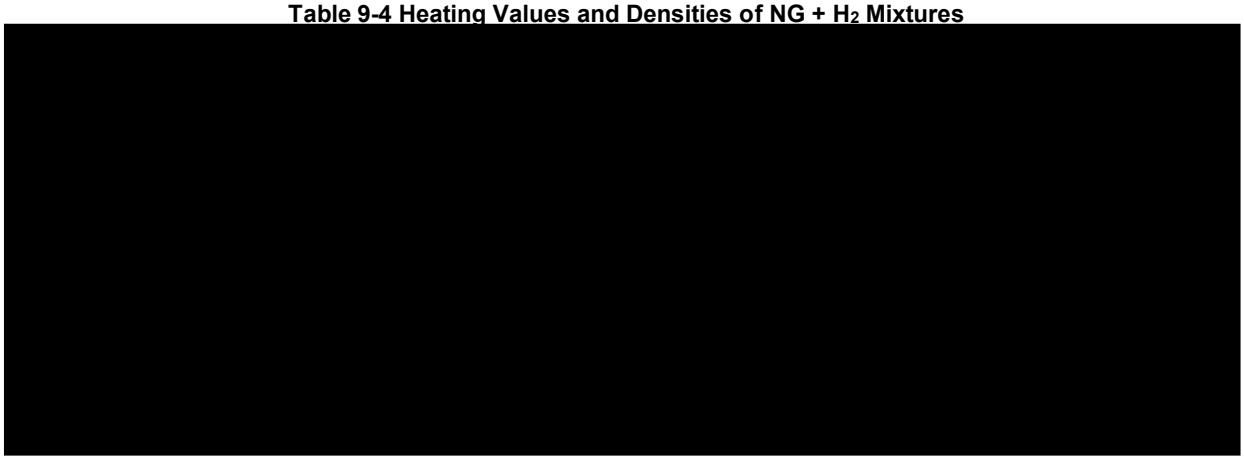

Table 9-5 Summary of NG GCS-LP data

Figure 9-1 Schematic of North Pipeline System (Zones 0, 1 and 2)

Figure 9-2 Static PEAK Case Gas Demand at Outlets for North Section

Table 9-6 Summary of Static PEAK Case Gas Demand at Outlets for [redacted] (North Section)

[redacted]

10 APPENDIX B – TIME CONCENTRATION AND TEMPERATURE

The following description is based on Reaction Kinetics by M.J. Pilling, which should be consulted for further details if required, Ref. [12]. Chemical kinetics is principally governed by the variables of time, concentration and temperature as described below.

10.1 Time and Concentration

The reaction rate φ may be defined as the rate of disappearance of a reactant, or as the rate of appearance of a product.

$$\varphi = -\frac{\partial[reactant]}{\partial t} \quad or \quad \varphi = +\frac{\partial[product]}{\partial t}$$

φ has units mol.dm^{-3}s-1 and is often found to depend on the molar concentration of the reactants:

$$\varphi = ka^{\alpha}b^{\beta}ac^{\gamma} \ldots$$

Where a, b, c are the concentrations of reactants A, B, C. The exponents α is termed the order of the reaction with respect to A, whilst the overall order n = α+β+γ… In elementary one step reactions, n, α, β and γ are integers, but in multi-step reactions they may be non-integer. The constant k is known as the rate constant; its units depend on the value of n as shown in Table 10-1. These equations are valid for like reactants (e.g. A+A), or for stoichiometrically equivalent reactants (e.g. A+B) with equal initial concentrations. When the initial molar concentrations are not the same, or when the reactants are not stoichiometrically equivalent (e.g. A + 2B), more complex expressions are required.

Table 10-1 Differential and Integral Forms of Rate Equations (Reproduced from Ref. [12])

Order	da/dt	kt	Units of k
0	-k	(a_0-a)	mol.dm^{-3}s^{-1}
1	-ka	Ln(a_0/a)	s^{-1}
2	-ka2	(1/a)-(1/a_0)	dm^{3}mol^{-1}s^{-1}
3	-ka3	(1/2a^2)-(1/2a_0^2)	dm^{6}mol^{-2}s^{-1}

10.2 Temperature

Reaction rates usually increase with temperature. An interpretation of this effect was developed by Arrhenius after initial work by vant Hoff [Ref. [12]].

The equilibrium constant for a reaction is given by the ration of the rate constants of the forward (k_1) and backward (k_{-1}) reactions

$$K_c = \frac{k_1}{k_{-1}} with\ k_1 = Ae^{-E_1/RT}, and\ k_{-1} = Ae^{-E_2/RT}$$

Where A is the pre-exponential factor, usually both E_1 and E_2 are non-zero, such that there is an energy barrier between reactants and products (in our case the oxygen/metal and corrosion product) which has to be overcome for the reaction to take place. E_1 and E_2 are termed the activation energies for the

forward and reverse reactions. As the temperature rises, the reaction rate increases, because the reactants acquire greater kinetic energy, and so can get over the barrier more easily. For this simplified work it is assumed that E2 >> E1 such that once corrosion has occurred there is very little reaction in the reverse direction.

11 APPENDIX C – ADDITONAL OLGA FIGURES SIMPLE PIPE MODEL

11.1 OS2 Gas vel. L2 (0.2 m/s)

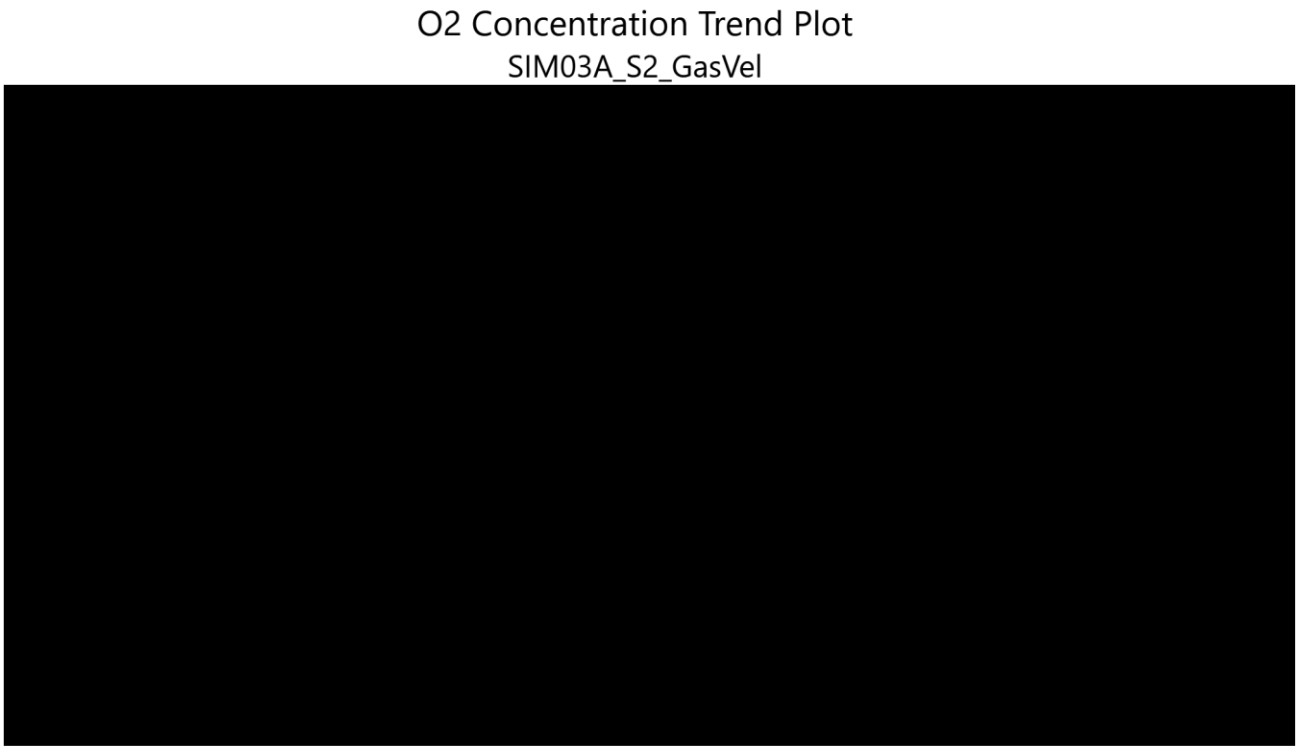

Figure 11-1 O_2 Concentration Trend – OS2

11.2 OS3 Gas vel. L2 (0.002 m/s)

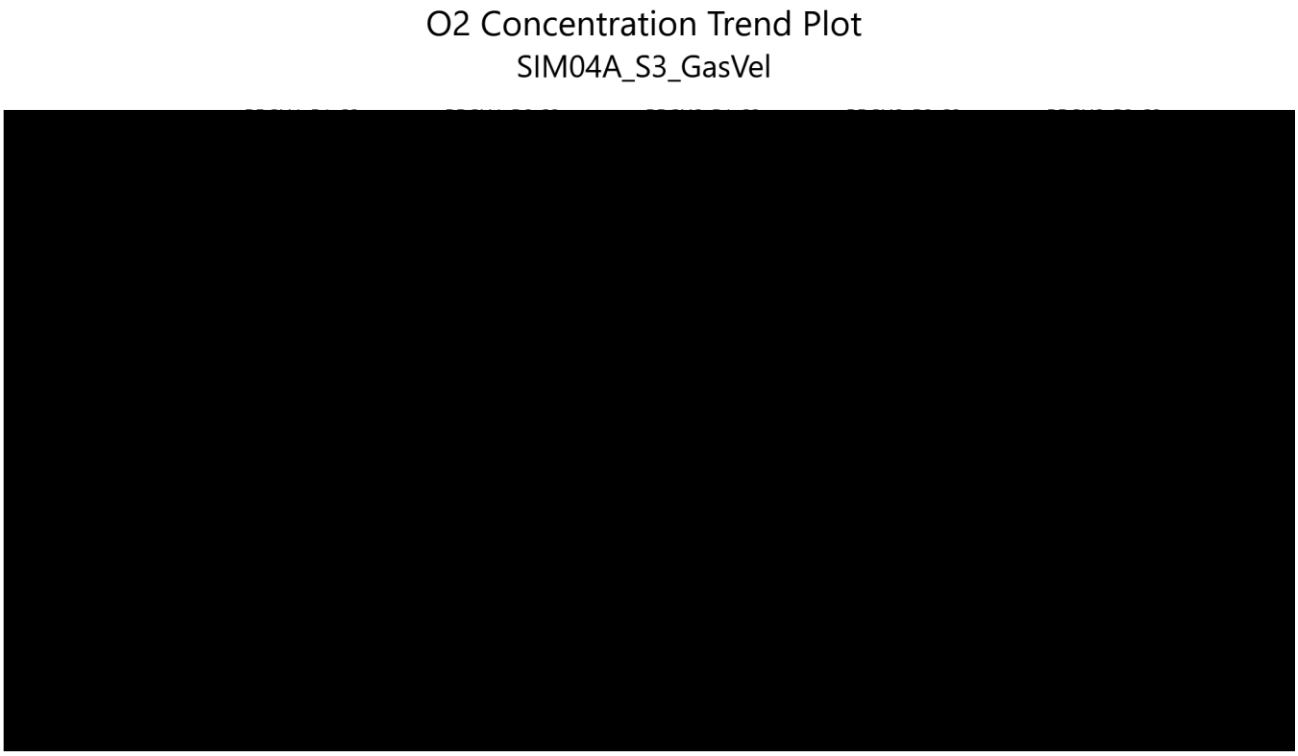

Figure 11-2 O_2 Concentration Trend – OS3

11.3 OS4 5% H2

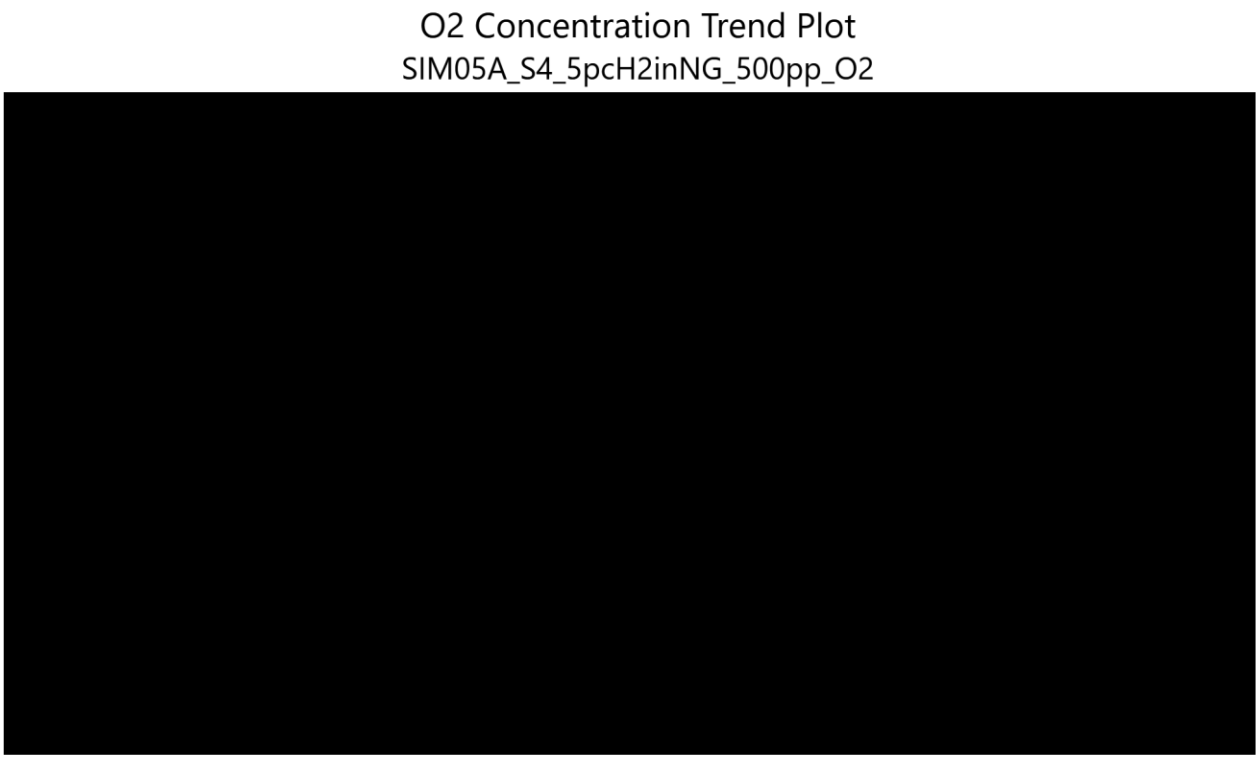

Figure 11-3 O_2 Concentration Trend – OS4

11.4 OS5 20% H2

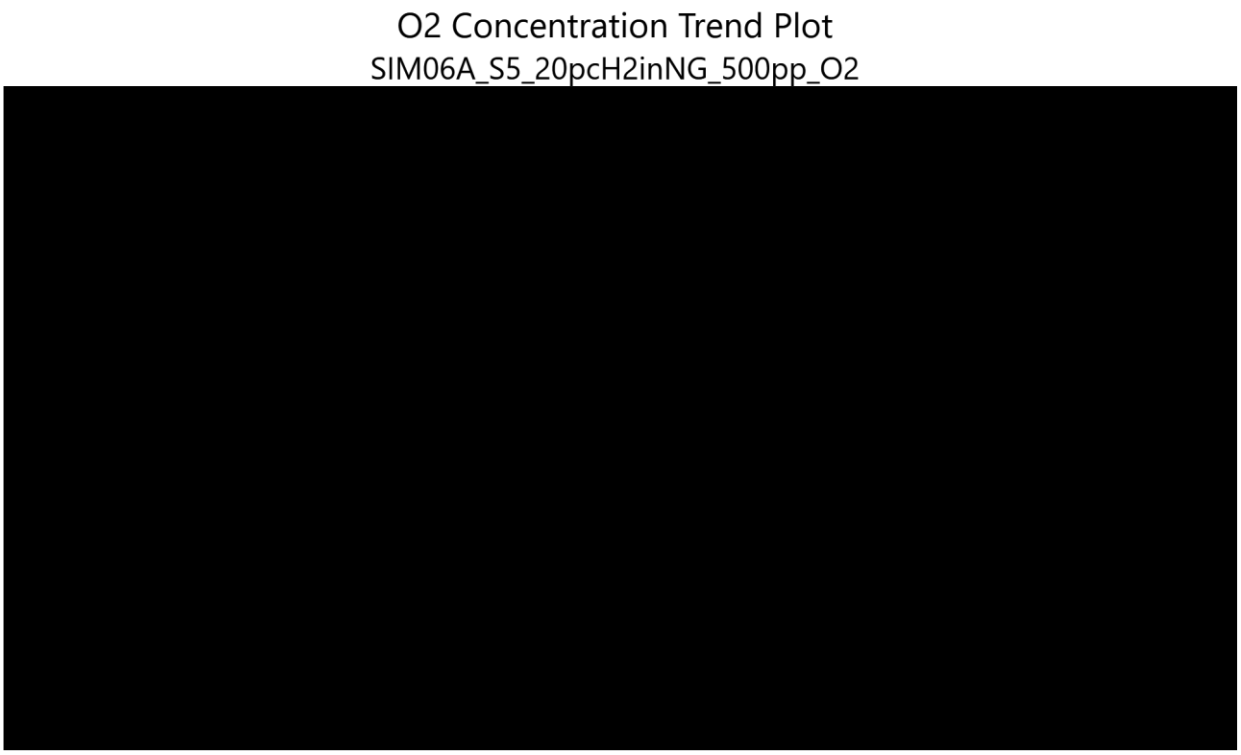

Figure 11-4 O_2 Concentration Trend – OS5

11.5 OS6 L2 with Internal Diameter of 100 mm

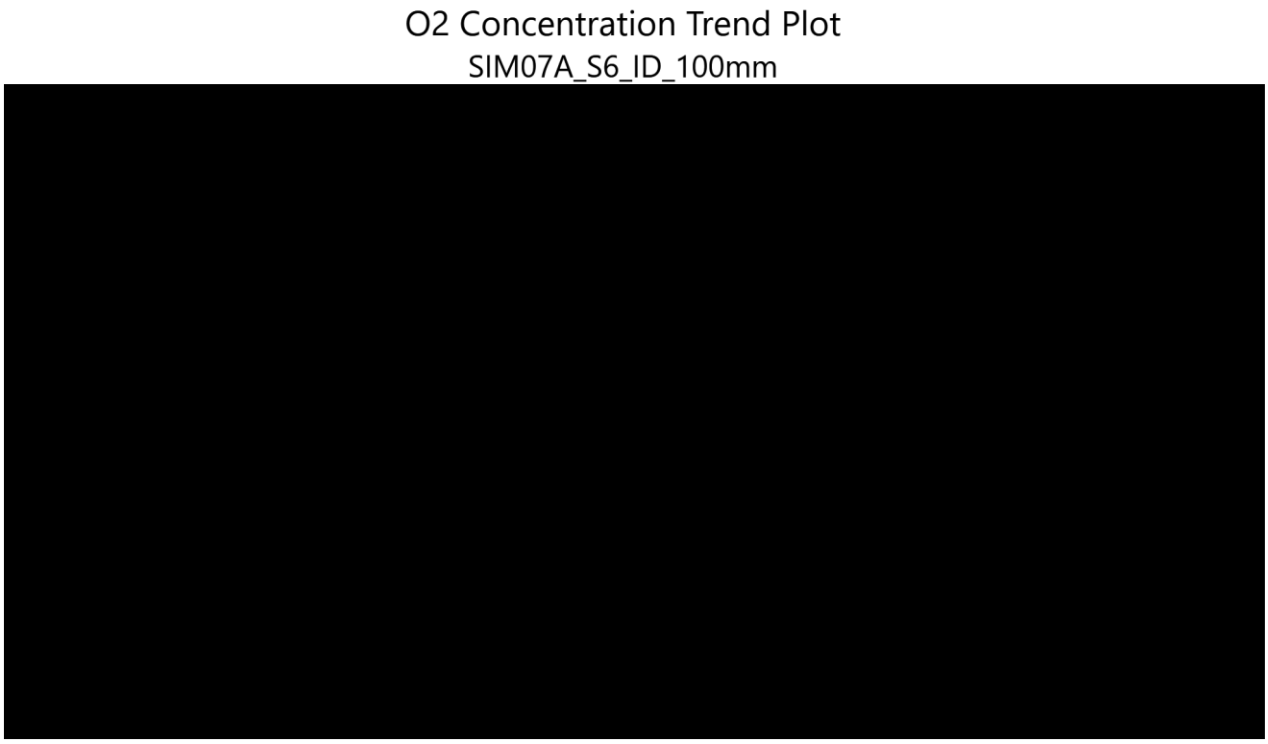

Figure 11-5 O_2 Concentration Trend – OS6

12 APPENDIX D – ADDITONAL OLGA FIGURES COMPLEX MODEL

12.1 CASE-1 NG

Figure 12-1 Gas Speed Contour Plot (Time vs Distance, [redacted], CASE-1, NG)

Figure 12-2 Gas Speed Contour Plot (Time vs Distance[redacted] CASE-1, NG)

Figure 12-3 Gas Speed Contour Plot (Time vs Distance, [redacted], CASE-1, NG)

Figure 12-4 Pressure Contour Plot (Time vs Distance, [redacted], CASE-1, NG)

Figure 12-5 Pressure Contour Plot (Time vs Distance, [redacted] CASE-1, NG)

Figure 12-6 Pressure Contour Plot (Time vs Distance, [redacted], CASE-1, NG)

Figure 12-7 Pressure Contour Plot (Time vs Distance, [redacted] CASE-1, NG)

12.2 CASE-2 20% H_2

Figure 12-8 Gas Speed Contour P9lot (Time vs Distance, [redacted] CASE-2, 20% H_2)

Figure 12-9 Gas Speed Contour Plot (Time vs Distance, [redacted], CASE-2, 20% H_2)

Figure 12-10 Gas Speed Contour Plot (Time vs Distance, [redacted], CASE-2, 20% H_2)

Figure 12-11 Pressure Contour Plot (Time vs Distance, [redacted], CASE-2, 20% H_2)

Figure 12-12 Pressure Contour Plot (Time vs Distance, [redacted], CASE-2, 20% H_2)

Figure 12-13 Pressure Contour Plot (Time vs Distance, [redacted], CASE-2, 20% H_2)

Figure 12-14 Pressure Contour Plot (Time vs Distance[redacted], CASE-2, 20% H_2)

13 APPENDIX E – CFD MODELLING

Technical Note for:

Commercial in Confidence

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Document title:

Oxygen inhibition in hydrogen pipelines

CFD simulation support to Rosen

Document reference:

240702-TN-001-B

B	4 Apr 25	Incorporating studies C and D	steve.howell	fiona.shearer	steve.howell
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Revision	**Date**	**Description**	**Prepared By**	**Checked By**	**Approved By**

CONTENTS

APPENDICES

1 INTRODUCTION

1.1 Background

Rosen is a global technology company specializing in pipeline inspection and asset integrity management solutions for critical industrial assets. Rosen is involved in a project with National Gas (NG) investigating the impacts of introducing hydrogen (H2) into the existing gas distribution network in the UK. Of particular interest is the phenomenon of H2 cracking and embrittlement in steel, which may lead to a strength reduction of steel pipes carrying H2 or its mixtures relative to pipes carrying natural gas. Any reduction in the strength of the steel may require a corresponding reduction in the Maximum Allowable Operating Pressure (MAOP) for the network, which could have a significant impact on its packing capacity for short-term storage of inventory.

The first phase of the project has identified that the strength reduction due to H2 cracking and embrittlement can be mitigated by introducing a small concentration of oxygen (O2) to the H2 mixture, with O2 seemingly acting as an inhibitor by preferentially adsorbing on the steel surface at the crack tip, preventing H2 entry into the steel [Ref. 1-2]. For this to be effective, the minimum O2 concentration should be maintained above 250 ppm, since this concentration is found to provide recovery of over 85% of the in-air fracture resistance with crack growth rates close to those in air [Ref. 3].

The second phase of work currently underway is concerned with the operational feasibility of using O2 as a gas inhibitor. This second phase includes three work packages:

- Work package 1 (WP1) – Feasibility of maintaining O2 inhibitor in the gas flow.
- Work package 2 (WP2) – Feasibility of technology implementation.
- Work package 3 (WP3) – Economic Considerations.

As part of WP1, Rosen has undertaken modelling to gain an understanding of how O2 concentration can be controlled within the gas flow, in terms of where the gas composition should be measured and where O2 should be injected. The modelling has been undertaken at the network scale using OLGA, which is widely recognized as one of the leading simulation tools for this kind of analysis. The model considers the north section of the National Transmission System (NTS) from [redacted] [Ref. 4].

In order to represent such large length scales, however, there are some pragmatic simplifications within the OLGA approach: specifically, all flow parameters (for example, velocity and composition) at each location along a pipeline are represented by a single average value at that location within the OLGA model. As such, it is not possible to consider stratification and the possibility for backflow with OLGA.

To validate OLGA for this application, Rosen has contracted Abercus to undertake a scope of analysis work using computational fluid dynamics (CFD). CFD is a first principles approach that is not subject to the same simplifications as OLGA. Flow behaviour including turbulence is solved in detail, such that the variation in

each flow parameter can be understood throughout the fluid domain of interest. Stratification and the possibility for backflow can, therefore, be considered with CFD.

This report presents four CFD studies, specifically for the case of a square wave O2 concentration perturbation travelling along a spur which has been modelled by Rosen with OLGA [Ref. 4]:

- Study A: assuming that transport of O2 is passive and does not affect the flow behaviour (so stratification effects are ignored). This is intended as a like-for-like comparison with the OLGA modelling.
- Study B: solving for the full flow behaviour, including stratification and the possibility for backflow.
- Study C: considering the effect of mixing at the junction at the entrance to the spur.
- Study D: considering the mixing effect due to a 90° bend within the spur.

2 TECHNICAL APPROACH

2.1 General

The simulations undertaken consider single-phase, isothermal flow. All simulations are undertaken using ANSYS FLUENT 2022 R2 [Ref. 5].

2.2 CFD model

For studies A and B, transport of O2 within a 300 m spur is considered. For both studies, the CFD model comprises an equivalent 2D slice with a diameter of 0.5858 m rather than a 3D round section for the spur, to allow the CFD simulations to run quickly.

Studies C and D focus on local mixing behaviour of O2 at the junction at the entrance to the spur, and at bends within the spur. For both studies, the CFD model comprises a 30 m 3D spur and, in the case of Study C, a 30 m 3D section of the main line. An equivalent square section with an edge length of 0.5858 m is considered rather than a round section, again to minimise the CFD mesh count and allow the CFD simulations to run quickly.

For all studies, the mesh edge length is 0.05 m in the vertical direction and 0.1 m and axial direction.

2.3 Boundary conditions

The simulation domain is bounded at the following locations:

- Wetted surfaces within the main bore: an adiabatic wall boundary is imposed.
  Input parameter: Surface Roughness (roughness height assumed to be 25 microns).
- Upstream: uniform flow is imposed.
  Input parameters: incoming flow velocity; turbulence quantities (turbulence kinetic energy assumed to be .
- Downstream: uniform static pressure or outgoing velocity is imposed.
  Input parameter: Static pressure, outgoing flow velocity.

The assumptions for the boundary conditions for each case considered are summarised in Section 3.

2.4 Fluid properties

The fluid is assumed to be a two specie mixture comprising H2 and O2. Each specie is assumed to behave as an ideal gas, described by its molecular weight. The corresponding assumptions are summarised in Section 3.

2.5 Turbulence

Turbulence effects are modelled using the standard-$k\varepsilon$ model. The wall function approach is used to capture the boundary layer in the near wall region.

3 ASSUMPTIONS

3.1 Boundary conditions

3.1.1 Wetted surfaces

The roughness for all wetted surfaces is assumed to be:

- Roughness height = 25 micron.

3.1.2 Upstream boundary for incoming flow

The turbulence quantities at the upstream boundary are assumed to be:

- Turbulence intensity = 5%.
- Mean turbulent diameter = 0.5858 m.

These assumptions are representative of fully-developed flow within a long pipe.

3.1.3 Downstream boundary

The static pressure at the downstream pressure is assumed to be:

- Downstream pressure = [redacted].

3.2 Fluid properties

3.2.1 Density

The fluid is assumed to be a two specie mixture corresponding to H2 and O2. Each specie is assumed to behave as an ideal gas, described by it's molecular weight: 2 kg/kmol for H2 and 32 kg/kmol for O2.

3.2.2 Molecular viscosity

The molecular viscosity of the fluid mixture is assumed to be 8.411E-06 Pa.s.

3.2.3 Mass diffusivity

The mass diffusivity for each specie is described by kinetic theory.

4 STUDY A – PASSIVE TRANSPORT OF O2 (LIKE-FOR-LIKE WITH OLGA)

The OLGA result for a square wave perturbation of O2 within the spur is shown in Figure 1. This is the result for the base case considered by Rosen, where the gas within the network is 100% H2 and the velocity within the spur is 0.02 m/s [Ref. 4]. The square wave represents a sudden increase in the O2 concentration from 500 ppm to 1000 ppm at the entrance to the spur, which lasts for 2 days (starting at day 35).

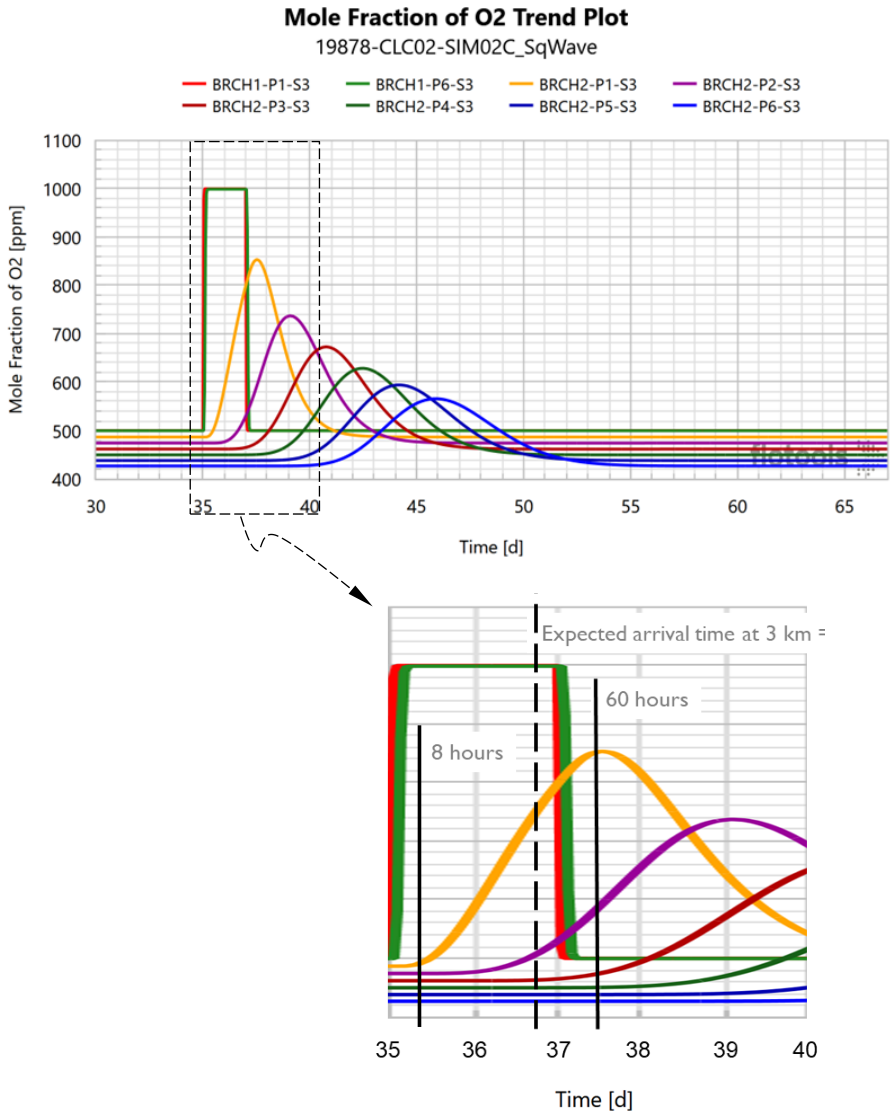


Figure 1 OLGA result for a square wave perturbation of O2 within the spur

Consider the orange curve, which is the prediction for the O2 concentration at a location 3 km downstream of the entrance to the spur. At a velocity of 0.02 m/s, the expected arrival time to reach 3 km (simply calculated as the quotient of the distance and flow velocity) is 42 hours (=1.7 days), as shown by the vertical black dashed line in Figure 1. The orange curve for the OLGA result, however, starts to increase much sooner after only 8 hours. This is unexpectedly short and is perhaps indicative of pseudo-diffusion within the OLGA model – an arrival time of 8 hours would correspond to a flow velocity of around 0.1 m/s, simply calculated as distance travelled divided by time taken.

In this study, the CFD model is constrained to replicate behaviour that is like-for-like with that expected in the OLGA model. Specifically, transport of O2 is forced to be passive within the CFD model, as it is in OLGA, such that buoyancy effects and the possibility of stratification and backflow are not considered, which is a reasonable assumption for small variations in O2 concentration. Three cases are considered within this study, as summarised in Table 1. The CFD predictions are presented in Appendix A.

Table 1 – Summary of cases for Study A

Case	Nominal flow velocity within spur	Square wave duration
A1	0.02 m/s	1500 s
A2	0.02 m/s	750 s
A3	0.02 m/s	250 s

The like-for-like CFD prediction for the spur is shown in Figure 2. This is for the same base case (Case A1: nominal flow velocity within the spur = 0.02 m/s, gas = 100% H2, diameter = 0.5858 m) but the CFD predictions shown in the graph are for shorter distances along the spur (the blue curve is at 100 m, the green curve is at 200 m, and the red curve is at 300 m, which is one-tenth of the distance of the orange curve for the OLGA prediction shown in Figure 1), and a shorter duration square wave at the entrance to the spur is considered (lasting only 1500 s). From this prediction, it is immediately apparent that the predicted arrival time at each of the three locations is consistent with the expected arrival time, (1.4 hours at 100 m, 2.8 hours at 200 m, and 4.2 hours at 300 m), and that the leading edge of the wave remains sharp in the sense that the time taken for O2 to rise from the base concentration of 500 ppm to the perturbed concentration of 1000 ppm remains a small fraction of the arrival time (of the order of 10%).

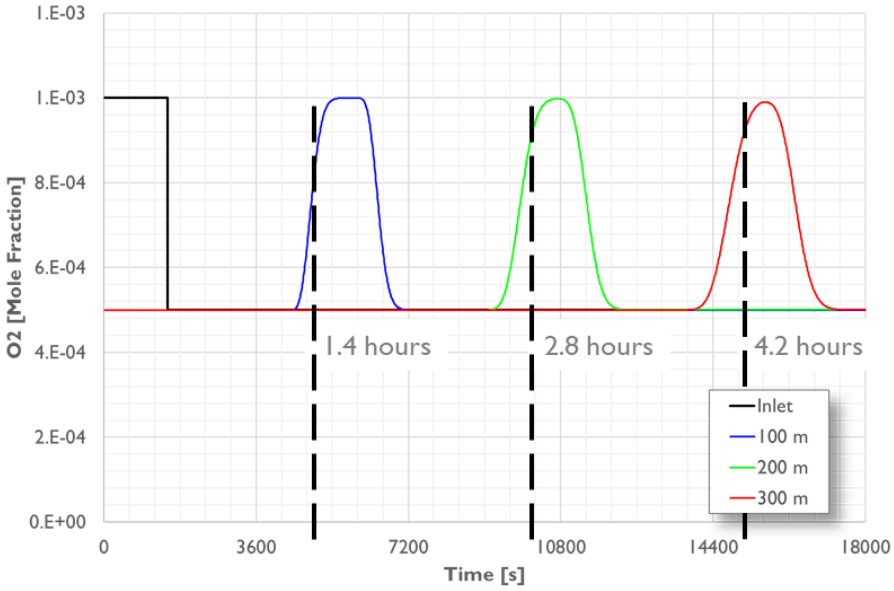


Figure 2 CFD result for Case A1: 1500 s square wave perturbation of O2 within the spur, assuming passive transport of O2 (like-for-like with OLGA)

It is noted that diffusion affects the behaviour at the leading and trailing edges of the wave as it propagates along the spur. For the 1500 s square wave perturbation considered in Figure 2, the leading and trailing edges are sufficiently separated so that diffusion effects at each edge do not interact, the mean O2 concentration within the central part of the square wave at each downstream location plateaus at 1000 ppm, which remains consistent with the perturbation at the spur inlet. The effect of diffusion does, however, become increasingly noticeable as the distance along the spur increases, as the leading and trailing edges become less sharp.

The prediction for a reduced square wave of 750 s (Case A2) is shown in Figure 3. For this case, it is clear that the leading and trailing edges are close enough for the diffusion effects at each edge to interact, and the maximum O2 concentration at each location no longer plateaus at 1000 ppm but instead its declines with distance along the spur. For the short square wave of 250 s in Figure 4, the diffusion effects at the leading and trailing edges are interacting significantly. It is clear, therefore, that the downstream response is not only dependent upon the magnitude of the square wave perturbation at the entrance to the spur, but also upon its duration, although it is noted that for the shorter pulses, the predicted arrival time remains in line with the expected arrival time.

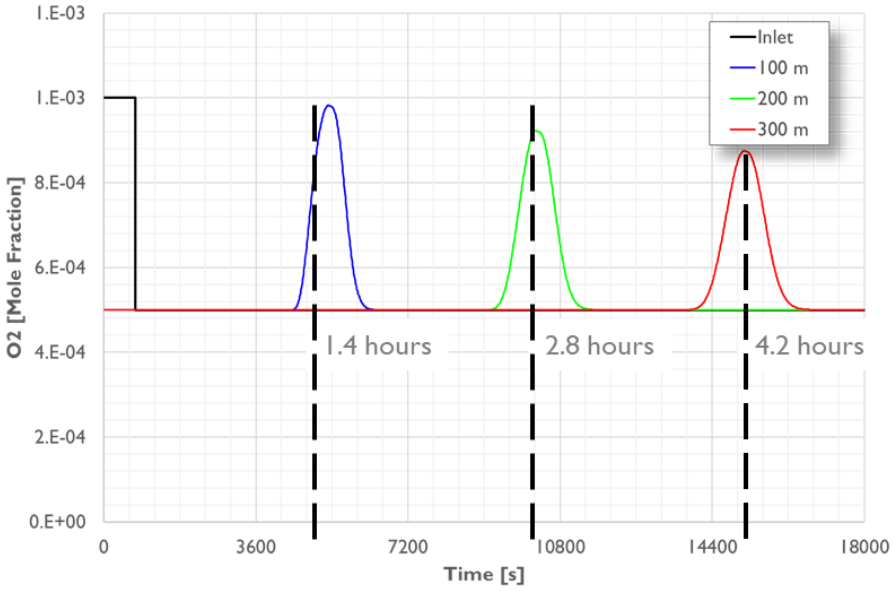


Figure 3 **CFD result for Case A2: 750 s square wave perturbation of O2 within the spur, assuming passive transport of O2 (like-for-like with OLGA)**

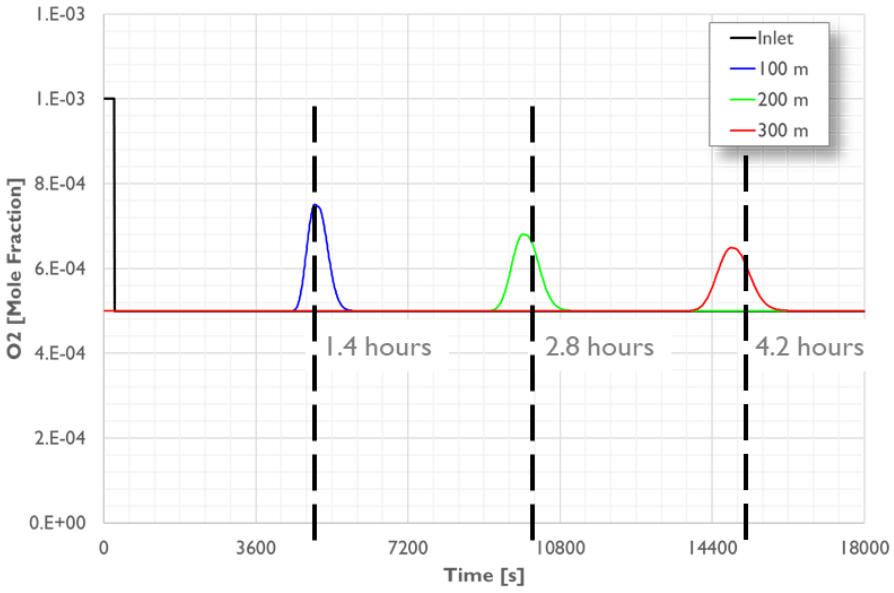


Figure 4 **CFD result for Case A3: 250 s square wave perturbation of O2 within the spur, assuming passive transport of O2 (like-for-like with OLGA)**

5 STUDY B – FULL CFD (INCLUDING STRATIFICATION)

For small variations in O2 concentration, it is reasonable to assume that the corresponding density differences and buoyancy effects due to these variations are also small and can be neglected – this is essentially the major assumption for the passive transport of O2 presented in Section 2. For this study, however, buoyancy effects due to the variations in O2 concentration are included within the CFD model, such that stratification can be resolved. Nine cases are considered within this study, as summarised in Table 2. The CFD predictions are presented in Appendix B.

Table 2 – Summary of cases for Study B

Case	Nominal flow velocity within spur	Square wave duration	Slope
B1	0.02 m/s	1500 s	Horizontal
B2	0.2 m/s	150 s	Horizontal
B3	0.5 m/s	60 s	Horizontal
B4	1.0 m/s	30 s	Horizontal
B5	2.0 m/s	15 s	Horizontal
B6	0.02 m/s	1500 s	Uphill, 1%
B7	0.02 m/s	1500 s	Uphill, 10%
B8	0.02 m/s	1500 s	Downhill, 1%
B9	0.02 m/s	1500 s	Downhill, 10%

The prediction for the base case (Case B1: velocity = 0.02 m/s, gas = 100% H2, diameter = 0.5858 m, perfectly horizontal spur) with O2 buoyancy effects included is shown in Figure 5: specifically, this shows the maximum O2 concentration at each downstream location with time. Comparing this graph with Figure 2, it is immediately apparent that the inclusion of O2 buoyancy effects has a significant influence upon the downstream response to the perturbation:

- The arrival time at each downstream location is much shorter than the expected arrival time – around 0.4 hour compared to an expected arrival time of 1.4 hour at 100 m, and around 0.9 hour compared with an expected arrival time of 2.8 hour at 200 m.
- The concentration at each downstream location no longer consistently reaches the 1000 ppm of the perturbation at the spur entrance, but instead this maximum decays with distance along the spur.
- A long tail is developed whereby the concentration remains at around 600 ppm (around 100 ppm above the baseline O2 concentration) for a prolonged period following the initial arrival of the wave.

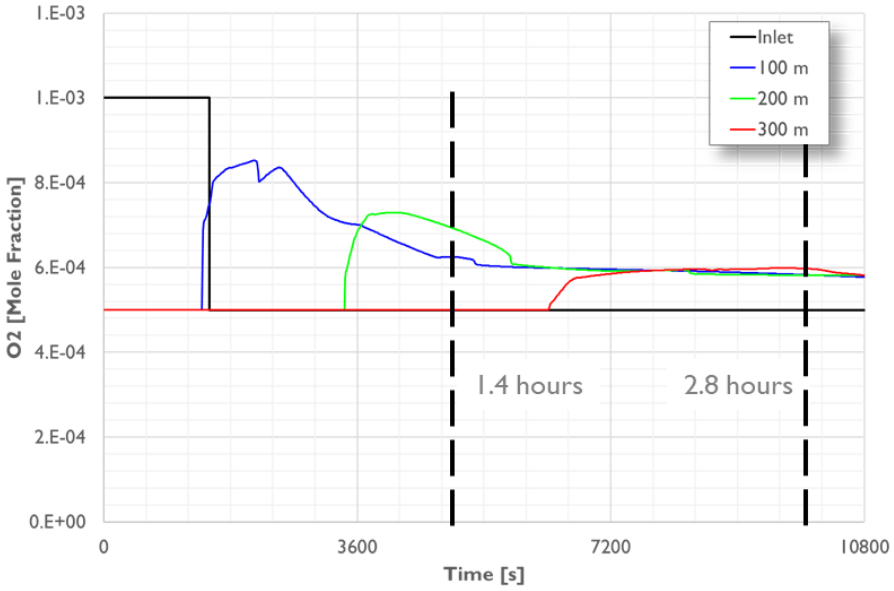


Figure 5 **CFD result for Case B1: 1500 s square wave perturbation of O2 within the spur, for a nominal flow velocity of 0.02 m/s (O2 buoyancy effects included)**

The cause of these differences is clear from Figure 6, which shows a snapshot of the predicted O2 concentration on a vertical slice within the spur at the end of the 1500 s perturbation (see also the prediction for Case B1 in Appendix B). Specifically, whilst a change in O2 concentration from 500 ppm to 1000 ppm may be small (around 0.05%) in a volumetric sense, when coupled with the significant difference in the molecular weight of the two gases (32 kg/kmol for O2, compared with 2 kg/kmol for H2), this represents a density difference of around 0.8% which is significant. As such, the flow for the base case is quickly predicted to become stratified, with dense O2-rich fluid propagating quickly along the spur in the lower part of the section (shown by the orange contours) and a counterflow with O2 at 500 ppm in the upper part of the section.

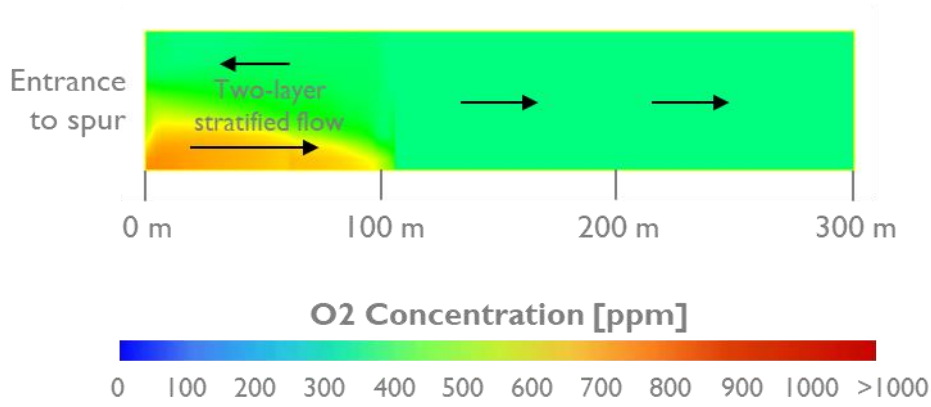


Figure 6 **Case B1: Snapshot of the predicted O2 concentration on a vertical slice within the spur at the end of the 1500 s perturbation (O2 buoyancy effects included)**

The effect of the flow velocity in the spur is considered as part of a first sensitivity set (cases B2, B3, B4 and B5). The prediction for Case B2, with a nominal flow velocity of 0.2 m/s, is shown in Figure 7. The predicted behaviour at this higher gas velocity is similar in some aspects to that observed in Study A:

- The arrival remains sharp and the arrival time is closer to the expected arrival time (although arrival is still a little sooner than expected).
- The maximum concentration at 100 m is predicted to be ~1000 ppm, which is consistent with the perturbation at the entrance (although this is predicted to decay along the spur).
- The long tail is still evident (and is clear in the contour plot for O2 for Case B2 in Appendix B). However, the length of this tail is shorter than that for Case B1, at the lower flow velocity.

This indicates that the higher gas velocity is sufficient to largely overcome the O2 buoyancy effects and associated stratification and counterflow predicted for Case B1.

The predictions for cases B3, B4 and B5 presented in Appendix B show that as the flow velocity in the spur increases further, the behaviour within the spur tends toward the ideal behaviour corresponding to the passive transport of O2, as considered in Study A. The prediction for Case B5 in particular, with a flow velocity of 2.0 m/s, corresponds closely to the behaviour observed in Study A.

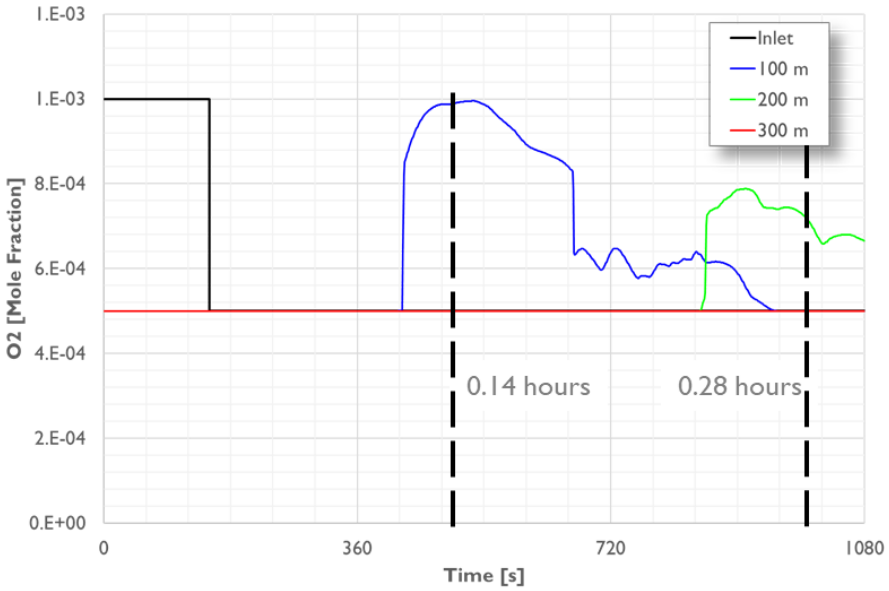


Figure 7 CFD result for Case B2: 150 s square wave perturbation of O2 within the spur, for a nominal flow velocity of 0.2 m/s (O2 buoyancy effects included)

The effect of the slope of the spur is considered as part of a second sensitivity set (cases B6, B7, B8 and B9). The prediction for Case B6, with the spur arranged on a 1% uphill slope, is shown in Figure 8. For this case:

- The arrival time is delayed compared to Case B1, so it is closer to the expected arrival time (although arrival is still arrives sooner than expected).
- The maximum concentration at 100 m is predicted to be ~680 ppm, which is less than that predicted for Case B1 (~850 ppm).
- The tail for this case remains significant (and is clear in the contour plot for O2 for Case B6 in Appendix B). This is to be expected for stratified flow at low flow velocity, as the propagation of O2 up the slope is working against the effect of gravity.

This indicates that the transport of O2 within the spur for the low gas velocity cases is dependent upon the terrain and associated slope of the spur. This is further supported by the predictions for cases B7, B8 and B9 in Appendix B.

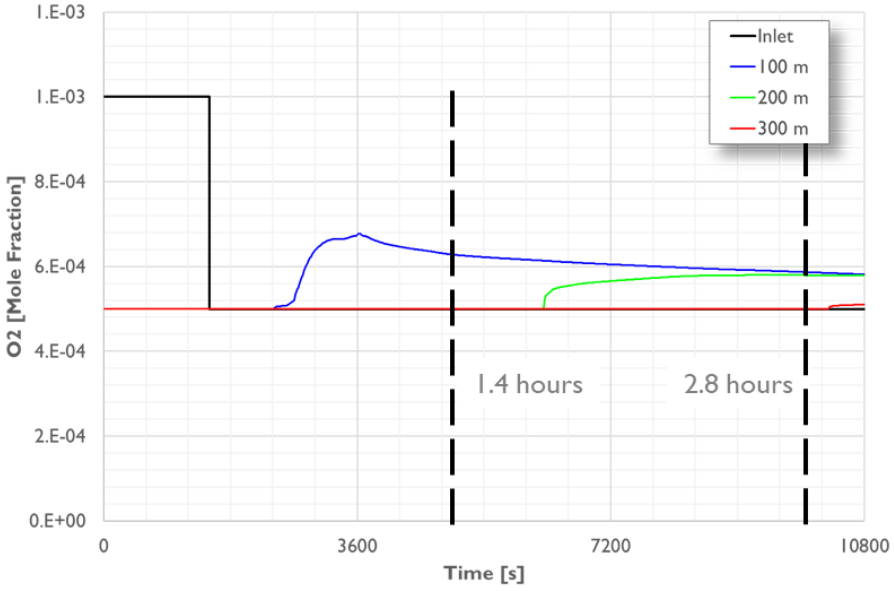


Figure 8 **CFD result for Case B6: 1500 s square wave perturbation of O2 within the spur, for a nominal flow velocity of 0.02 m/s and a 1% uphill slope (O2 buoyancy effects included)**

6 STUDY C – MIXING AT THE JUNCTION AT THE ENTRANCE TO THE SPUR

For this study, nine cases are considered as summarised in Table 3. The CFD predictions are presented in Appendix C. The velocity within the main line is assumed to be 2.0 m/s for all cases, and the perturbation is assumed to be long (essentially a step increase in the O2 concentration from 500 ppm to 1000 ppm is considered within the main line).

Table 3 – Summary of cases for Study C

Case	Nominal flow velocity within spur	Slope
C1	0.02 m/s	Horizontal
C2	0.2 m/s	Horizontal
C3	Zero (dead leg)	Horizontal
C4	0.02 m/s	Uphill, 10%
C5	0.2 m/s	Uphill, 10%
C6	Zero (dead leg)	Uphill, 10%
C7	0.02 m/s	Downhill, 10%
C8	0.2 m/s	Downhill, 10%
C9	Zero (dead leg)	Downhill, 10%

The prediction for Case C1 in Figure 9 shows stratified flow, with O2 migrating along the lower part of the spur. It also shows that the concentration of O2 entering the spur at may be lower than the concentration of O2 within the main line due to mixing at the junction. This is due to mixing within a recirculation zone that becomes established within the entrance to the spur, as shown in Figure 10. The recirculation zone is driven by the flow in the main line and causes the incoming fluid from the main line (at 1000 ppm O2) to mix with the fluid already within the spur, thus lowering the concentration of O2 effectively entering the spur. This mixing effect is most apparent if the nominal flow velocity in the spur is low, and if the slope of the spur off the main line is horizontal or downward:

- If the slope of the spur off the main line is upward, the concentration of O2 entering the spur is predicted to approach that within the main line and the migration of O2 along the spur is relatively slower – see Case C4 in Appendix C.

- At higher flow velocities within the spur, the incoming flow is sufficient to dominate such that the concentration of O2 entering the spur is equal to that within the main line, 1000 ppm – see cases C2, C5 and C8 in Appendix C.

- In the case of a dead leg (cases C3, C6 and C9), the concentration of O2 entering the spur is predicted to be lower than for the corresponding low velocity cases (nominal flow velocity of 0.02 m/s, cases C1, C4 and C7) and the rate of propagation of O2 along the spur is also reduced – see Appendix C.

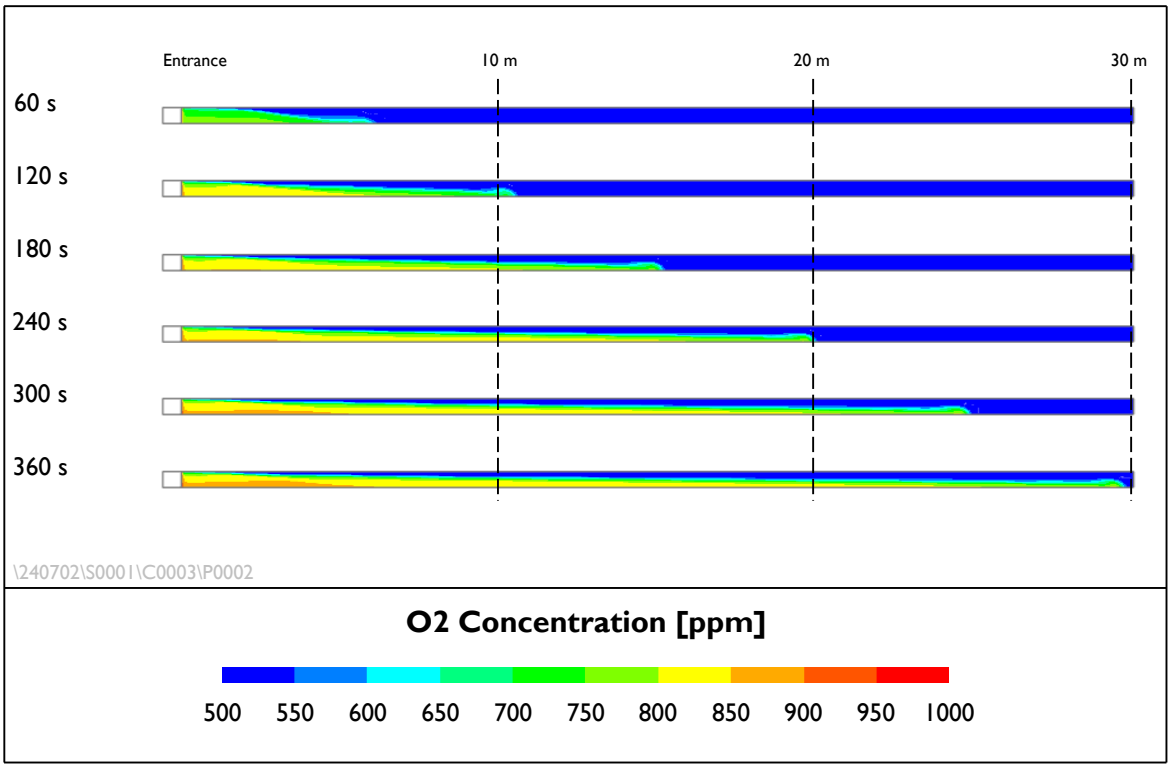


Figure 9 **CFD result for Case C1: 1500 s square wave perturbation of O2 within the spur, for a nominal flow velocity of 0.02 m/s and a 1% uphill slope (O2 buoyancy effects included)**

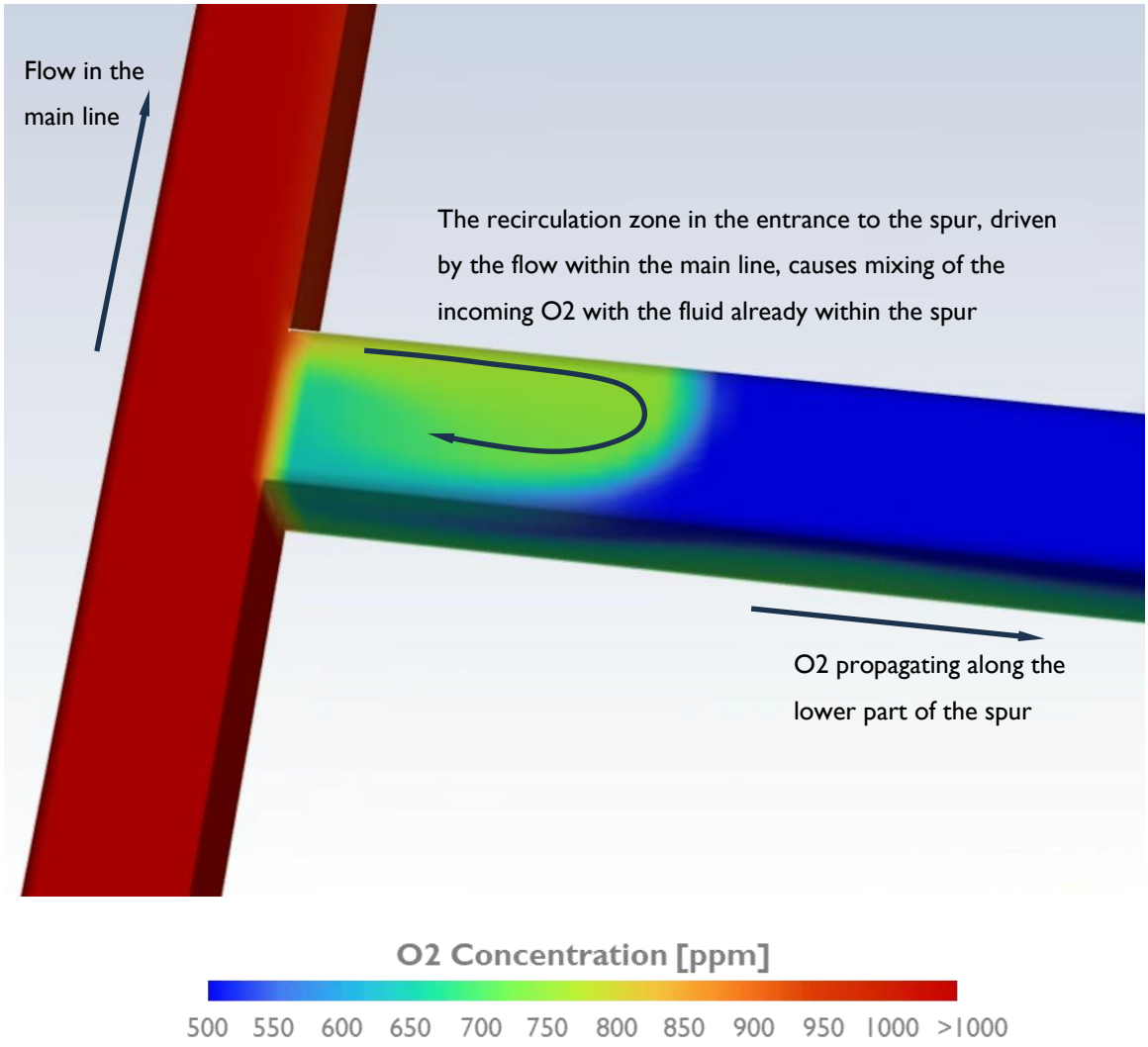


Figure 10 Recirculation zone in the entrance to the spur

7 STUDY D – MIXING AT A BEND WITHIN THE SPUR

For this study, the effect of bend radius is considered for six cases, as summarised in Table 4. The bend is a 90° bend located 15 m downstream of the entrance to the spur. The nominal flow velocity within the spur is 0.02 m/s for all cases, and the spur is horizontal.

Table 4 – Summary of cases for Study D

Case	Radius of bend
D1	Zero (square bend)
D2	1 m
D3	2 m
D4	4 m
D5	8 m
D6	14 m

The CFD predictions in Figure 11 (and Appendix D) show the O2 concentration before and after the bend. The first graph shows that the profiles entering the bends are identical for each simulated case, which is to be expected. From the second graph, there are two inferences:

- The arrival time is shorter for the larger radius bends. In fact, this is to be expected and is a consequence of monitoring the O2 concentration in a fixed location in the CFD model – the distance travelled is shorter for the larger radius bends (with a larger radius, the flow effectively cuts the corner.)

- The concentration for the larger radius bends is higher than for the square bend. This indicates that there is most turbulent mixing at the square bend and that this falls as the radius of the bend is increased. The effect is modest, with the fall in O2 concentration from around 820 ppm for the largest radius bend to 790 ppm for the 1 m bend, and a further fall to around 760 ppm for the square bend.

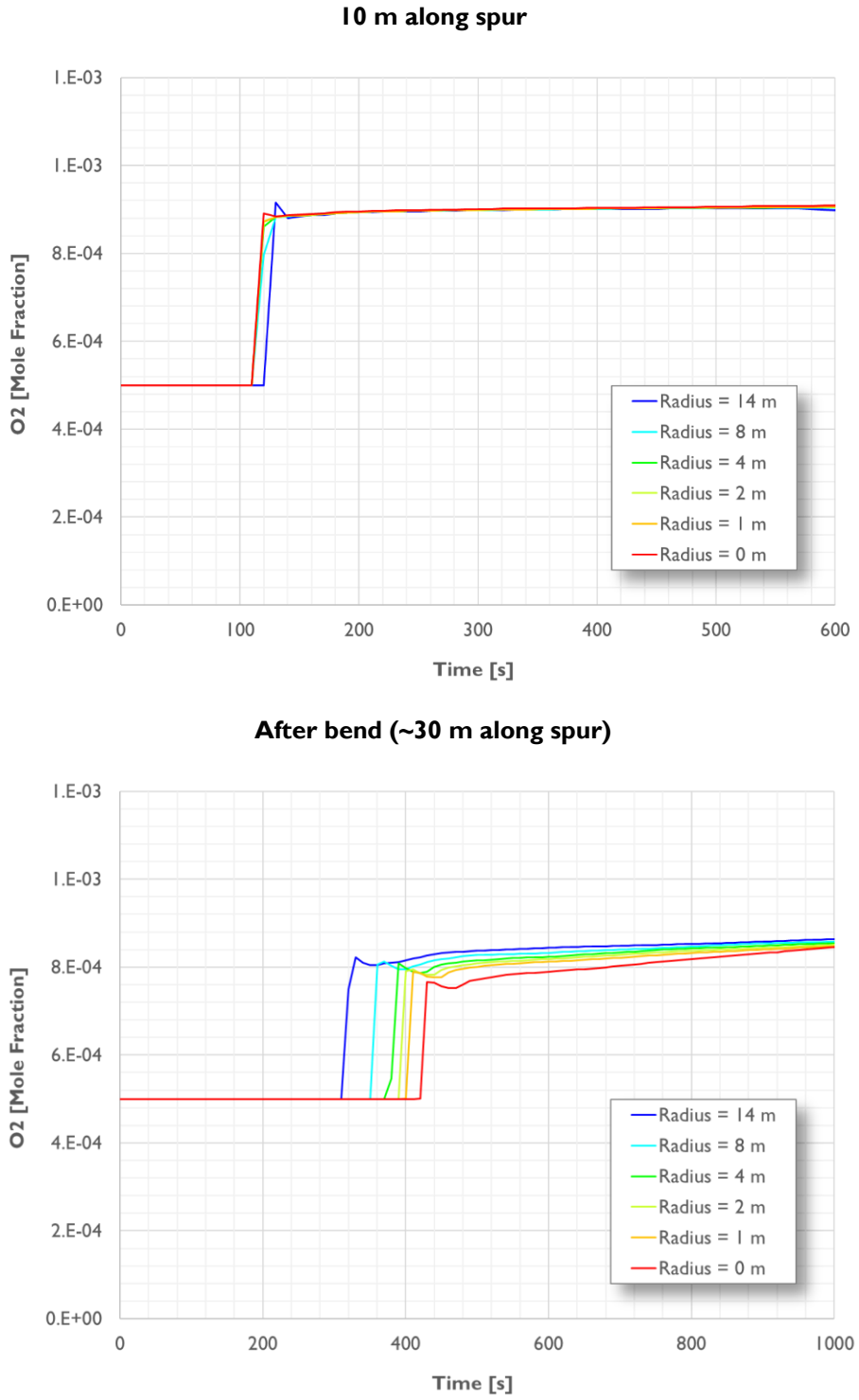


Figure 11 Concentration of O2 upstream and downstream of bend

8 INFERENCES

8.1 Study A – Passive transport of O2 (like-for-like with OLGA)

From the discussion in Section 4, the following inferences are drawn:

- When stratification effects are ignored, the predicted arrival time from the CFD model at the downstream locations considered is in close agreement with the expected arrival time.
- This is not the case for the OLGA model. This discrepancy is likely due to numerical diffusion within the OLGA model caused by the long discretisation of the spur (segments are 1 km each) [Ref. 4].

  (It is understood that the reason for the long segments in the OLGA model is related to the practicality of programming the O2 removal term due to corrosion within OLGA.)

8.2 Study B – Full CFD (including stratification)

From the discussion in Section 5, the following inferences are drawn:

- An O2 concentration variation of 500 ppm is not insignificant – whilst this may only be 0.05% on a volumetric basis, it is around 0.8% on a density basis.
- For the base case (Case B1: nominal flow velocity within the spur of 0.02 m/s), an 0.8% density difference is sufficient to quickly establish a two-layer stratified flow, with dense O2-rich fluid propagating quickly along the spur in the lower part of the section and a counterflow with O2 at 500 ppm in the upper part of the section.
- The first set of sensitivity cases (cases B2, B3, B4 and B5) show that as the flow velocity in the spur increases, the behaviour within the spur tends toward the ideal behaviour corresponding to the passive transport of O2, as considered in Study A. The prediction for Case B5 in particular, with a flow velocity of 2.0 m/s, corresponds closely to the behaviour observed in Study A.
- The second set of sensitivity cases (cases B6, B7, B8 and B9) show that the transport of O2 within the spur for the low gas velocity cases is dependent upon the terrain and associated slope of the spur.

8.3 Study C – Mixing at the junction at the entrance to the spur

From the discussion in Section 6, the following inferences are drawn:

- The concentration of O2 entering the spur at may be lower than the concentration of O2 within the main line due to mixing at the junction. This is due to mixing within a recirculation zone that becomes established within the entrance to the spur.
- This mixing effect is most apparent if the nominal flow velocity in the spur is low, and if the slope of the spur off the main line is horizontal or downward.
  - If the slope of the spur off the main line is upward, the concentration of O2 entering the spur is predicted to approach that within the main line and the migration of O2 along the spur is relatively slower.
  - At higher flow velocities within the spur, the incoming flow is sufficient to dominate such that the concentration of O2 entering the spur is equal to that within the main line.
  - In the case of a dead leg, the concentration of O2 entering the spur is predicted to be lower than for the corresponding low velocity cases (nominal flow velocity of 0.02 m/s) and the rate of propagation of O2 along the spur is also reduced.

8.4 Study D – Mixing at bends within the spur

From the discussion in Section 7, the following inference is drawn:

- The concentration for the larger radius bends is higher than for the square bend, which indicates that there is most turbulent mixing at the square bend and that this falls as the radius of the bend is increased. The effect is modest, with the fall in O2 concentration from around 820 ppm for the largest radius bend to 790 ppm for the 1 m bend, and a further fall to around 760 ppm for the square bend.

8.5 General comment

It is important to note that the two-layer stratification predicted by the full CFD model does not constitute reseparation of O2 from a fully mixed mixture. When fluid within the spur is fully mixed, there is no evidence to suggest that O2 can separate out of the mixture for the time and length scales of interest to the gas network. The two-layer stratification presented within this document is strictly related to an increase in the concentration of O2 at the entrance of the spur – this incoming O2 is not mixed with the fluid already within the spur and the stratification is not related to separating of the mixture.

9 RECOMMENDATIONS

9.1 Study A – Passive transport of O2 (like-for-like with OLGA)

Whilst it is understood that the reason for the long segments in the OLGA model is related to the practicality of programming the O2 removal term due to corrosion within OLGA:

- It is recommended that a mesh sensitivity study be undertaken for the OLGA model, with the corrosion term removed, to allow the sensitivity of the numerical diffusion with discretisation length within OLGA to be better understood for the zero-corrosion case.

9.2 Study B – Full CFD (including stratification)

For the low gas velocity cases of interest within this study, stratification with counterflow may become established, and the transport of O2 may then become dependent upon the local terrain and associated slope of the pipeline of interest. This behaviour is not realistically predicted with OLGA.

If realistic prediction of O2 transport for low gas velocities is required, two options are recommended:

1. Consider using CFD for specific scenarios of interest. This option is appropriate for geographically local studies but may not be appropriate for modelling behaviour on a larger network scale.

2. Consider developing a network flow model, similar to OLGA in many respects but including vertical discretisation such that stratification and counterflow may be considered (either through localised coupling to CFD, or by utilising correlations developed in advance by CFD/machine learning). Development of such a tool may not be trivial and would require investment, but it may provide a capability for realistic prediction of O2 transport on a larger network scale.

9.3 Study C – Mixing at the junction at the entrance to the spur

For the low gas velocity cases of interest within this study, mixing at the junction at the entrance to the spur can have a significant impact upon the concentration of O2 entering the spur. This behaviour is not realistically predicted with OLGA, and is dependent upon both the nominal flow velocity within the spur and the slope of the spur off the main line.

If realistic prediction of O2 transport for low gas velocities is required, consider using CFD for specific scenarios of interest.

9.4 Study D – Mixing at bends within the spur

For the cases considered, the mixing effect due to bends within the spur is modest, particularly if the bend radius exceeds 2-4 m. The mixing effect due to bends is of secondary importance compared to the effects described in Study B and C relating to stratification/terrain effects at low flow and mixing at the junction at the entrance to the spur at low flow velocities.

10 REFERENCES

1 Atrens A, Gray E, Venezuela J et al., *Feasibility of the use of gas phase inhibition of hydrogen embrittlement in gas transmission pipelines carrying hydrogen: a review*. JOM 75, 232–238 (2023). https://doi.org/10.1007/s11837-022-05559-8

2 Zhou C, Zhou H and Zhang L, *The impact of impurity gases on the hydrogen embrittlement behavior of pipeline steel in high-pressure H2 environments*, Materials 2024, 17, 2157. https://www.mdpi.com/1996-1944/17/9/2157

3 *Inhibition of Hydrogen Embrittlement Effects in Pipeline Steels*, National Gas Transmission Project NIA_NGGT0183, June 2024. https://smarter.energynetworks.org/projects/nia_nggt0183/

4 *O2 inhibition of H2 lines – OLGA simulations*, Rosen report 19878 Rev 0, 6 February 2025.

5 ANSYS FLUENT. https://www.ansys.com/en-gb/products/fluids/ansys-fluent

APPENDICES

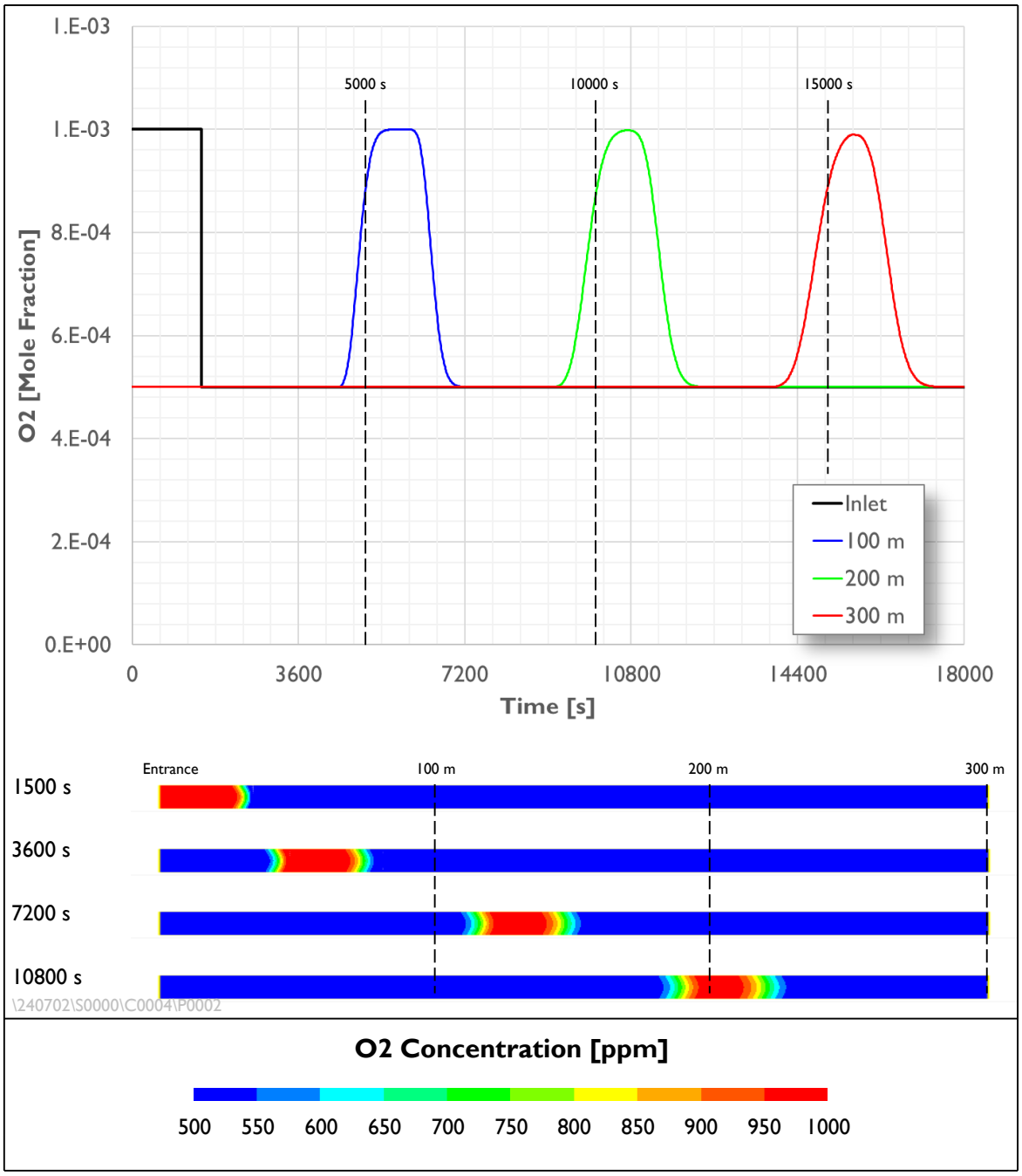
APPENDIX A CFD PREDICTIONS FOR STUDY A, PASSIVE TRANSPORT OF O2 (LIKE-FOR-LIKE WITH OLGA)

APPENDIX B CFD PREDICTIONS FOR STUDY B, FULL CFD (INCLUDING STRATIFICATION)

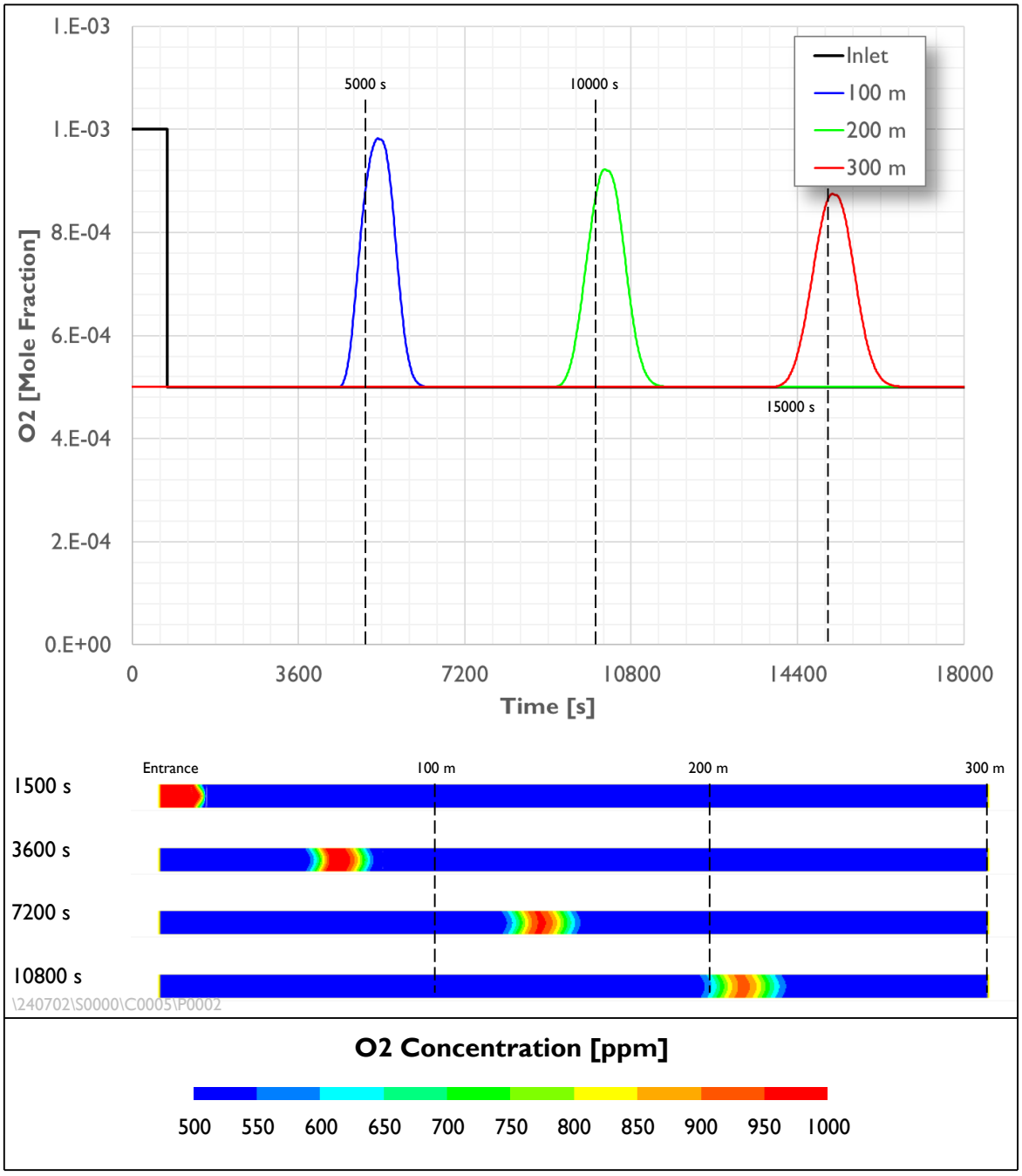
APPENDIX C CFD PREDICTIONS FOR STUDY C, MIXING AT THE JUNCTION AT THE ENTRANCE TO THE SPUR

APPENDIX D CFD PREDICTIONS FOR STUDY D, MIXING AT BENDS

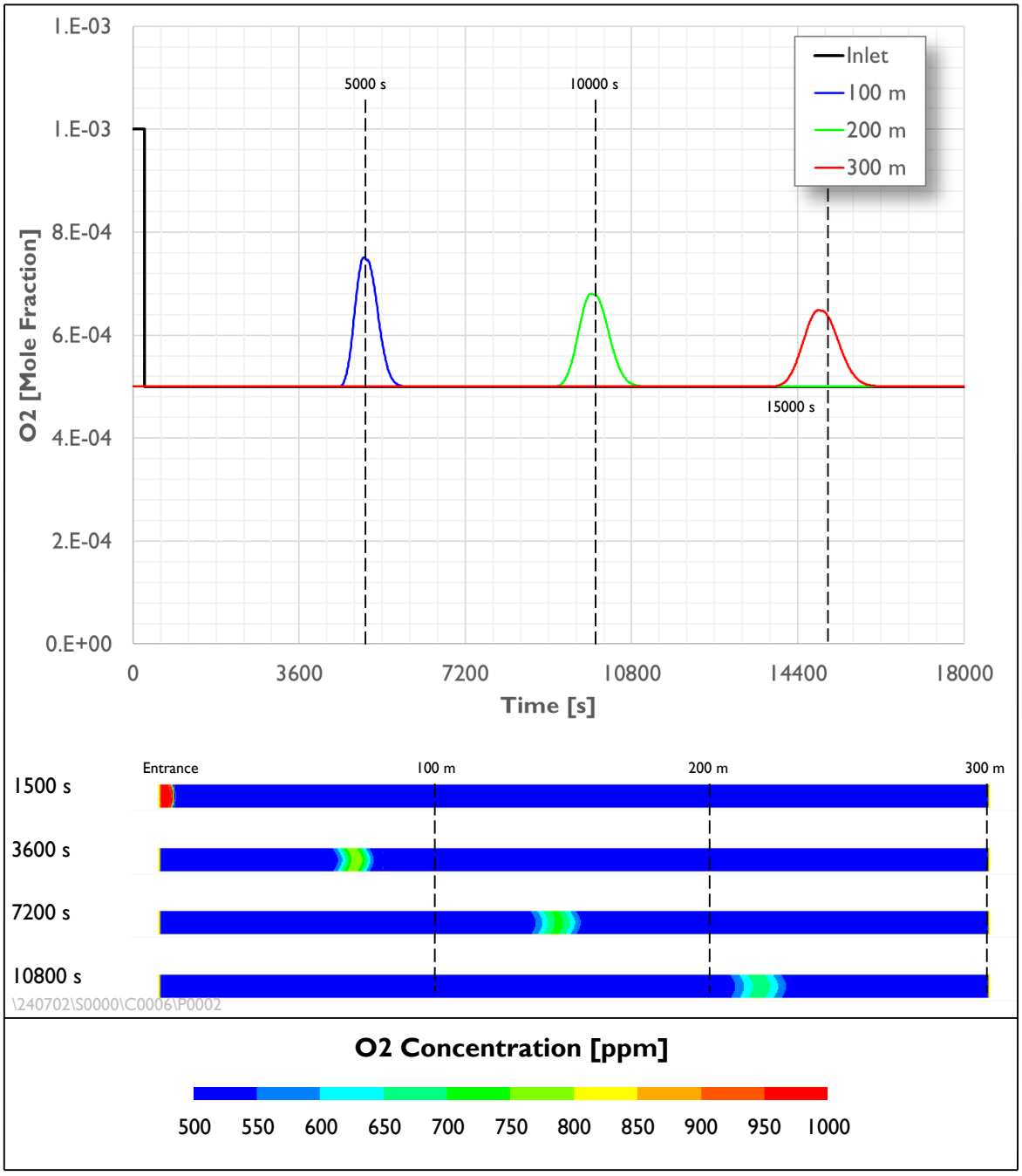
APPENDIX A CFD PREDICTIONS FOR STUDY A, PASSIVE TRANSPORT OF O2 (LIKE-FOR-LIKE WITH OLGA)



Case:	A1
Flow velocity:	0.02 m/s
Pulse duration:	1500 s

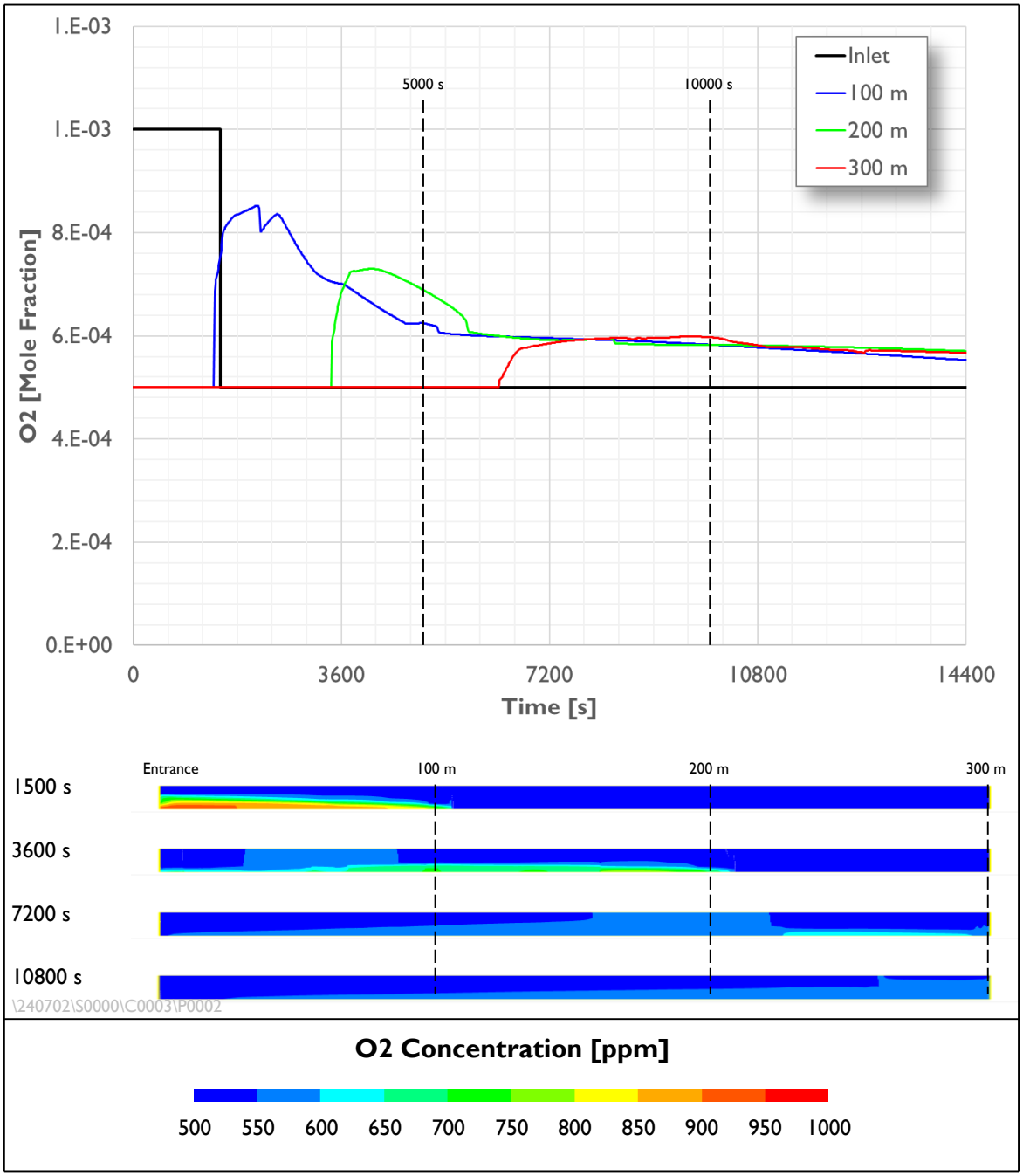


Case:	A2
Flow velocity:	0.02 m/s
Pulse duration:	750 s

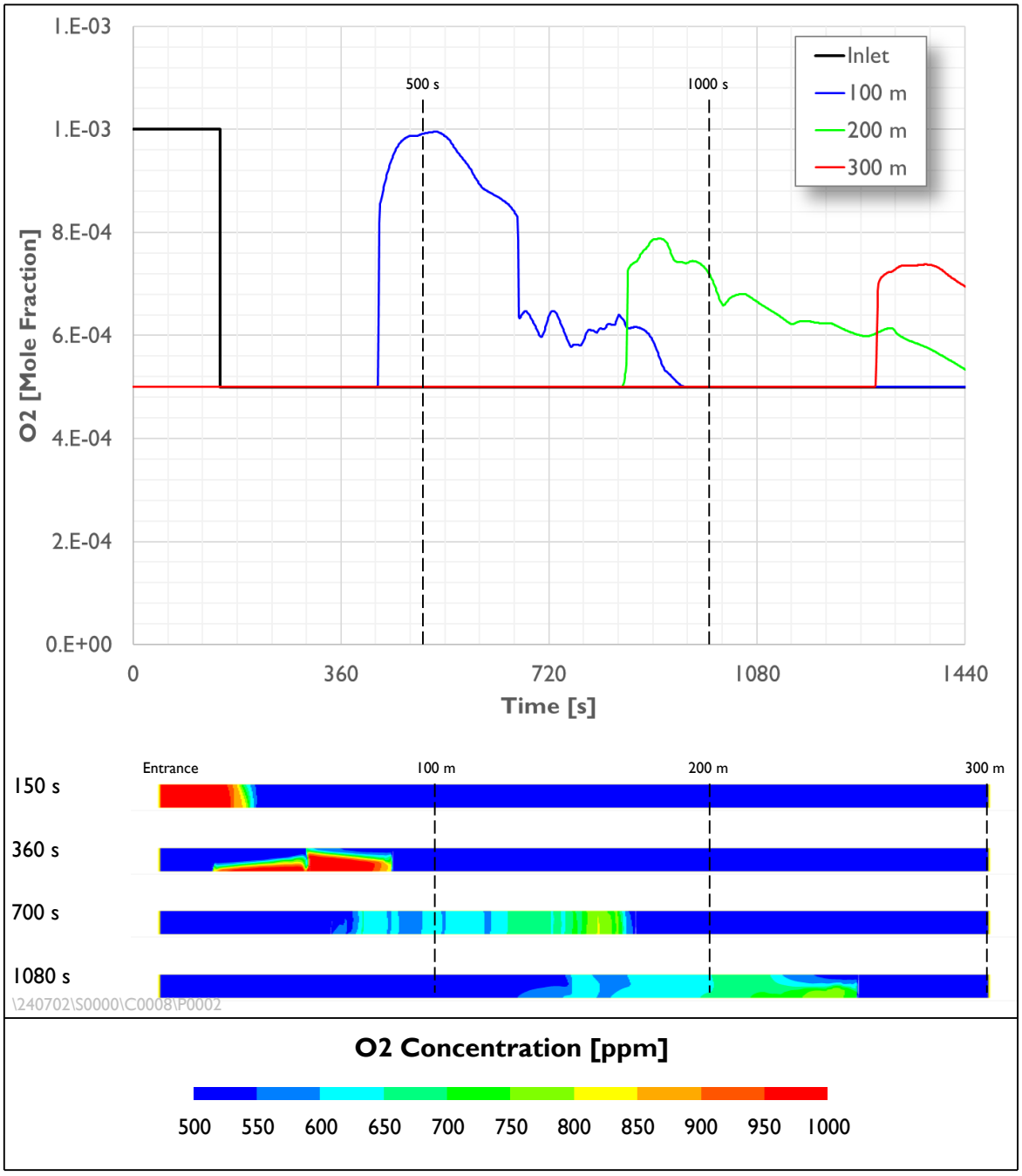


Case:	A3
Flow velocity:	0.02 m/s
Pulse duration:	250 s

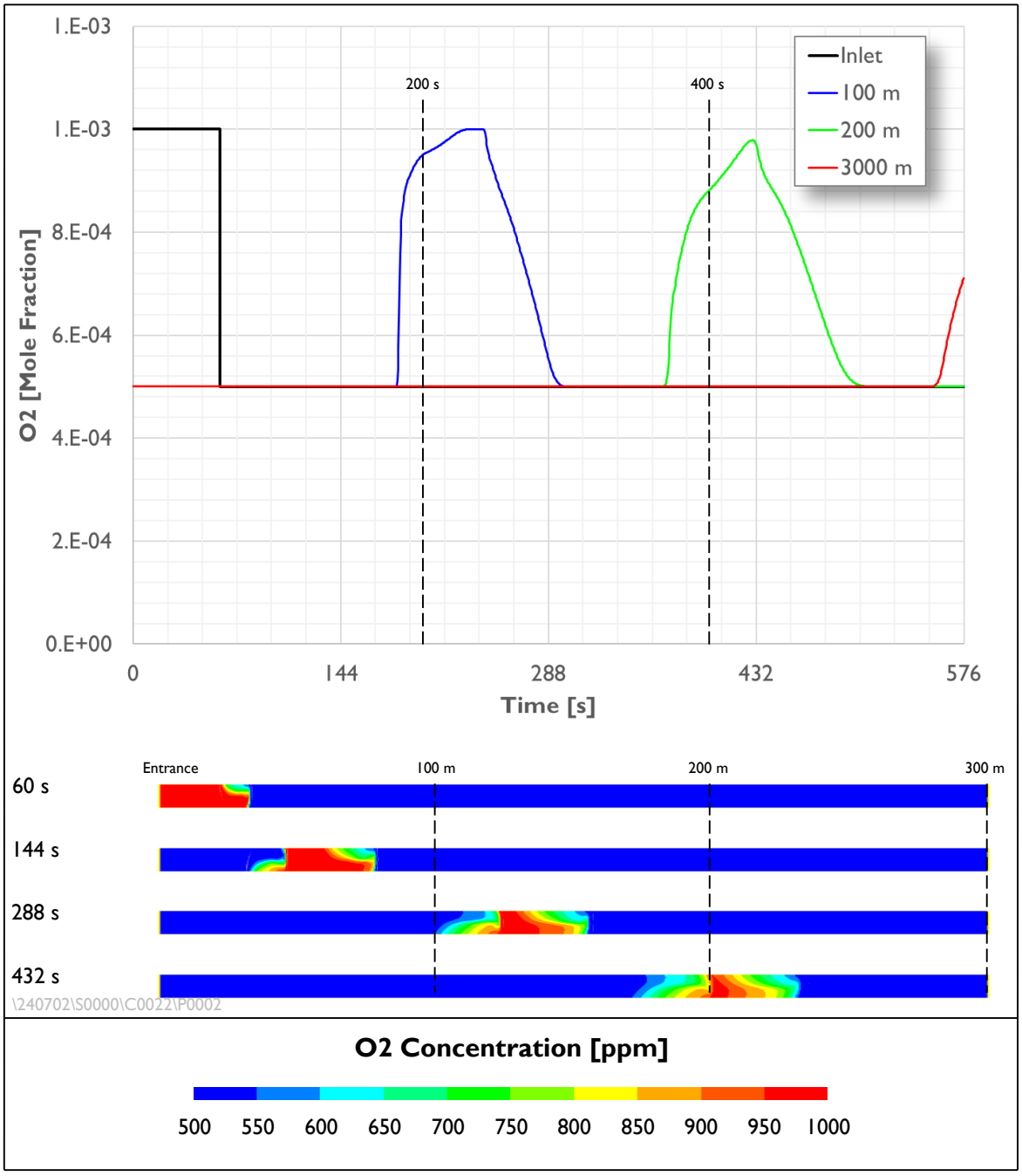
APPENDIX B CFD PREDICTIONS FOR STUDY B, FULL CFD (INCLUDING STRATIFICATION)



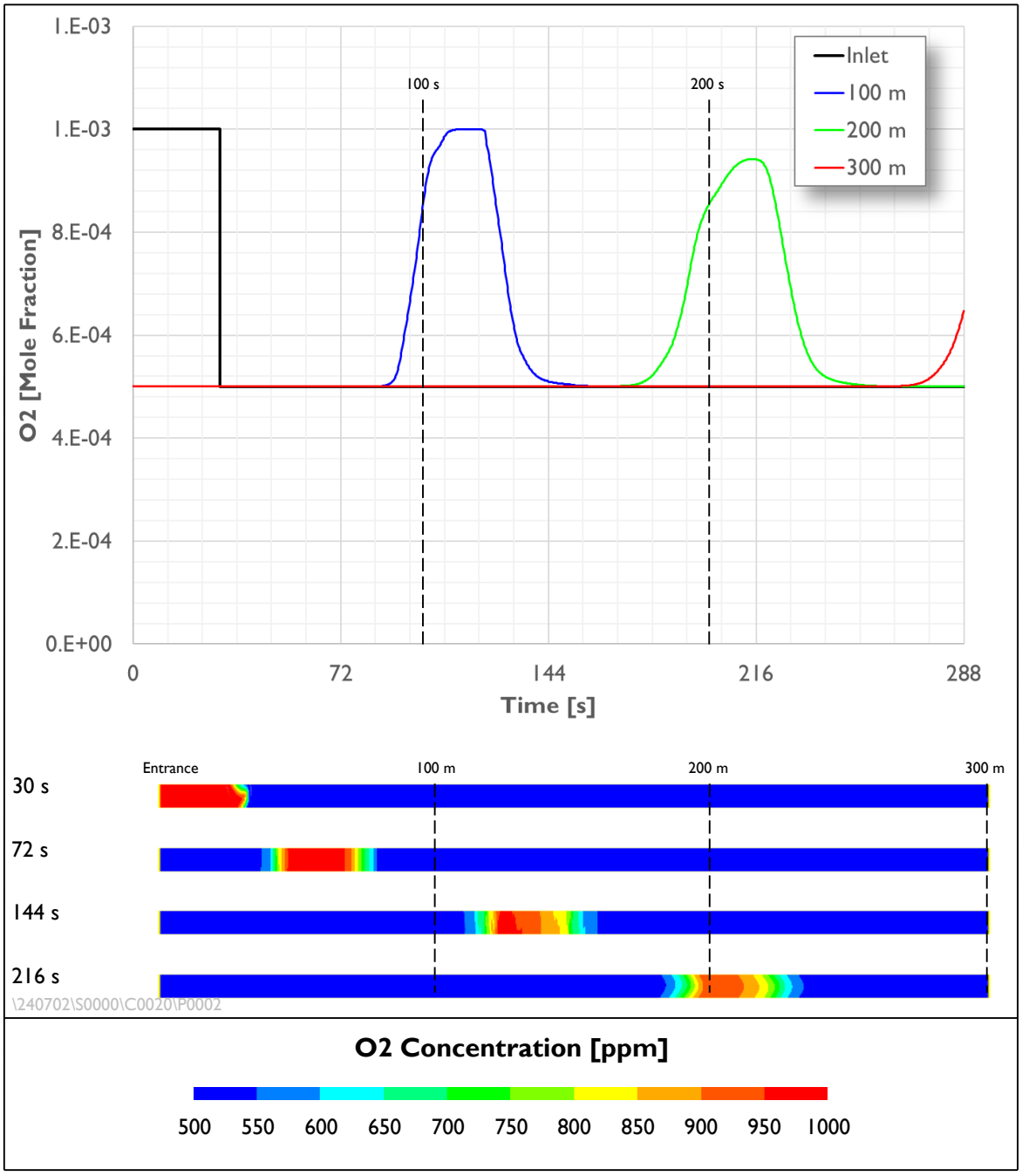
Case:	B1
Flow velocity:	0.02 m/s
Pulse duration:	1500 s
Slope:	Horizontal



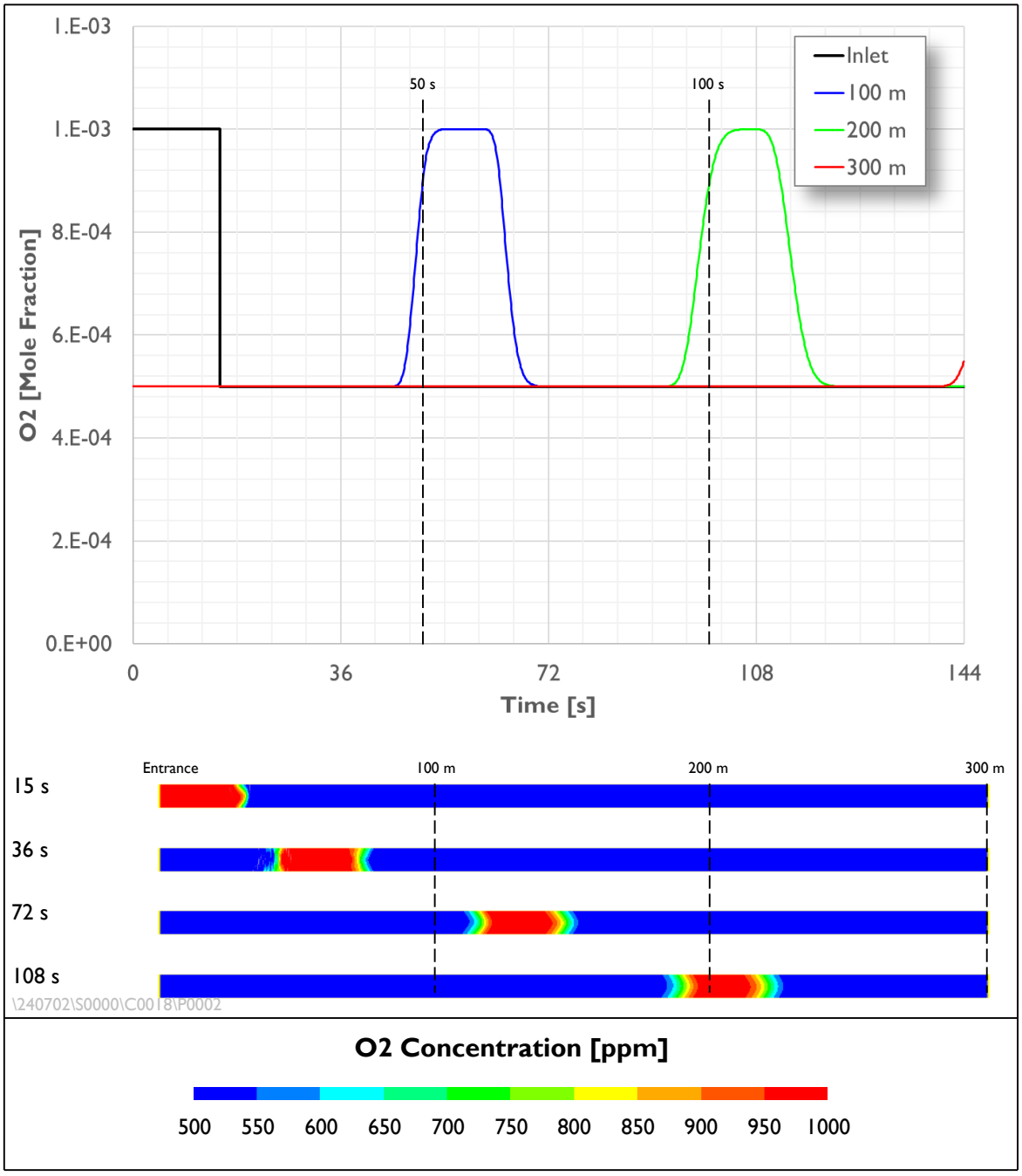
Case:	B2
Flow velocity:	0.2 m/s
Pulse duration:	150 s
Slope:	Horizontal



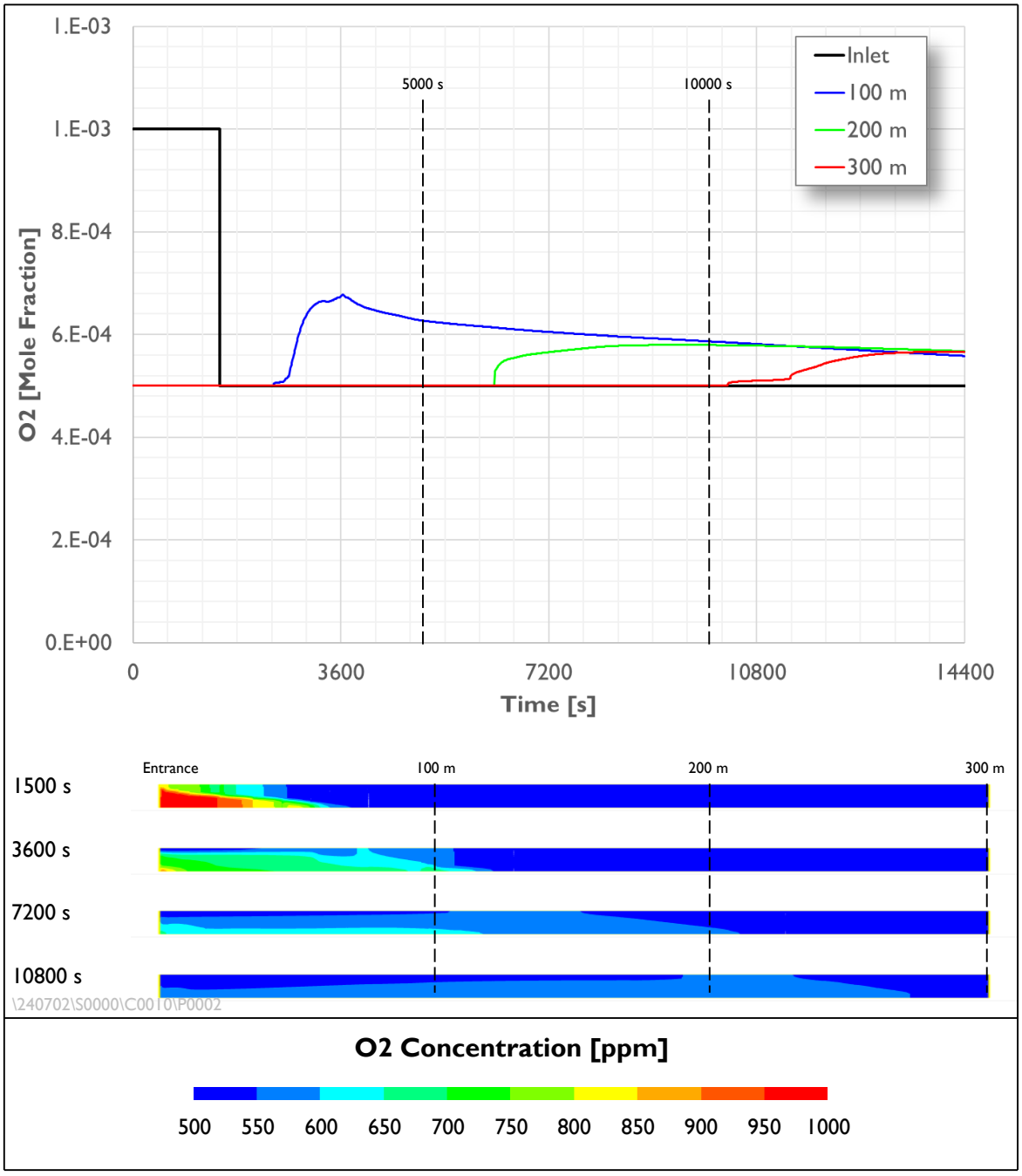
Case:	B3
Flow velocity:	0.5 m/s
Pulse duration:	60 s
Slope:	Horizontal



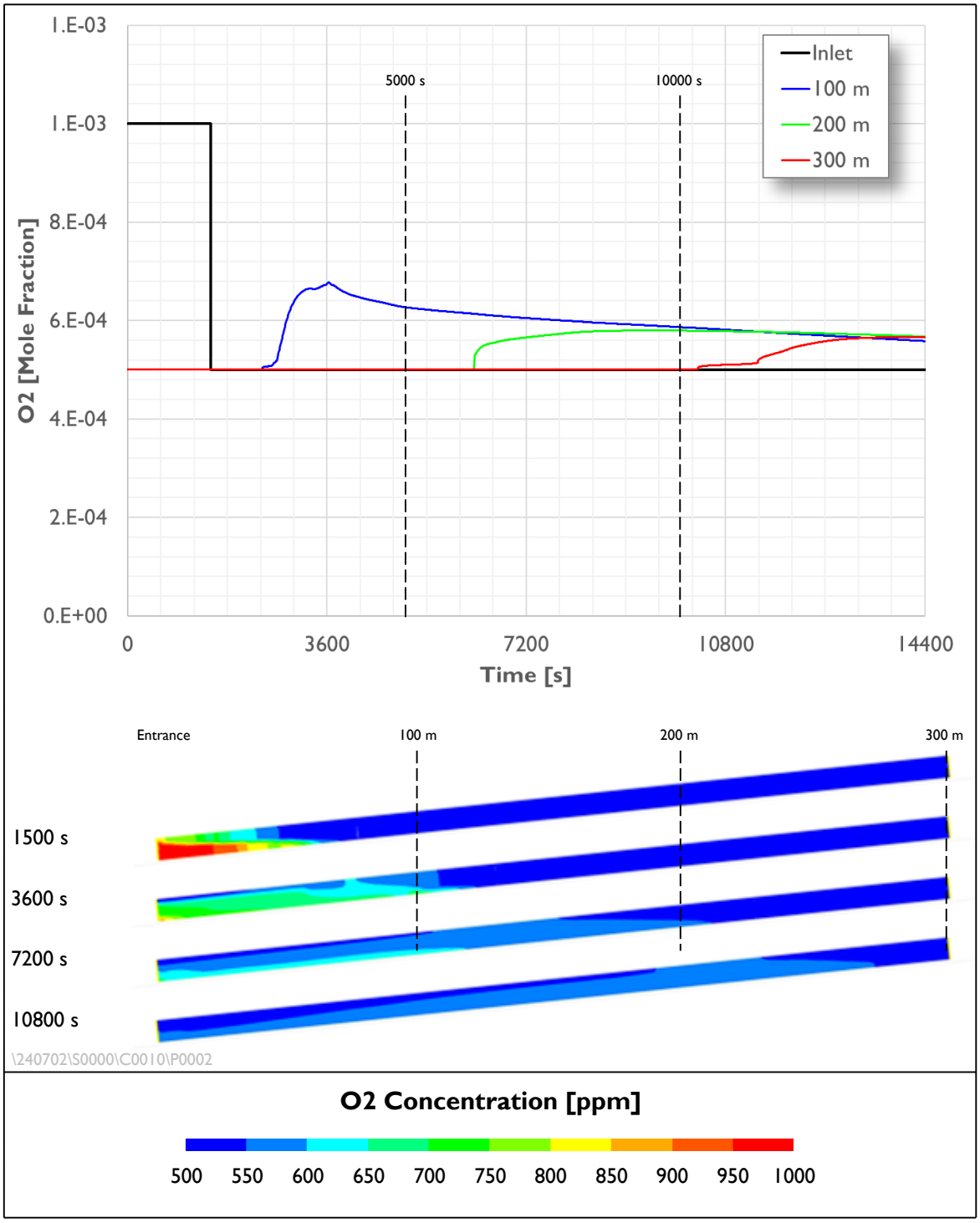
Case:	B4
Flow velocity:	1.0 m/s
Pulse duration:	30 s
Slope:	Horizontal



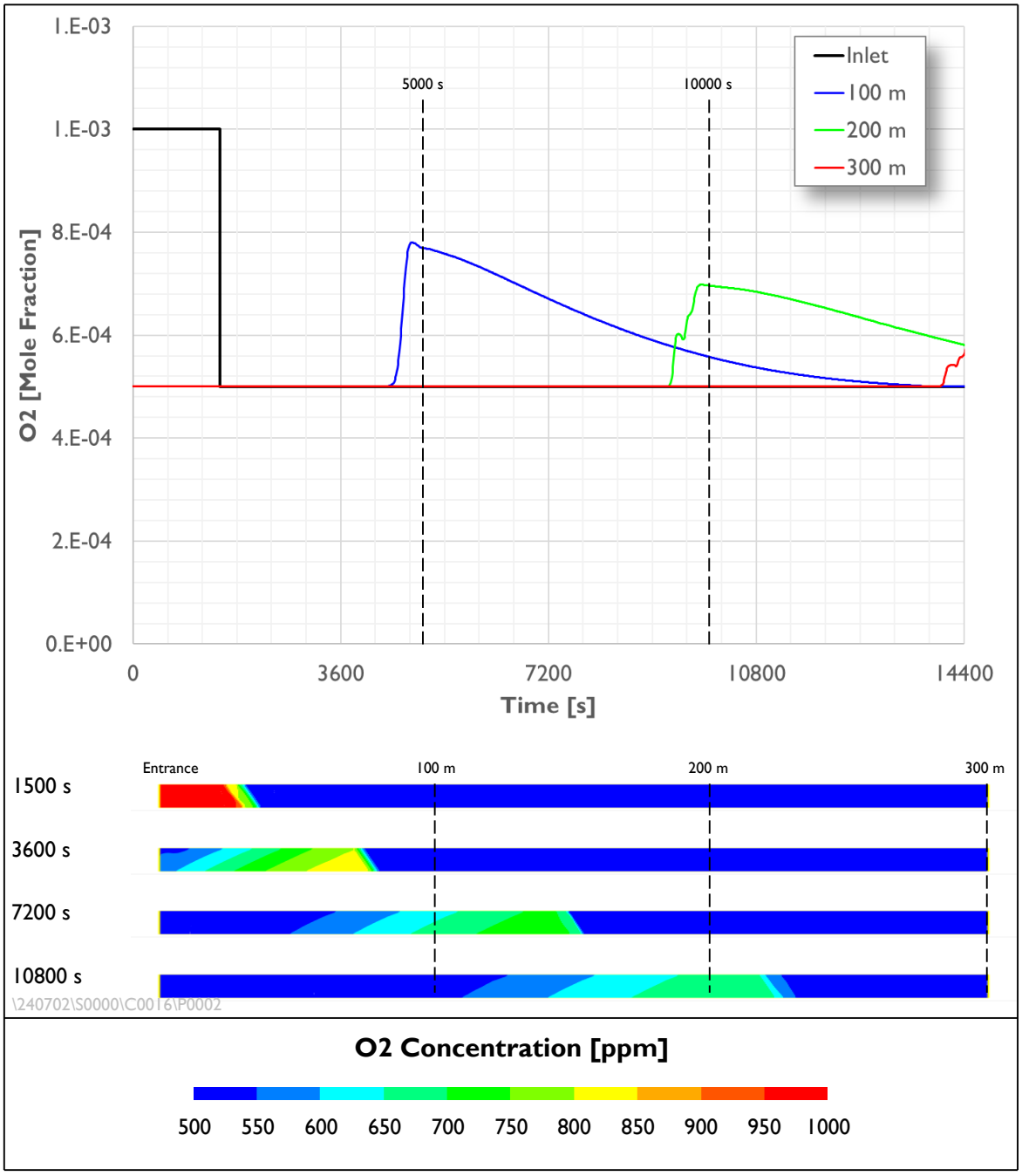
Case:	B5
Flow velocity:	2.0 m/s
Pulse duration:	15 s
Slope:	Horizontal



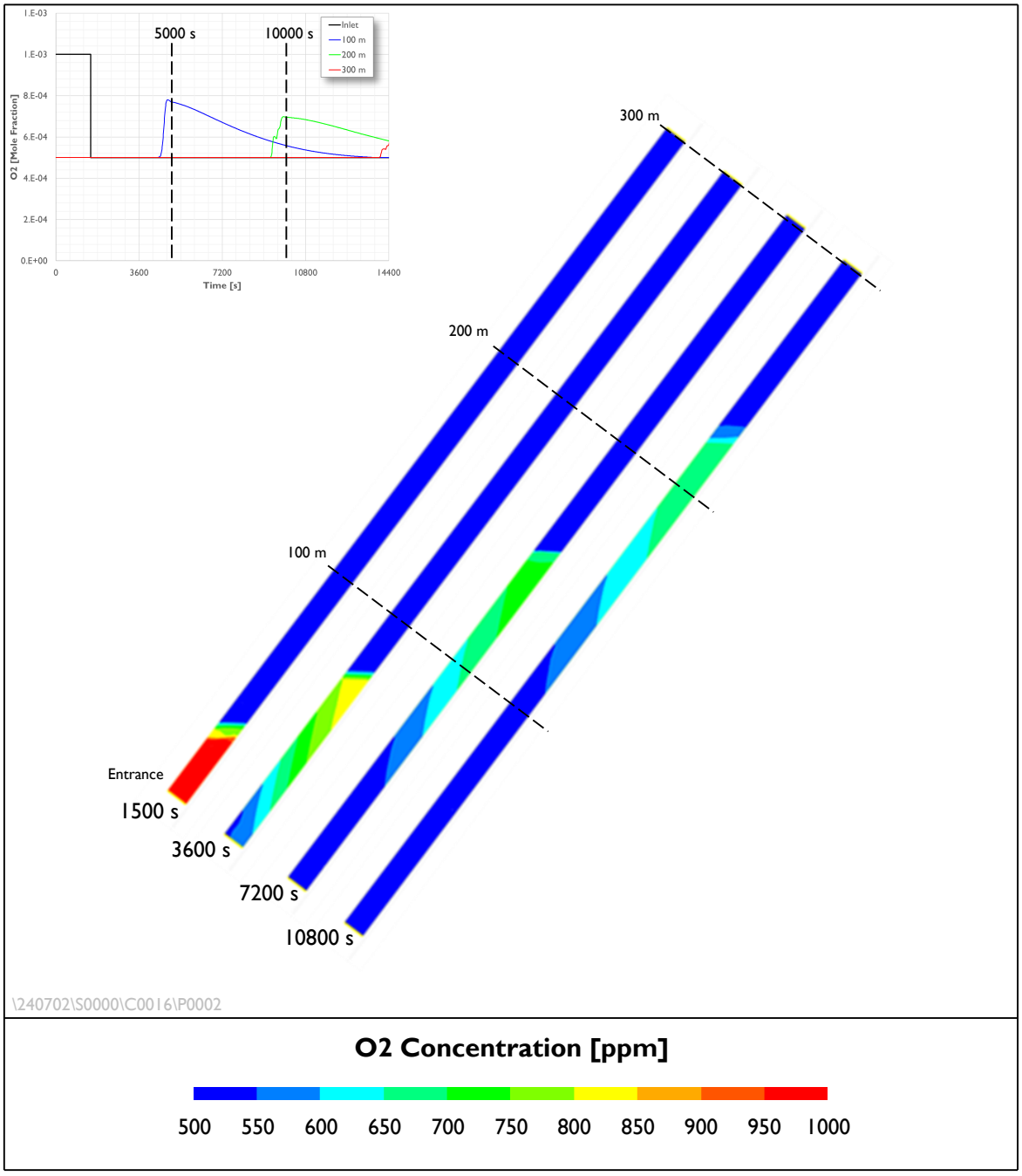
Case:	B6 (shown horizontally)
Flow velocity:	0.02 m/s
Pulse duration:	1500 s
Slope:	Uphill, 1%



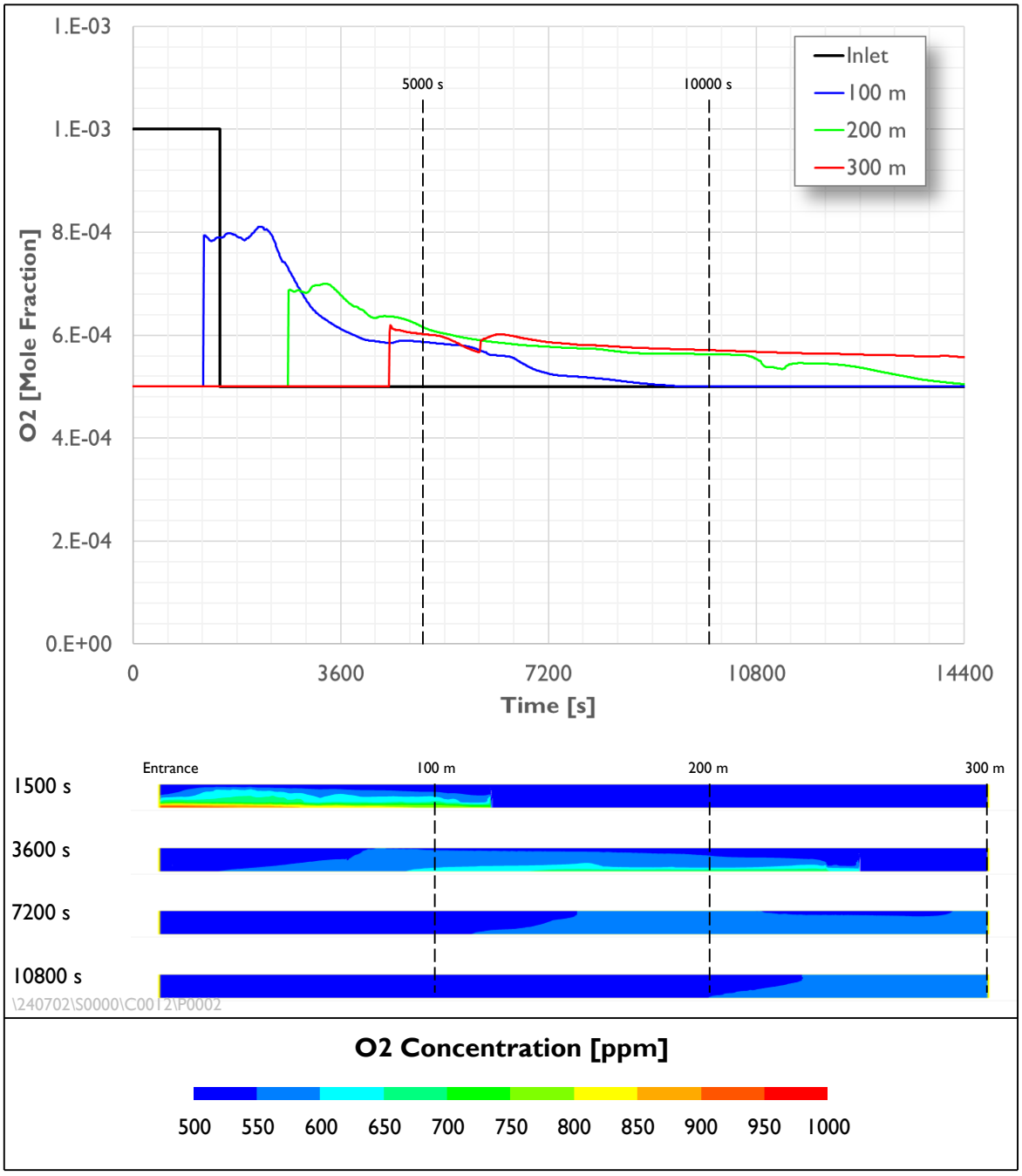
Case:	B6 (shown inclined)
Flow velocity:	0.02 m/s
Pulse duration:	1500 s
Slope:	Uphill, 1%



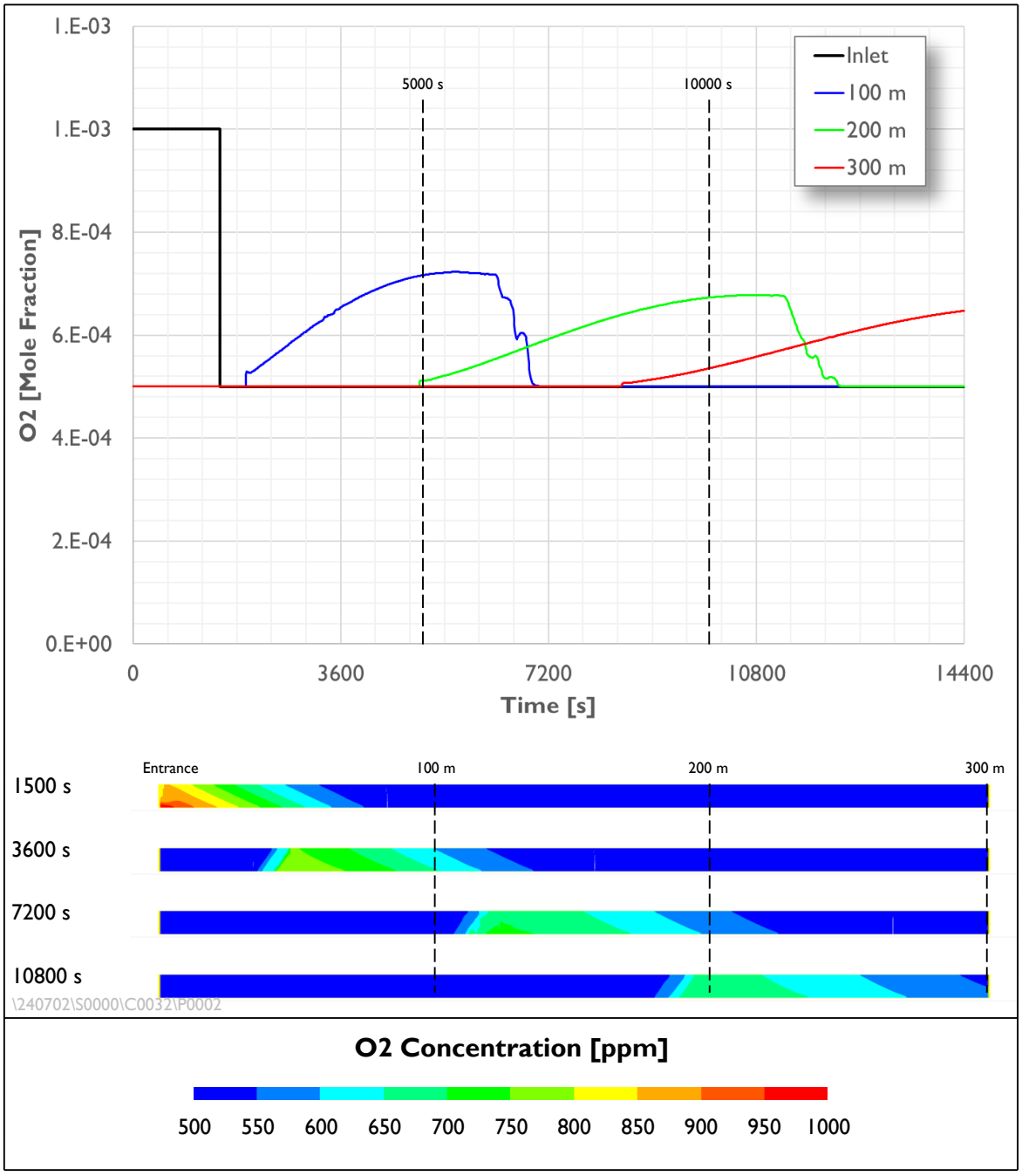
Case:	B7 (shown horizontally)
Flow velocity:	0.02 m/s
Pulse duration:	1500 s
Slope:	Uphill, 10%



Case:	B7 (shown inclined)
Flow velocity:	0.02 m/s
Pulse duration:	1500 s
Slope:	Uphill, 10%

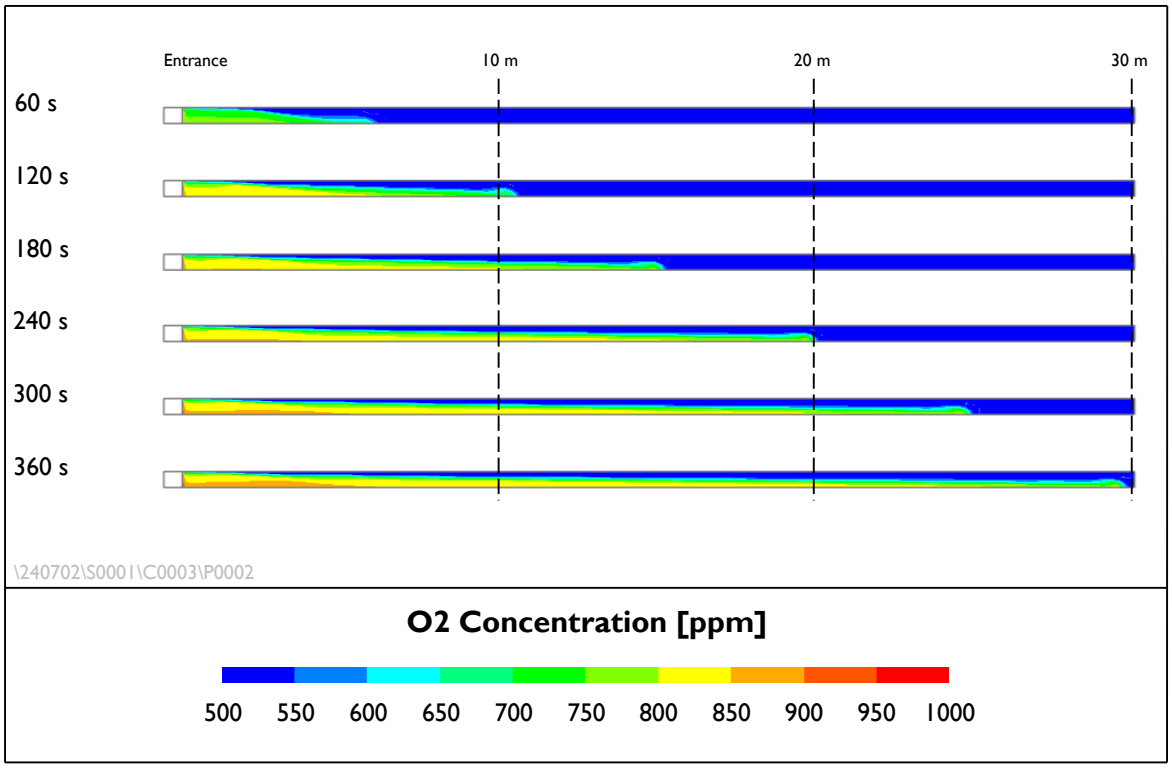


Case:	B8 (shown horizontally)
Flow velocity:	0.02 m/s
Pulse duration:	1500 s
Slope:	Downhill, 1%

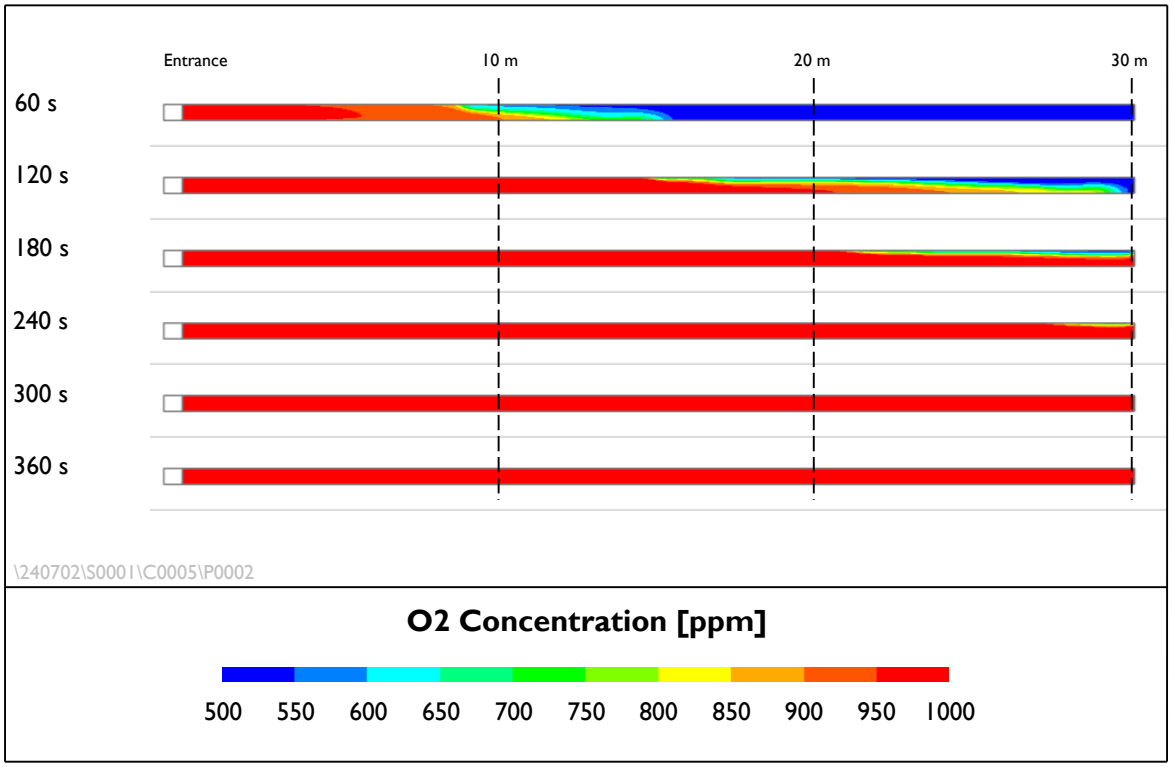


Case:	B9 (shown horizontally)
Flow velocity:	0.02 m/s
Pulse duration:	1500 s
Slope:	Downhill, 10%

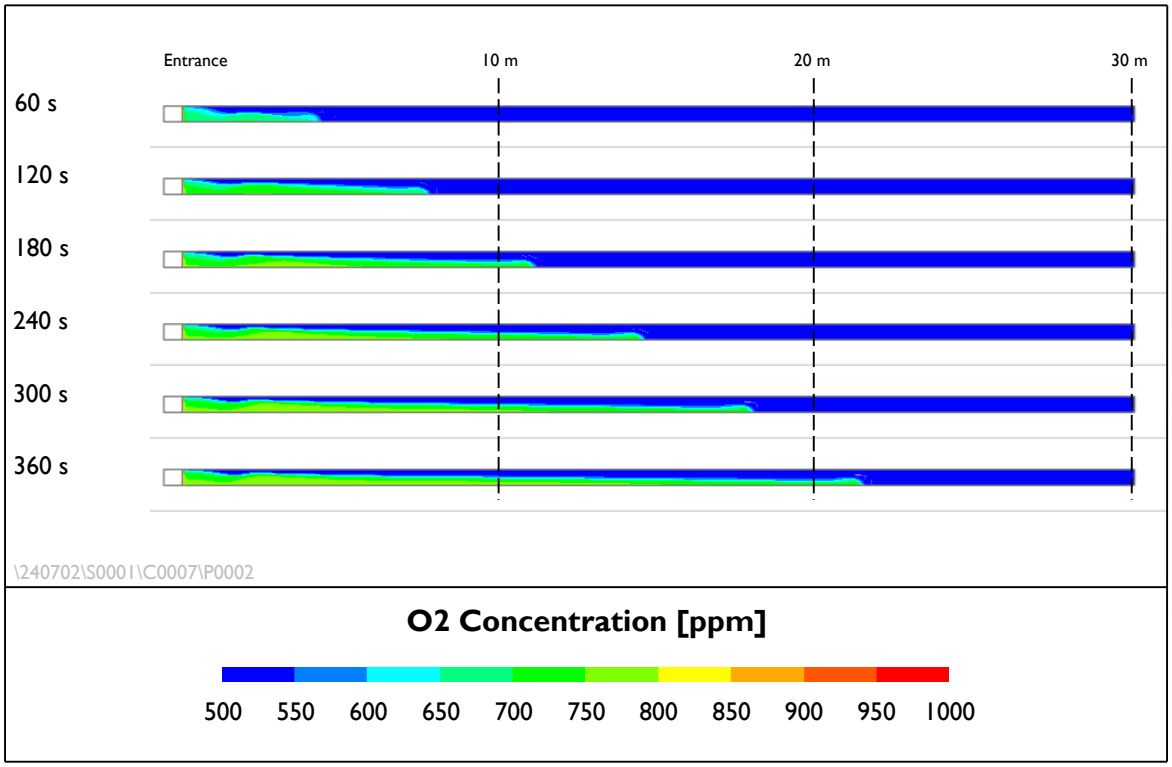
APPENDIX C CFD PREDICTIONS FOR STUDY C, MIXING AT THE JUNCTION AT THE ENTRANCE TO THE SPUR



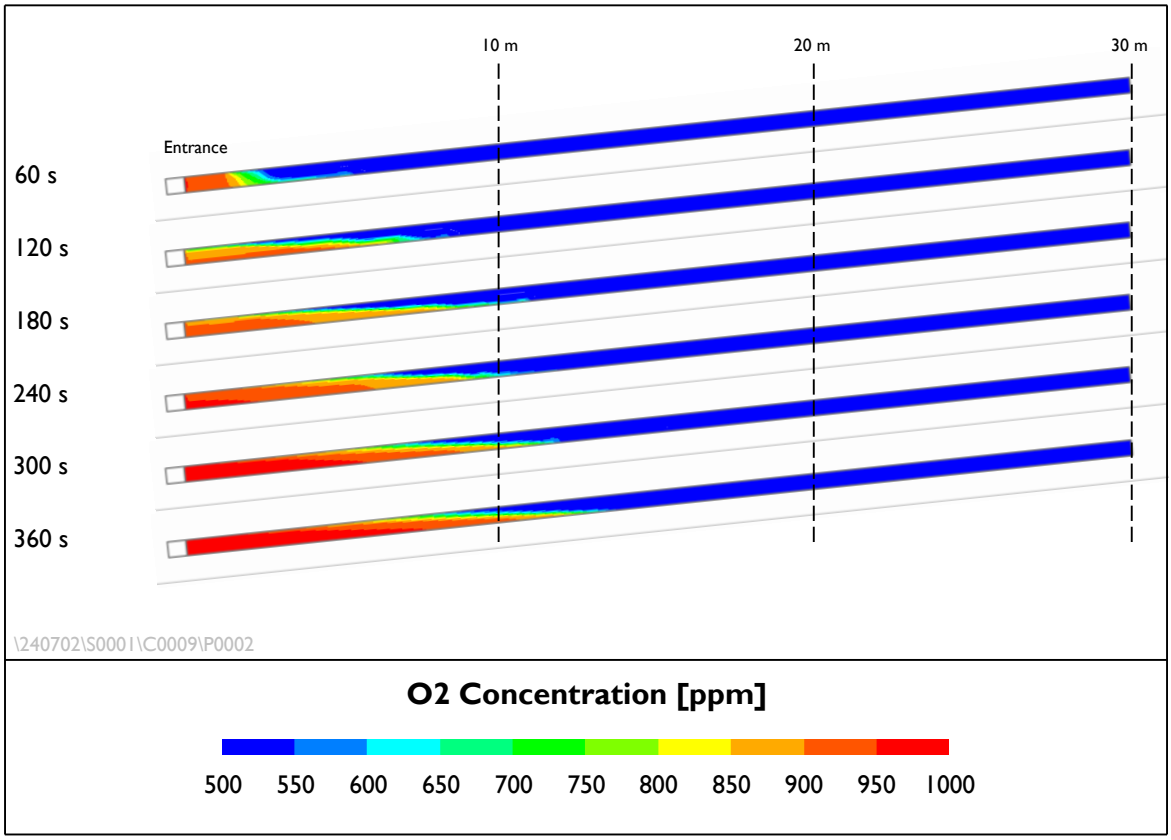
Case:	C1
Flow velocity in spur:	0.02 m/s
Flow velocity in main line:	2.0 m/s
Slope:	Horizontal



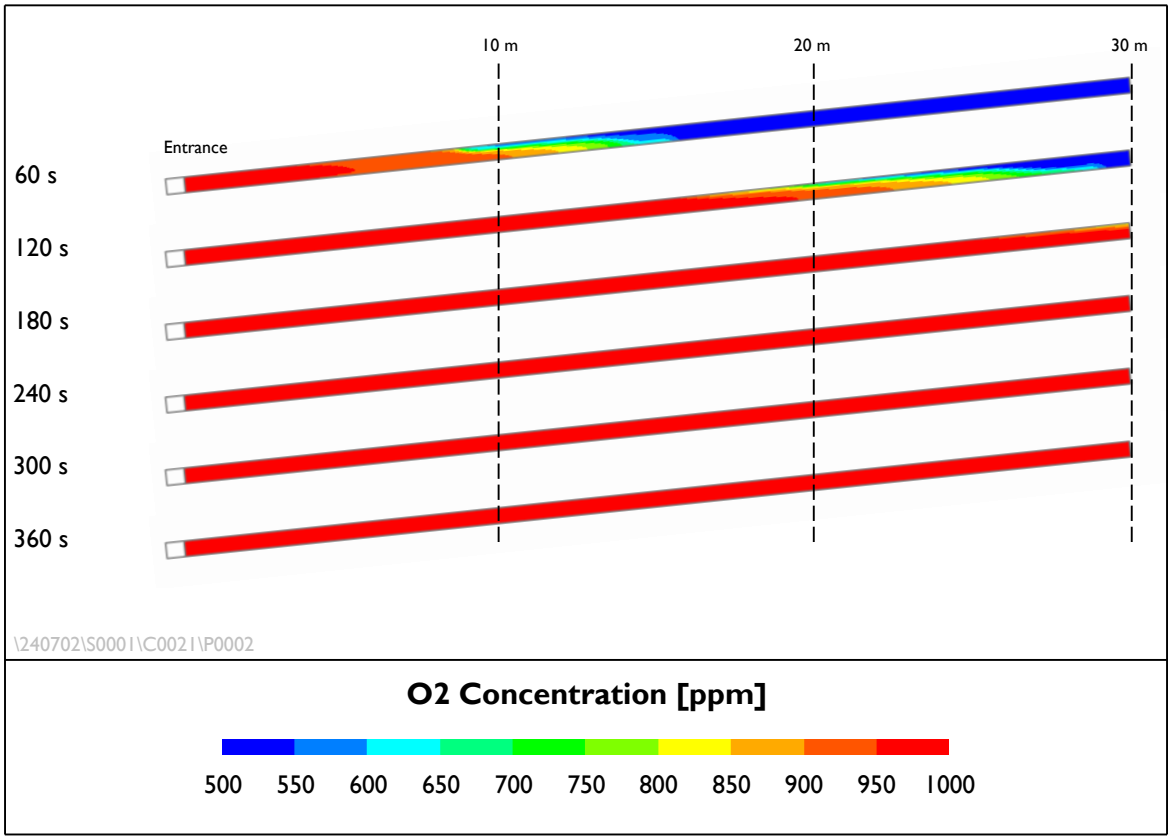
Case:	C2
Flow velocity in spur:	0.2 m/s
Flow velocity in main line:	2.0 m/s
Slope:	Horizontal



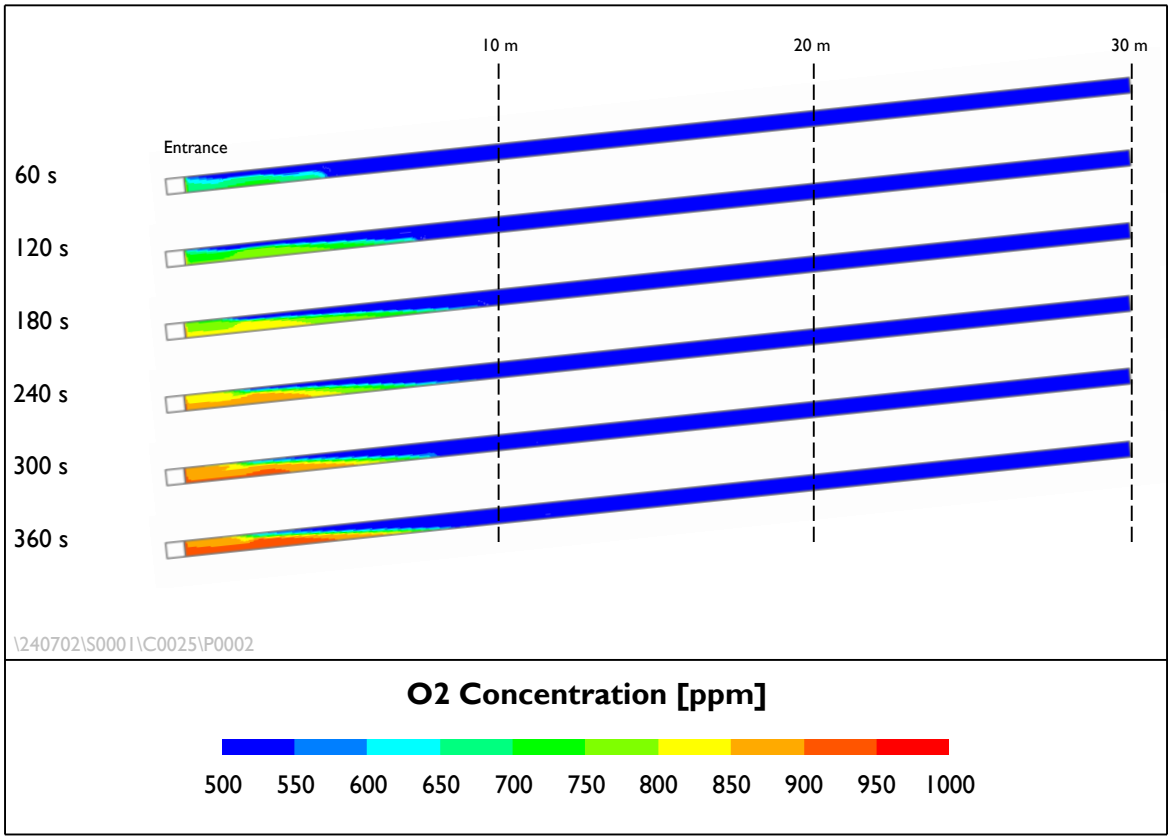
Case:	**C3**
Flow velocity in spur:	Zero (Dead leg)
Flow velocity in main line:	2.0 m/s
Slope:	Horizontal



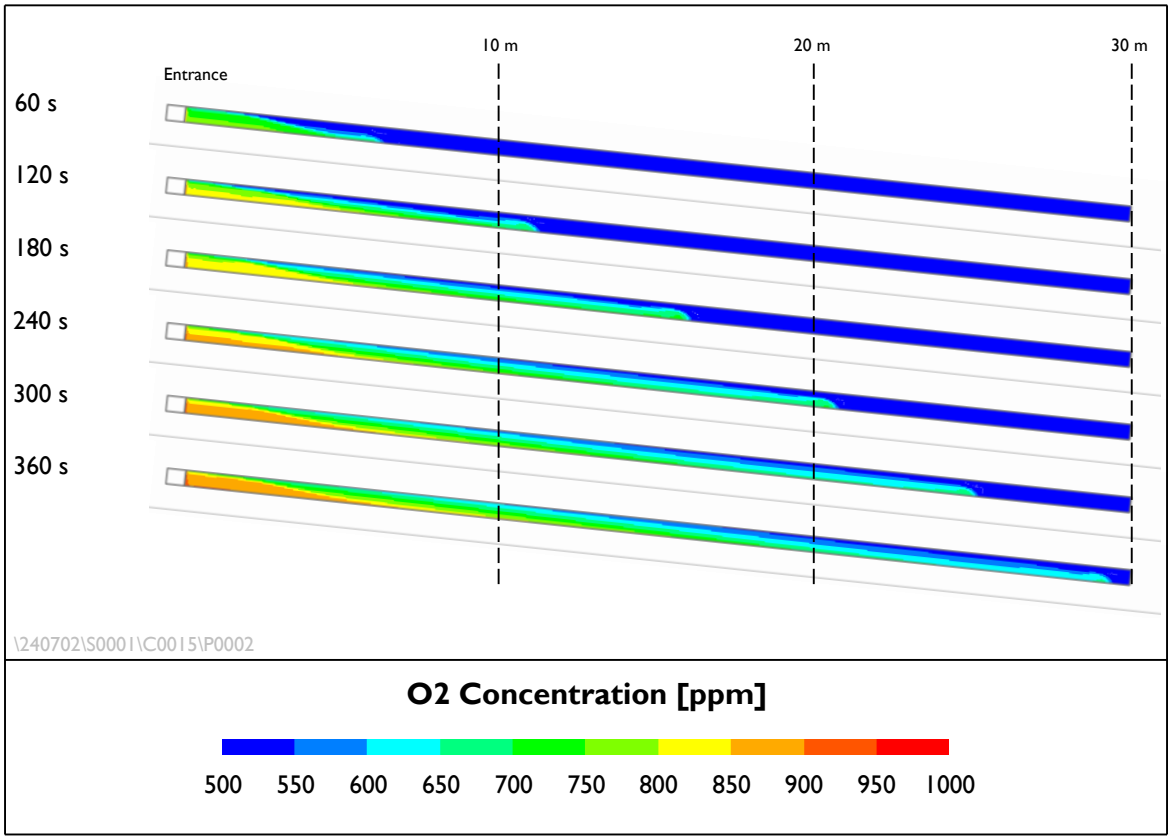
Case:	C4
Flow velocity in spur:	0.02 m/s
Flow velocity in main line:	2.0 m/s
Slope:	Uphill, 10%



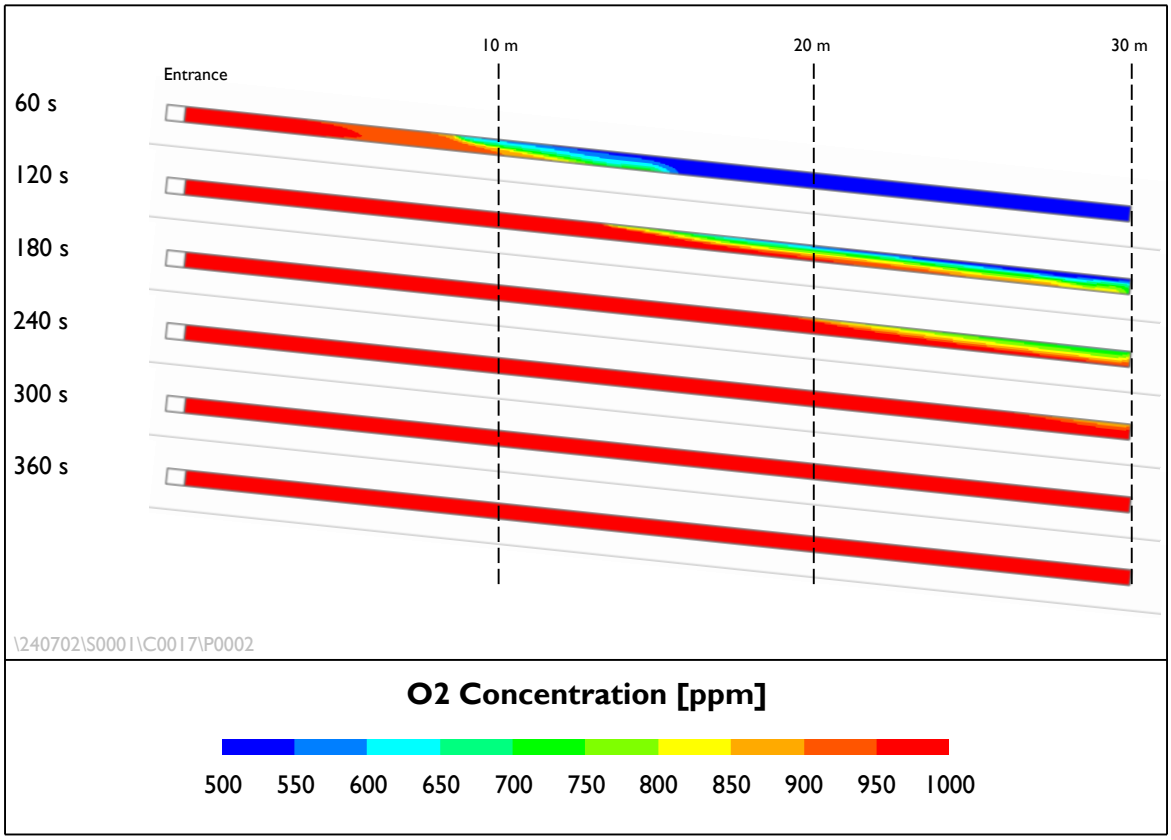
Case:	C5
Flow velocity in spur:	0.2 m/s
Flow velocity in main line:	2.0 m/s
Slope:	Uphill, 10%



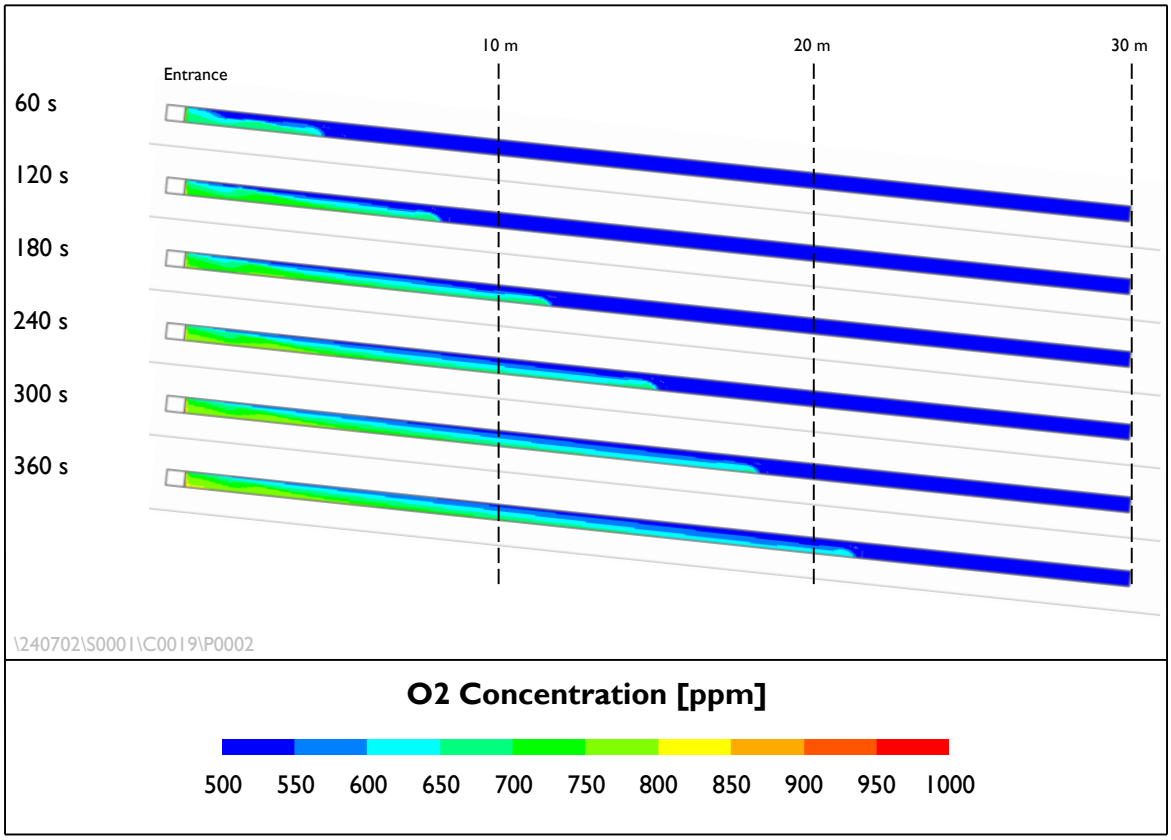
Case:	C6
Flow velocity in spur:	Zero (Dead leg)
Flow velocity in main line:	2.0 m/s
Slope:	Uphill, 10%



Case:	C7
Flow velocity in spur:	0.02 m/s
Flow velocity in main line:	2.0 m/s
Slope:	Downhill, 10%



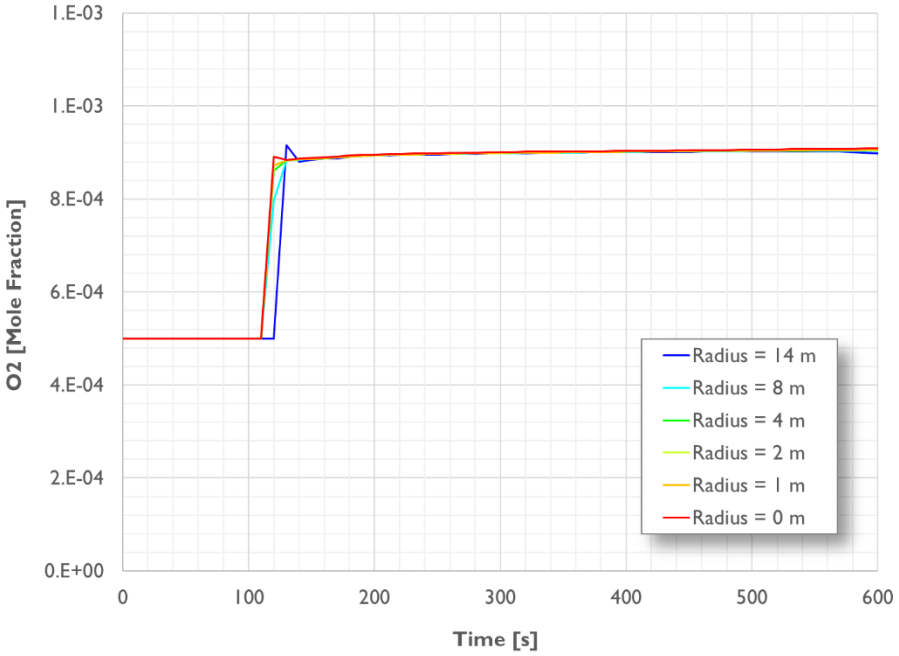
Case:	C8
Flow velocity in spur:	0.2 m/s
Flow velocity in main line:	2.0 m/s
Slope:	Downhill, 10%



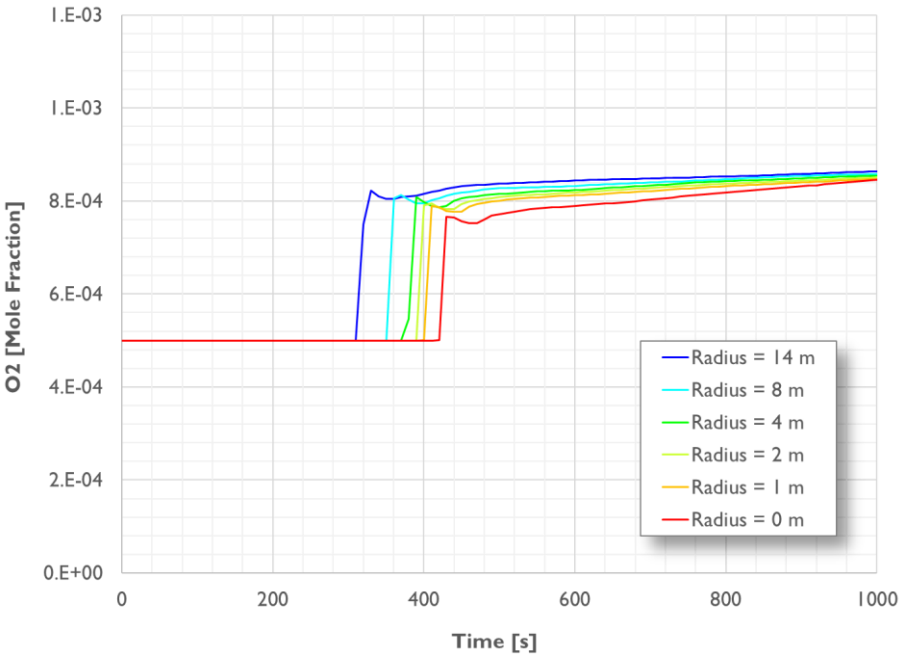
Case:	C9
Flow velocity in spur:	Zero (Dead leg)
Flow velocity in main line:	2.0 m/s
Slope:	Downhill, 10%

APPENDIX D CFD PREDICTIONS FOR STUDY D, MIXING AT BENDS

10 m along spur



After bend (~30 m along spur)



Case:	**D1-6**
Flow velocity:	0.02 m/s
Pulse duration:	1500 s
Slope:	Horizontal

APPENDIX B – WP2: COMPREHENSIVE LIST OF TECHNOLOGY REQUIREMENTS

OXYGEN INHIBITION – CRITICAL TECHNOLOGY ELEMENTS

CLIENT:	National Gas Transmission
PROJECT NUMBER:	19878
REVISION:	1
DATE:	05/09/2025

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Rev.	Date	Description	Prepared by	Reviewed by	Approved by
0	22/08/2025	Draft for comment	J.Sheppard	N.Gallon S.Daniels	D.Phelps
1	05/09/2025	Added solution and output columns in priorities summary	J.Sheppard	D.Phelps	D.Phelps

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1 INTRODUCTION

The purpose of this task is to identify a list of critical technology elements (CTE's) related to the adoption of an Oxygen inhibitor on the National Transmission System (NTS).

While all CTE's need to be addressed prior to full technology implementation; the path to implementation is iterative and this process will also allow a prioritised approach to be taken with the CTE's scored based on technology risk, cost and time.

This report presents the methodology and key findings from the assessment – the full assessment findings are populated in the associated excel file[1].

1.1 Approach

In order to provide a robust process of identifying critical technology elements; IGEM TD/1 Edition 6 (Steel pipelines for high pressure gas transmission), IGEM TD/1 Edition 6 Supplement 2 (High pressure Hydrogen pipelines) and IGEM TD/16 Edition 2 (Biomethane injection) were reviewed and problem statements considered for each Section headers based on the content in each standard. In this process each header became a critical technology element to be considered for problem statements associated with the use of oxygen as an inhibitor.

1.2 Scoring

Each problem statement was then considered against the technology risk, the problem solving cost and the time to solve each problem. A qualitative scoring was considered based on numbers 1 to 3.

1. What is the technology risk where; 1 is low, 2 is medium and 3 is high
2. What is the problem solving cost where; 1 is low, 2 is medium and 3 is high ([redacted])

   Note – *this is separate from any potential cost of implementation on the network*

3. What is the expected time to answer the problem, where; 1 is low, 2 is medium and 3 is high (<1week, <1month, <1year)

An overall score for ranking was then calculated as = (3*technology risk) + (1 * cost) + (1 * timescale), with the technology risk being weighted more heavily to account for the potentials for showstoppers.

1.3 RAG status

A RAG status (Red, Amber, Green) was then applied based on the following scores:

Green = 5

Amber = 6 to 9

Red = Greater than 10

[1] ROSEN(UK), *"19878 O2 Inhibition – CTE Matrix, Rev0.xlsx"*, J.Sheppard, 22.08.2025.

1.4 CTE Priorities

The CTE's have been ranked based on their overall score with the reds detailed in work sheet 'CTE Priorities' ranked by their score from high to low with duplicates removed; therefore, identifying what are considered the biggest risks to the introduction of oxygen as an inhibitor. Additional information on potential solutions and outputs has been included for high priority items.

2 KEY FINDINGS

Rank	Problem Statement	Solution	Output	Tech. Risk	Problem Solving Cost	Time to Solve problem	RAG	Score
1	Full scale experimental testing is required to physically test performance of full system including injection, storage, top up, etc the results of which is unknown	Full scale demonstration of design across operating envelope	Validation of design and system performance	3	3	3		15
2	Oxygen inhibition does not mitigate against hydrogen embrittlement and failure by fracture occurs	Lab and full scale testing to demonstrate inhibiting effect across range of materials on NTS	Validation of previous testing across wider pipe and fitting population	3	3	2		14
3	Oxygen inhibition does not mitigate against hydrogen embrittlement therefore fatigue life is reduced to unacceptable levels	Lab and full scale testing to demonstrate inhibiting effect across range of materials on NTS	Validation of previous testing across wider pipe and fitting population	3	3	2		14
4	Oxygen inhibition may not be effective over industrial timescales	Lab and full scale testing to demonstrate inhibiting effect across range of materials on NTS over applicable timescales	Validation of previous testing across proposed timescales for the wider pipe and fitting population	3	3	2		14
5	Legislation may restrict use of oxygen as an inhibitor	Desktop study requiring industry and government engagement	Legislation updated	3	1	3		13
6	Maximum level must not reach lower explosive limit across the network including any dead legs	Full scale demonstration of design across operating envelope	Validation of proposed mitigation	3	2	2		13

7	Significant volumes of oxygen will be required this may be tankered in or piped. Site storage may be required and sufficient precautions to ensure safety	Agreed design solution and full scale demonstration across operating envelope	Validation of design and system performance	3	2	2		13
8	A method to maintain 500 ppm of oxygen into the gas product to be developed across the range of flows and pressures	Agreed design solution and full scale demonstration across operating envelope	Validation of design and system performance	3	2	2		13
9	A minimum level shall be maintained for inhibitor to work; consider oxygen consumption rate and other variables	Lab and full scale testing to identify oxygen consumption rate across range of materials on NTS over applicable timescales	Confirmed operating variables for design	3	2	2		13
10	The recommended oxygen concentration based on testing in pure Hydrogen has not been confirmed for hydrogen blends.	Lab and full scale testing to demonstrate inhibiting effect across range of materials on NTS with H2 blends	Confirmed operating variables for design	3	2	2		13
11	Gas with oxygen inhibitor may be outside of gas quality requirements and customers (& storage or interconnectors) cannot accept gas or the customer may not want to accept gas with increased oxygen content	Desktop study requiring industry and government engagement	Confirmation of acceptance by industry and government	3	1	2		12
12	Understand all other components/impurities in the line which could consume oxygen	Lab and full scale testing to identify oxygen consumption rate across range of materials on NTS over applicable timescales	Confirmed operating variables for design	2	3	3		12

13	Oxygen inhibitor loss of supply leading to immediate pipeline failure	Agreed design solution with appropriate control measures and mitigations demonstrated across the operating envelope	Validation of design and system performance	2	2	2		10
14	Operating parameters with oxygen inhibitor to be defined	Agreed design solution and full scale demonstration across operating envelope	Validation of design and system performance	2	2	2		10
15	Oxygen inhibitor alters the purging and venting procedures so IGEM/SR/22 or IGEM/SR/23 can no longer be followed	Desktop study and full scale demonstration to validate updated procedures	Validation of current purging / venting procedures or acceptance of updates / new procedures	2	2	2		10
16	Sufficient oxygen is required to be available to inhibit the network	Agreed design solution and full scale demonstration across operating envelope	Validation of design and system performance	2	2	2		10

APPENDIX C – WP2: HIGH LEVEL HAZARD REVIEW

PHASE 2 – GAS INHIBITORS FOR HYDROGEN PIPELINES – HIGH LEVEL HAZARD REVIEW

CLIENT: National Gas

PROJECT NUMBER: 19878

REVISION: 1

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Rev.	Date	Description	Prepared by	Reviewed by	Approved by
0	08/08/2025	Draft for Comment	K Dahlgren/ D Anderson	G Smith	D.Phelps
1	02/09/2025	Final Issue addressing NGT comments	D.Phelps	D.Anderson	D.Phelps

EXECUTIVE SUMMARY

ROSEN completed an initial project to investigate the Inhibition of hydrogen embrittlement effects in pipeline steels using gaseous inhibitors. The Phase I work helped to quantify the inhibiting effect from the presence of oxygen on hydrogen embrittlement. ROSEN are currently in the process of completing Phase II work regarding the operational feasibility of using a gas inhibitor.

As part of the Phase II, Work Pack 2 (WP-2) a high level hazard assessment was requested by National Gas to run through the proposed process to identify potential hazards and consider whether they can be effectively managed and mitigated.

The Hazard Review Workshop was held on Wednesday the 23rd of July in a Microsoft Teams call between National Gas and ROSEN. It covered the following areas:

- Area 1 is the primary oxygen generation for the network
- Area 2 is the primary oxygen injection and control into the network
- Area 3 is the contingency for oxygen top-up into the network should it be required to maintain required levels.

There were considered to be no major Hazards identified in the workshop that could not be overcome in the Conceptual Design phase of the project.

The most significant discussion points were;

1. It was considered unlikely that it would be practical to transport in, and store liquid oxygen in the volumes required to feed the network demand at the primary entry point. This method would likely be suitable for top up at remote locations where piping oxygen in could be difficult and if on-site production using bespoke technology is not possible.
2. The importance of the control system for oxygen injection is key to the safe operation of the network,
    a. Primarily to ensure sufficient oxygen injection to mitigate the threat of hydrogen cracking as there is thought to be very limited tolerability to under injection. The risk of hydrogen cracking is predicted to manifest itself almost immediately when oxygen injection stops.
    b. The control system also needs to accommodate the potential for ‘no flow’ or ‘reverse flow’ scenarios in the network.
    c. Of secondary concern is over injection of oxygen which could ultimately lead to an explosive mixture within the gas network. The likelihood of this is thought to be lower given the injection rate is orders of magnitude lower than the concentrations required to realise this threat.
3. The physical process of getting a homogeneous mix of oxygen into the network at the required dosage needs careful consideration to avoid local parts of the network immediately adjacent to the injection point being over or under dosed. This is not thought to be an insurmountable issue.
4. There is currently ambiguity over the likely oxygen consumption rate within the network and the possible need for oxygen top up stations to maintain the required dosage. This needs further investigation in the next phase of the work.

The table below presents the full list of actions identified during the Workshop:

No.	Action Description
1	Consider if metering systems (equation of state) need to be modified if oxygen is in the system.
2	Investigate whether direct oxygen injection or premixing is more appropriate for this application considering risks associated with storage of mixed gas and associated on site equipment.
3	Investigate the process/equipment required to ensure homogenous oxygen mixture considering current operational requirements, i.e. inline inspection.
4	Consider the potential for hydrogen leakage through materials or fittings.
5	Clarify that the required oxygen concentration for inhibition is either in relation to the total pressure or the partial pressure of hydrogen.
6	Investigate the effects of oxygen on the aging of seals. Related to this are the risks of explosive decompression of seals.
7	Investigate the compatibility of oxygen with current materials and seals in network.
8	Investigate if failed compressor bearings, or any other ignition source, could reach autoignition temperature of hydrogen-oxygen mixture.
9	Investigate the compatibility of current odorant with O2 / H2 network.
10	Further evaluate the measures to be put in place to manage reverse flow and its effect on oxygen concentrations exceeding the LFL.
11	Evaluate appropriate emergency shutdown requirements e.g. ESV/control system/procedures to safeguard against abnormal process events.
12	Further investigate the threats associated with overdosing oxygen into the pipeline, i.e. flammable mixtures, reduced calorific value, etc.
13	National Gas to provide details of the frequency of process trips (low/no flow) in the network to understand the impact on O2 injection and more generally the effect on protecting all components in the network from hydrogen embrittlement.
14	Investigate the viability of lowering the pressure in the line as a safeguard if oxygen supply is compromised.
15	Assess the risks associated with the treatment of gaseous oxygen, including mixing, compression, drying, etc. once process design is confirmed.
16	Identify and assess any confined spaces within the Gas Network infrastructure where oxygen could accumulate such as valve pits.
17	Reconsider explosion risk and whether current mitigations are adequate following concept design.
18	Review suitability of vibration monitoring in line with industry best practice (Energy Institute AVIFF guideline) as part of next phase of work
19	Consider the viability of piping in gaseous oxygen to meet volume requirements for various entry locations.
20	Consider Pressure Swing Adsorption (PSA) or membrane technologies for separating gases or oxygen.
21	Consider the possibility of injecting oxygen straight into the pipeline without storing it.
22	Investigate potential impurities which may be present in the gaseous oxygen that could ignite (commissioning hazard).
23	Consider the viability of using liquid oxygen to meet volume requirements.
24	Investigate current condition of the pipeline. Any defects present that will alter safety considerations of new oxygen system should be known
25	Investigate compatibility of oxygen with current odorisation methods.
26	Investigate the presence of other components/impurities in the line which could consume oxygen.
27	Investigate the fuel for compressor gas turbines, will oxygen have an effect on the fuel apart from the slightly reduced energy density?
28	Recommended 250ppm concentration is based on testing in pure Hydrogen – further test work is required to confirm volumes of oxygen required for hydrogen blends.
29	Full scale experimental testing is required to physically test performance of full system including injection, storage, top up, etc.
30	Assess the suitability of the compressor stations in terms of space for new equipment or changes to the safety case regarding the change of use.
31	Investigate the impact on end users considering gas quality

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ABBREVIATIONS

Abbreviation	Details
AGI	Above Ground Installation
CFD	Computational Fluid Dynamics
CV	Calorific Value
FEED	Front End Engineering Design
HAZID	Hazard Identification
HAZOP	Hazard & Operability Study
H2	Hydrogen
O2	Oxygen
HHV	Higher Heating Value
ID	Inner Diameter
LFL	Lower Flammability Limit
LOL	Lower Oxygen Limit
LTS	Local Transmission System
MAH	Major Accident Hazard
NGT	National Gas Transmission
NG	Natural Gas
NTS	National Transmission System
PPM	Parts Per Million (expressed on a mole/standard volume basis for this work)
UFL	Upper Flammability Limit
UOL	Upper Oxygen Limit
WP1 / 2 / 3	Work package 1 / 2 / 3
ESV	Emergency Shutdown Valve
PSSR	The Pressure Systems Safety Regulations 2000

1 INTRODUCTION

ROSEN completed an initial project to investigate the Inhibition of hydrogen embrittlement effects in pipeline steels using gaseous inhibitors. The Phase I work helped to quantify the inhibiting effect from the presence of oxygen on hydrogen embrittlement. ROSEN are currently in the process of completing Phase II work regarding the operational feasibility of using a gas inhibitor. Results from Work Pack 1 (WP-1) of the Phase II work were issued recently [1].

As part of the Phase II, Work Pack 2 (WP-2) a high level HAZID type assessment was requested by National Gas to run through the proposed process to identify potential hazards and consider whether they can be effectively managed and mitigated. ROSEN proposed following the general principals of National Gas Transmissions Specification for Hazard Identification Studies [2] section 3.2 for HAZIDs undertaken at the Feasibility stage.

However, at the start of the workshop on the 23rd July 2025, Justin George, National Gas Process Safety, requested that the session was altered to focus more generally on project risk rather than following the principals of a HAZID as it wasn't completely aligned with National Gas Specification. This document provides the background and structure for the workshop as well as summarising its outputs. The scope of the review is focused on the Oxygen stream and its introduction into the gas transmission network, the boundaries of which are shown in Figure 1-1.

Workshop Agenda

- Introductions – Chair
- Purpose of meeting – David Phelps
- Brief overview of work done to date overview Justin Sheppard/Gareth Smith
- Team review of the high level threats

Workshop Purpose

- Identify possible threats in the methodology
- Assess the possible consequenses of the threats
- Identify possible safeguards
- Recommend prevention, control, or mitigation methods

Inputs

- Summarise work done to date
- Outline schematic of Gas Network
- Worksheet template (See Appendix)

Outputs

- Complete worksheet for Oxygen injection section of nework.
- Agree scribed notes for the workshop.

National Gas Attendees

- Robert Best, Kousseyla Hamadi, Justin George, Steven Johnstone, Simon Kidd, Matthew Hammond, Mick Jarvis, Daniel Knowles

ROSEN Attendees

David Phelps, Gareth Smith, Justin Sheppard, Neil Gallon, Dave Anderson (chair), Karl Dahlgren (scribe)

1.1 Background and Design Intent

The primary purpose of the ROSEN project for NGT is to establish the feasibility of using Oxygen as an inhibitor to prevent hydrogen embrittlement and to define what equipment and procedures would be required for oxygen to work as an inhibitor within the NTS pipework in the future.

A previous ROSEN report [3] concluded that, based on the laboratory results, oxygen was an effective inhibitor of hydrogen embrittlement at levels of 250 ppm or greater. The use of such an inhibitor could allow National Gas Transmission to continue to operate Hydrogen pipelines and Hydrogen / Natural gas blended pipelines in the National Transmission System (NTS) at the same pressures and design factors that they currently operate with for Natural Gas. If no inhibitor is injected into the network it can be assumed that design factors in line with IGEM/TD/1 Edition 6 Supplement 2 [4] will be introduced for hydrogen and blended pipelines; this would limit operating pressures across the NTS.

1.1.1 How is the process / system likely to function:

Based on current knowledge the use of Oxygen as an inhibitor to hydrogen embrittlement will require:

- A continuous mix of at least 500 PPM oxygen in the gas flow at inlet points and all points in the system must be kept above 250 PPM.
- A maximum level of 1000 PPM oxygen.
- No loss of supply is acceptable
- Oxygen could potentially be mixed and injected at all entries of the NTS. Until a better definition of the project is established this could be at methane and or hydrogen inlet points.
- At compressor stations, gas quality measurements will be taken and any additional oxygen mixed and injected, where required. The initial assumption is that any additional oxygen top-up would only occur at the existing (or new) compressor stations[1]. There are currently circa 24 compressor stations across the NTS system for NG operation. This may well change for hydrogen blends or pure hydrogen operation. The number of oxygen top-up points will depend on the actual consumption of oxygen at the pipe wall. oxygen consumption has not been validated with experimental work at the time of writing.
- A system of monitoring and control will be required to ensure continuous injection of oxygen relative to the quantity of hydrogen and NG that it is being mixed with.
    - Safe system requirements may need to be in place ensuring a secondary injection line should the initial system fail (i.e. duty and standby for failure and or maintenance). Also additional storage as a contingency for oxygen supply interruptions.

[1] No assessment was conducted as part of this work to assess the suitability of the compressor stations in terms of space for new equipment or changes to the safety case regarding the change of use.

- Similarly it will be important to ensure that the oxygen concentration does not exceed the maximum concentration of 1000 PPM.

1.1.2 At each injection site:

Oxygen will be required to be safely stored and managed (see §1.1.5).

- Gas quality measurements will need to be taken and the required oxygen mixed and injected.
- Flow and pressure control will be required, with pressure relief valves for safety precautions.
- Metering will be required.

1.1.3 In situations of no flow in NTS:

The Oxygen injection system design will be required to have suitable provision to prevent the risk of backflow from NTS into the Oxygen supply system when there is no flow in the NTS (i.e. when no Oxygen injection is required). This will likely require to be of a higher integrity than a non-return valve.

1.1.4 At offtakes to the LTS and customers:

There may be customers that require the removal of oxygen depending on future gas quality requirements.

- This may be possible via deblending [this will not be within the scope of this hazard review]
- Offtakes to LTS and customers will be metered.

Further to the above, a system block diagram has been developed as shown in Figure 1-1 below.

1.1.5 High Level Estimate of Likely Oxygen Volumes

A high level estimate was made of the likely oxygen demand at one of the entry points in the UK NTS:

- The 1 in 20 year peak demand flow at [redacted] is circa [redacted]
- If we assume for the worst case of pure hydrogen, the volumetric flow would be three times that of NG due to the lower calorific value on a volume basis. Hence, the volumetric flowrate of oxygen (at 500 PPM by volume) would be of the order of [redacted]
- It was concluded that storage of oxygen as compressed gas (at [redacted] in 26 inch pipe bullets) would only be possible for relatively short periods of duty, since this would require 5.8 km of pipe storage for each day of operation.
- If oxygen was stored as cryogenic liquid and delivered to site in road based tankers (26.1 m^3), then approximately 6.7 tankers per day would be required, which may not be practical.
- Obviously if oxygen is co-generated with the hydrogen during the electrolysis of water then the oxygen could simply be compressed, dried and filtered on the same site and delivered by plant pipework.
- However, if oxygen consumption requires top-up of oxygen at compressor stations or other AGI, then piped oxygen supply would be a more difficult option. If we assume that the oxygen required would be that to boost the level from the minimum level of 250 PPM back up to 500 PPM then would be expected that the oxygen demand would range from 0.6 tankers/day at [redacted] Compressor Station to 4 tankers/day at [redacted] compressor station.

1.2 Engineering Design Process

It should be noted that we are currently at the early stage of the design process and no significant engineering design or safety studies have been performed. The first part of a design process for a novel technology such as this would (at a minimum) include at least some of the items defined in Table 1-1.

1.3 Odorisation of Gas at Boundary of NTS and LTS

Natural gas is odourless, so odorants are added to it as a safety measure to detect leaks. This normally occurs as the gas enters the LTS from the NTS. In the UK, natural gas (primarily methane) distributed through the NTS is odorized using a blend known as Odorant NB, which consists of t-butyl mercaptan (TBM) and dimethyl sulphide. ROSEN's current understanding is that the odorant used for hydrogen is likely to stay the same as for NG.

Although the LTS is outside the scope of the current HAZID, it is noted that adding oxygen to hydrogen and or hydrogen + NG mixtures may lead to the reaction of the chemicals within the odorant with oxygen leading to the potential for elevated corrosion rates in the low pressure system or in consumer equipment.

Tert-butyl mercaptan reacts with oxygen in a redox reaction. This reaction typically produces a disulfide and water, and in some cases, can also produce sulphur dioxide (SO_2). The reaction is often catalysed by metal oxides (such as iron oxide e.g. on the inside pipe wall), the specific products and reaction conditions can vary. It is known that some parts of the LTS are water wet due to the ingress of standing water from outside the pipeline; this would exacerbate corrosion with sulphur compounds. This should be covered in later HAZIDs dealing with the complete system.

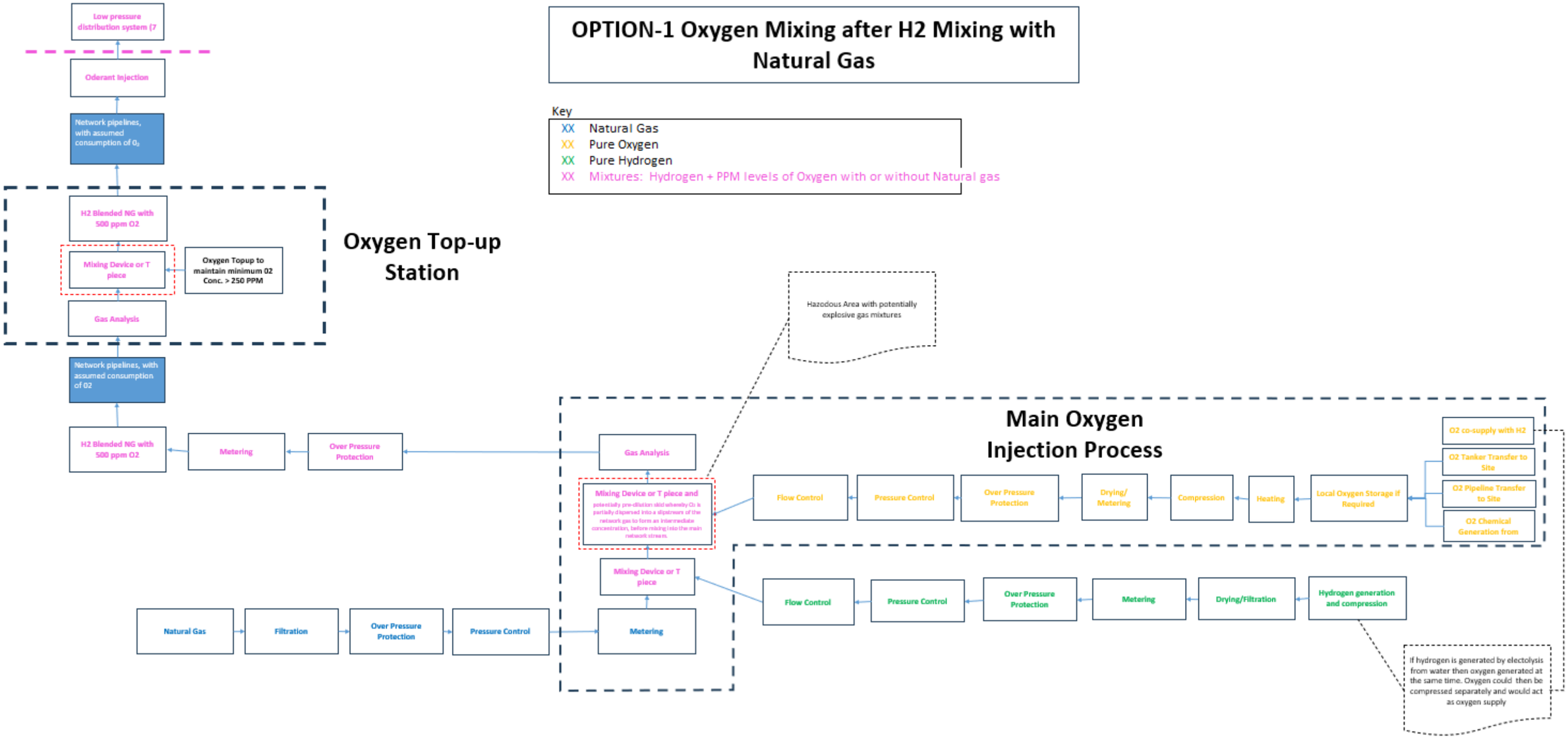

Figure 1-1: High Level Schematic of O2 Inhibitor Injection and Boundaries of the Hazard review

Table 1-1: Summary of Engineering Design Process and Progress in Current ROSEN Project

Engineering Design Phase	Progress in ROSEN Project
Basic Feasibility Assessment:	
Basic investigation of technical feasibility – desk top studies	Completed as part of Phase II work
Basic laboratory scale investigations:	
o Proof of inhibition effect at 250 PPM	Completed as part of Phase I work
o Underlying chemistry of oxygen inhibition	Basic understanding from existing literature.
o oxygen consumption by the pipeline walls	Preliminary discussions held with university researchers, but no detailed desk top or experiment work within current scope.
o Initial ideas for concepts	Some ideas generated as part of WP1 studies, but WP2 and WP3 have not been completed.
Concept Selection:	
Problem Definition: Clearly identifying the problem or need that the design aims to address.	Much of this should be identified at high level as part of WP2 and WP3. However, full definition will not occur until a full concept engineering study is conducted.
Research: Gathering information related to the problem, including existing solutions, user needs, and technical constraints.	The rate and order of the reaction for consumption of oxygen at the pipe wall must be defined by experimental studies, before more detailed engineering or costing can be properly developed. It is outside the scope of the current ROSEN work.
Brainstorming: Generating a wide range of potential solutions and ideas.	Some elements of this will be addressed as part of the WP2 and WP3. However, a full concept engineering study will be required after this with discipline engineering support to generate engineering drawings, develop operating philosophies, safety studies and define the cost of each concept.
Concept Generation: Developing and refining these ideas into distinct design concepts.	
Concept Evaluation: Assessing the feasibility, cost, and performance of each concept against the defined criteria.	
Selection: Choosing the most promising concept(s) for further development.	
Experimental Evaluation: Given that this is a relatively new concept, laboratory or small scale pilot plant studies would be useful to confirm the basic concept and inform the future FEED studies.	
Concept Phase HAZID or high level HAZOP: A full HAZID/HAZOP assessments can not take place until each concept is well defined with engineering drawings, safety definition and a basic operating philosophy.	
Front End Engineering Design (FEED): Further definition of selected concept.	HAZOP would be conducted as part of FEED. Outside scope of current ROSEN project.
Detailed Design: Design at level to build plant.	HAZOP would be conducted as part of design. Outside scope of current ROSEN project

1.4 Flammability

Fire, or burning, is the rapid exothermic oxidation of an ignited fuel. Combustion always occurs in the vapor phase and for this HAZARD the fuels of interest all exist in vapour form at normal pipeline conditions. Hence, the flash point and flame point associated with liquid fuels can be ignored [5].

When fuel, oxidizer, and an ignition source are present at the necessary levels, burning will occur. This means a fire will not occur if:

(1) fuel is not present or is not present in sufficient quantities,

(2) an oxidizer is not present or is not present in sufficient quantities, and

(3) the ignition source is not energetic enough to initiate the fire.

A common example of the three components of the fire triangle are gas, air, and a spark where the terms Lower Flammability Limit (LFL) and Upper Flammability Limit (UFL) are used to define the fuel concentration limits (% vol) of combustion. However, for this HAZARD the main concern is hydrogen (or hydrogen and NG) with pure oxygen such that the combustion limits are different and the terms Lower Oxygen Limit (LOL) and Upper Oxygen Limit (UOL) are used.

In the past, the sole method for controlling fires and explosions was elimination of or reduction in ignition sources. Practical experience has shown that this is not robust enough, since ignition energies for most flammable materials are too low and ignition sources too plentiful. As a result current practice is to prevent fires and explosions by continuing to eliminate ignition sources while focusing efforts strongly on preventing flammable mixtures.

Table 1-2 summarises the limits of flammability in oxygen, the minimum ignition energy and the autoignition temperature (sometimes called the Spontaneous Ignition Temperature) for hydrogen, methane and ethane. It can be seen that the ignition energy of hydrogen is a factor of fifteen lower than that of methane. The other value of particular interest is the UOL, it can be seen that the maximum hydrogen concentration is 94%, so for a mixture of hydrogen and oxygen the minimum oxygen concentration would be circa 6%. For hydrogen and natural gas mixtures the maximum fuel concentration is lower, so the minimum oxygen concentration would be higher.

It should be noted that the local pressure and temperature of the gas at pipeline conditions will influence all the parameters shown in Table 1-2.

Table 1-2: Limits of flammability in oxygen for hydrogen, methane and ethane

Compound	Formula	Lower (LOL) in pure oxygen (%vol)	Upper (UOL) in pure oxygen (%vol)	Minimum Ignition Energy (mJ)	Autoignition Temperature (°C)
Hydrogen	hydrogen	4	94	0.018	535
Methane	CH4	5.1	61	0.28	600
Ethane	C2H6	3	66	0.24	515

1.5 Summary of Issues Identified in WP1

For convenience the summary of the main conclusions / observations for WP1 are reproduced as Table 1-3. The most significant items affecting this hazard review are shown in bold.

It is noted that one of the most important findings of the WP1 work was that if oxygen consumption is equivalent to circa 10 micron/year steel corrosion, it would take more than 30 days of residence time for oxygen to fall below 250 PPM, with the associated velocity of 2 m/s. However, the operating procedures must guard against system shut-in scenarios of no/very low flow.

Table 1-3: Conclusions and Observations from WP1 with Significant impact on Hazards

#	Issue	Conclusion / Observation
i	Can oxygen concentration be controlled within the prescribed safe operating limits? (250 – 1000ppm)	Preliminary assessment suggests implementation should be possible if oxygen consumption is equivalent to circa 10 micron/year steel corrosion. At this consumption rate it would take > 30 days of residence time for oxygen to fall below 250 PPM, with the associated velocity of 2 m/s in L1 & 3 and 0.02 in the L2 branch. **However, operating procedures must guard against system shut-in scenarios of no/very low flow.**
ii	Initial findings on adding oxygen to form the mixture.	Without static mixer, it would typically take 80 to 100 pipe diameters to get uniform mixture for gas streams that are closely matched in rate. However, this can be **far more difficult if the flow rates of the mixing streams are widely different as is the case here. It may be worth considering a pre-dilution skid whereby oxygen is partially dispersed into a slipstream of the network gas to form an intermediate concentration, before mixing into the main network stream. However, there would be a safety implication[Note1] if mixtures were too high in oxygen**.
iv	Define the positions / intervals of injection points.	Recommendation to incorporate injection with existing measuring or equipment sites on the network. If average velocities are greater than 1 m/s, possibly no need for additional injection sites apart from the hydrogen injection point (as above). **Likely requirement for multiple measurement points. If oxygen is injected in sections with potential for low or shuttle type flow, then provision must be made for monitoring High/Low oxygen concentration either side of injection.**
ix	Will stratification of oxygen occur where the concentration can then build up outside of the safe limits?	Not predicted. It is **important to note that the two-layer stratification predicted by the full CFD model does not constitute reseparation of oxygen from a fully mixed mixture. When fluid within the spur is fully mixed, there is no evidence to suggest that oxygen can separate out of the mixture for the time and length scales of interest to the gas network.**

Notes:
1. It is important to consider the oxygen concentration of any intermediate blends of oxygen with hydrogen so as to minimise or preferably eliminate mixtures within the flammability limits. However, this may lead to longer mixing lengths or higher differential pressures (if static mixers are employed).

2 HAZARD REVIEW

The Hazard Review Workshop was held on Wednesday the 23rd of July in a Microsoft Teams call between National Gas and ROSEN. A diagram of the envisaged additions to the gas network was prepared to facilitate the review (Figure 1-1) and the 3 key focus areas identified (Figure 4-1), namely:

- Area 1 is the primary oxygen generation for the network
- Area 2 is the primary oxygen injection and control into the network
- Area 3 is the contingency for Oxygen top-up into the network should it be required to maintain required levels.

The key hazards discussed at the workshop are recorded in the Table 4-3 along with likely consequences, safeguards and actions. Also included in Table 4-4 are the minutes of the meeting in table form to record the discussions held.

2.1 Summary of outputs

There were considered to be no major Hazards identified in the workshop that could not be overcome in the Conceptual Design phase of the project.

The most significant discussion points were:

1. It was considered unlikely that it would be practical to transport in, and store liquid oxygen in the volumes required to feed the network demand at the primary entry point. This method would likely be suitable for top up at remote locations where piping oxygen in could be difficult.
2. The importance of the control system for oxygen injection is key to the safe operation of the network,
    a. Primarily to ensure sufficient oxygen injection to mitigate the threat of hydrogen cracking as there is thought to be very limited tolerability to under injection. The risk of hydrogen cracking is predicted to manifest itself almost immediately when oxygen injection stops.
    b. Of secondary concern is over injection of oxygen which could ultimately lead to an explosive mixture within the gas network. The likelihood of this is thought to be lower given the injection rate is orders of magnitude lower than the concentrations required to realise this threat.
3. The physical process of getting a homogeneous mix of oxygen into the network at the required dosage needs careful consideration to avoid local parts of the network immediately adjacent to the injection point being over or under dosed. This is not thought to be an insurmountable issue.
4. There is currently ambiguity over the likely oxygen consumption rate within the network and the possible need for oxygen top up stations to maintain the required dosage. This needs further investigation in the next phase of the work.

While none of these points are viewed as showstoppers, it is recommended that future scopes further evaluate them as well as the other actions summarised in section 2.2, to develop solutions.

2.2 Workshop Actions

Table 2-1: Workshop Actions

No.	Action Description
1	Consider if metering systems (equation of state) need to be modified if oxygen is in the system.
2	Investigate whether direct oxygen injection or premixing is more appropriate for this application considering risks associated with storage of mixed gas and associated on site equipment.
3	Investigate the process/equipment required to ensure homogenous oxygen mixture considering current operational requirements, i.e. inline inspection.
4	Consider the potential for hydrogen leakage through materials or fittings.
5	Clarify that the required oxygen concentration for inhibition is either in relation to the total pressure or the partial pressure of hydrogen.
6	Investigate the effects of oxygen on the aging of seals. Related to this are the risks of explosive decompression of seals.
7	Investigate the compatibility of oxygen with current materials and seals in network.
8	Investigate if failed compressor bearings, or any other ignition source, could reach autoignition temperature of hydrogen-oxygen mixture.
9	Investigate the compatibility of current odorant with O2 / H2 network.
10	Further evaluate the measures to be put in place to manage reverse flow and its effect on oxygen concentrations exceeding the LFL.
11	Evaluate appropriate emergency shutdown requirements e.g. ESV/control system/procedures to safeguard against abnormal process events.
12	Further investigate the threats associated with overdosing oxygen into the pipeline, i.e. flammable mixtures, reduced calorific value, etc.
13	National Gas to provide details of the frequency of process trips (low/no flow) in the network to understand the impact on O2 injection and more generally the effect on protecting all components in the network from hydrogen embrittlement.
14	Investigate the viability of lowering the pressure in the line as a safeguard if oxygen supply is compromised.
15	Assess the risks associated with the treatment of gaseous oxygen, including mixing, compression, drying, etc. once process design is confirmed.
16	Identify and assess any confined spaces within the Gas Network infrastructure where oxygen could accumulate such as valve pits.
17	Reconsider explosion risk and whether current mitigations are adequate following concept design.
18	Review suitability of vibration monitoring in line with industry best practice (Energy Institute AVIFF guideline) as part of next phase of work
19	Consider the viability of piping in gaseous oxygen to meet volume requirements for various entry locations.
20	Consider Pressure Swing Adsorption (PSA) or membrane technologies for separating gases or oxygen.
21	Consider the possibility of injecting oxygen straight into the pipeline without storing it.
22	Investigate potential impurities which may be present in the gaseous oxygen that could ignite (commissioning hazard).
23	Consider the viability of using liquid oxygen to meet volume requirements.
24	Investigate current condition of the pipeline. Any defects present that will alter safety considerations of new oxygen system should be known
25	Investigate compatibility of oxygen with current odorisation methods.
26	Investigate the presence of other components/impurities in the line which could consume oxygen.
27	Investigate the fuel for compressor gas turbines, will oxygen have an effect on the fuel apart from the slightly reduced energy density?
28	Recommended 250ppm concentration is based on testing in pure Hydrogen – further test work is required to confirm volumes of oxygen required for hydrogen blends.
29	Full scale experimental testing is required to physically test performance of full system including injection, storage, top up, etc.
30	Assess the suitability of the compressor stations in terms of space for new equipment or changes to the safety case regarding the change of use.
31	Investigate the impact on end users considering gas quality

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[8] ROSEN, O2 Inhibition of H2 Lines - Modelling Basis, 2025.

4 APPENDICES

4.1 Appendix A - Summary of Main Conclusions / Observations for WP1

Table 4-1: Summary of Main Conclusions / Observations for WP1

#	Issue	Conclusion / Observation
i	Can oxygen concentration be controlled within the prescribed safe operating limits? (250 – 1000ppm)	Preliminary assessment suggests implementation should be possible if oxygen consumption is equivalent to circa 10 micron/year steel corrosion. At this consumption rate it would take > 30 days of residence time for oxygen to fall below 250 PPM, with the associated velocity of 2 m/s in L1 & 3 and 0.02 in the L2 branch. However, operating procedures must guard against system shut-in scenarios of no/very low flow.
ii	Initial findings on adding oxygen to form the mixture.	Without static mixer, it would typically take 80 to 100 pipe diameters to get uniform mixture for gas streams that are closely matched in rate. However, this can be far more difficult if the flow rates of the mixing streams are widely different as is the case here. It may be worth considering a pre-dilution skid whereby oxygen is partially dispersed into a slipstream of the network gas to form an intermediate concentration, before mixing into the main network stream. However, there would be a safety implication[Note1] if mixtures were too high in oxygen.
iii	Where is a suitable location to inject and measure oxygen to maintain and manage the concentration?	As noted above, for normal network velocities (>1 m/s) it would require >> 1000 kilometres of residence time to reduce the oxygen concentration to 250 PPM. This suggests injection as close as possible to the source of hydrogen, measuring either side of injection with alarms to warn of flow reversals or similar leading to a slug of higher concentration oxygen building up. The complex model suggests that average velocities are > 1 m/s, so no significant reduction in oxygen based on consumption rates considered in this work [1].
iv	Define the positions / intervals of injection points.	Recommendation to incorporate injection with existing measuring or equipment sites on the network. If average velocities are greater than 1 m/s, possibly no need for additional injection sites apart from the hydrogen injection point (as above). Likely requirement for multiple measurement points. If oxygen is injected in sections with potential for low or shuttle type flow, then provision must be made for monitoring High/Low oxygen concentration either side of injection.
v	Are positions / intervals of injection points dependant on pipe condition or other factors?	Residence time of gas through the pipework is the primary controlling factor. Flowrates would have to be extremely low to produce a significant reduction of oxygen over distances between key operating sites (i.e. circa 100 km). Pipe condition in terms of: (a) pipe roughness, is likely to have little impact since most flows are highly turbulent. (b) MAOP may have to be lowered for hydrogen service. This would actually give lower residence times since density of gas would be lower. It should be noted that residence time can be averaged over many days, so if oxygen injection is stopped completely for a short period 1 hour it likely have minimal impact on the average oxygen concentration seen by the majority of the pipework.
vi	Impact of key features of the model:	At normal flows the system is highly turbulent, so mixing is likely to be rapid. The CFD work has shown that if a significant spike in concentration does arise then the combination of forced turbulence and diffusion would take circa a hundred pipe diameters at 0.2 m/s velocity (flat pipe). At very low velocities such as 0.02 m/s diffusion and turbulence will take many hundreds pipe diameters to re-establish a homogeneous mixture[Note2]. Branches and fittings will only make a small difference since they typically contribute circa 50 extra diameters of effective mixing / pressure drop (see below).
	• Flow velocity	Large Mol. Wt. difference between hydrogen and oxygen leads to significant density difference with a 500 PPM conc. difference in oxygen. At low flows (0.02 m/s) this is sufficient to allow stratified flow to establish and potential for counter current flow. At normal

#	Issue	Conclusion / Observation
		flows (~2m/s) momentum dominates over buoyancy effect (i.e. stratified flow not expected) and rate of oxygen migration is close to the mean flow velocity.
	• Terrain	At low flow velocities, transport of oxygen becomes dependent upon the local slope of the pipeline, particularly when the slope is near to horizontal. For horizontal and downward terrain, oxygen migrates within the lower part of the spur at a rate that is faster than the mean flow velocity. For slight upward terrain, the rate of oxygen migration is reduced compared to horizontal and downward terrain, but remains above the mean flow velocity.
	• Branches	A perturbation of increased oxygen concentration entering a spur at a tee junction will be lower than the concentration of oxygen within the main line due to mixing at the junction. This is most apparent if the slope of the spur off the main line is horizontal or downward. If the slope of the spur off the main line is upward, the concentration of oxygen entering the spur is predicted to approach that within the main line.
	• Bends	Bends predicted to make only make a marginal difference to the mixing of the oxygen as it migrates along the spur. The greatest degree of turbulent mixing at bends occurs at high flow velocities, but this coincides with non-stratified flow when the oxygen concentration will already be fairly uniform. At low flow velocities, when the flow may be stratified and the oxygen concentration is non-uniform, the degree of turbulent mixing at bends will be much reduced[Note3].
viia	Square wave perturbation of oxygen concentration - Simple Pipe Model	Using OLGA for perturbation spikes lasting up to two days it was found that the spike was almost unchanged in sections of the network at normal flow. However, in spurs with very low velocity (0.02 m/s) the concentration spike was diluted by the pre/post spike gas, such that the change in concentration was significantly less extreme. The CFD work showed that much of this was due to numerical smearing, and that in reality true molecular diffusion will produce a somewhat similar effect, but of much smaller magnitude.
		In spurs with very low velocity (0.02 m/s) the concentration spike was diluted by the pre/post spike gas, such that the change in concentration was significantly less extreme. Much of this was due to numerical smearing, and that in reality turbulent diffusion will produce a somewhat similar effect, but of much less magnitude.
viib	Square wave perturbation of oxygen concentration – Complex Network Model	For all branches except one, the concentration spike went through as a bell curve within circa 2.5 days. However, in the longest continuous branch (and lowest flow) the concentration spike was shuttled back and fore in the pipe as part of the diurnal swing. Although this is not a concern when the oxygen is added outside the boundaries of the pipe, it might become a concern (for controlling oxygen below say an upper bound of 1000 PPM) if oxygen were added inside the branch boundaries, particularly at a low flow node within the pipe, such that the concentration could potentially accumulate over time if oxygen were added at a fixed rate rather than in relation to the flow to achieve a certain concentration.
viii	How long / far will the oxygen last within the pipeline and at what repeat distance must additional oxygen be added to maintain the minimum requirement for both steady state and during no flow conditions.	See above. For a 250 PPM margin between the injected (500 PPM) vs the minimum oxygen concentration (250 PPM). At normal network velocities (>1 m/s) it would require >> 1000 kilometres of residence time to reduce the oxygen concentration to 250 PPM. For low flow rate spurs a very small improvement was seen in the oxygen concentration when the diurnal pressure variation was included in the model. No flow spurs (i.e. dead legs) are covered by the same residence time constraints listed above i.e. if the combination of low and no flow results in an average gas residence time of 30 days or more then the oxygen concentration is predicted to fall below the minimum concentration of 250 PPM.
ix	Will stratification of oxygen occur where the concentration can then build up outside of the safe limits?	Not predicted. It is important to note that the two-layer stratification predicted by the full CFD model does not constitute reseparation of oxygen from a fully mixed mixture. When fluid within the spur is fully mixed, there is no evidence to suggest that oxygen can separate out of the mixture for the time and length scales of interest to the gas network.

#	Issue	Conclusion / Observation

Notes:

1. It is important to consider the oxygen concentration of any intermediate blends of oxygen with hydrogen so as to minimise or preferably eliminate mixtures within the flammability limits. However, this may lead to longer mixing lengths or higher differential pressures (if static mixers are employed).
2. In the absence of sources/sinks of oxygen, the concentration is bounded by the concentration at the injection and the background concentration - 1000 ppm and 500 ppm respectively. There is a sink due to corrosion, so the concentration can fall below 500 ppm. Without a mechanism to act as a source (other than the injection itself), the concentration must be less than (or equal to) 1000 ppm. (The mixture will not unmix within the spur to form a higher concentration oxygen accumulation.)
3. Once mixed the mixture will not "unmix" to higher oxygen concentrations. Hence, not predicted to see oxygen concentration higher than that injected.

4.2 Appendix C – Focus areas in the plant

Table 4-2: Focus Areas

Area Number:	Design Intent:	P&ID Number(s):	Major Equipment Items:
1	Gaseous oxygen storage and treatment	ROSEN Diagrams	oxygen storage tank, dryer, heater
2	Oxygen injection process into hydrogen or hydrogen/gas stream, including control system	ROSEN Diagrams	Injection equipment, control system
3	HAZID Area 2 (liquid oxygen storage)	ROSEN Diagrams	Cryogenic liquid oxygen storage

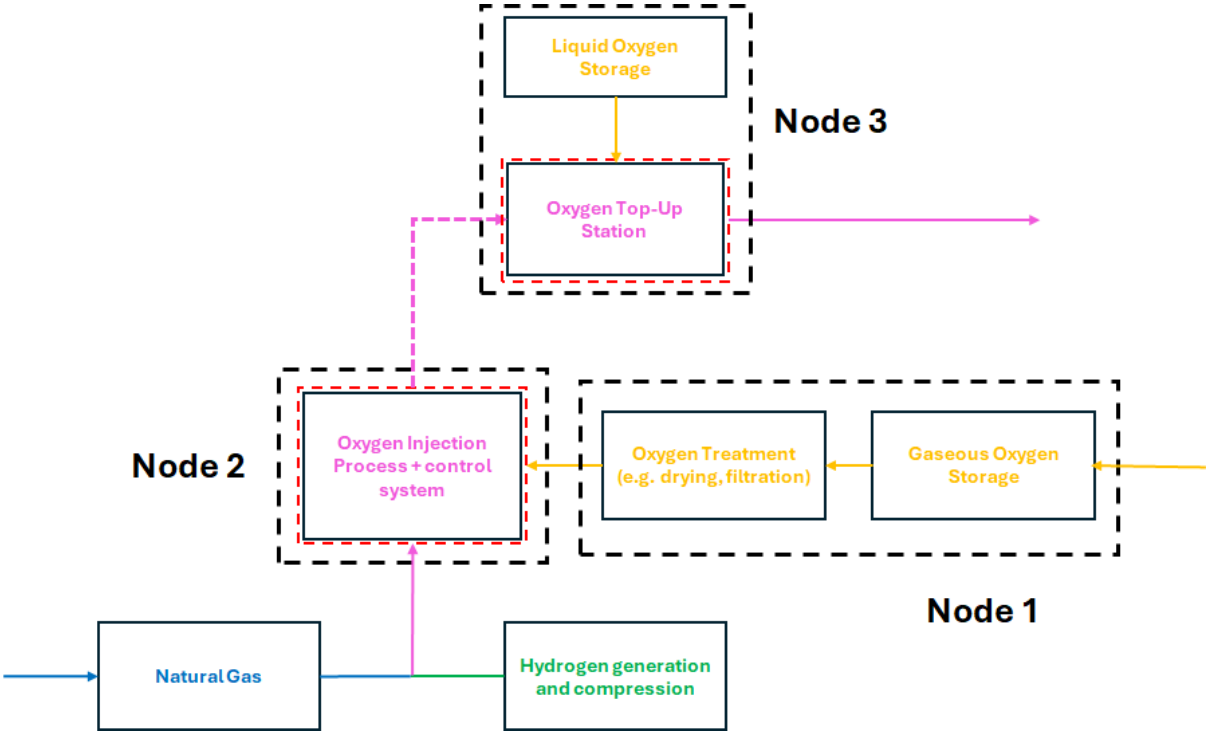

Figure 4-1: Simplified Process Flow Diagram with Focus areas shown

4.3 Appendix D – Threat review Table

Table 4-3 shows the Threat review table which was populated during the workshop.

Table 4-3: Threat Review Table

Node	Process Description	Ref.	Event	Hazardous Event	Consequence	Safeguards	Action	Workshop Notes
1	Gaseous Oxygen Storage and Treatment	1.01	Loss of containment	Loss of containment leading to oxygen accumulation and potential risk of asphyxiation.	High oxygen concentrations can have long term health impacts. 25% oxygen is damaging to health over long term exposure. oxygen is slightly heavier than air so pure oxygen would sink relative to air.	VSA2 and VF4 inspections for external corrosion. Pressure Systems Safety Regulations 2000 (PSSR) visual inspections as a baseline.	No agreed actions	Air vs oxygen density differences more pertinent to liquid oxygen than gas. Gas leak more likely to mix into air. NG have confined spaces in network for example around valve pits.
		1.02	Fire	Combustion of any oxygen which has accumulated as a result of a leak / upset process.	Enhanced risk of fire with higher concentrations of oxygen.	Prevention against fire by protecting against loss of containment so same safeguards are relevant as 1.01. Oils and greases on threads are prohibited on lines with oxygen.	No agreed actions	
		1.03	Explosion	Ignition in the presence of large oxygen source in a confined area.	Potential for extreme damage and potential loss of life if an explosion was to occur.	Prevention against fire by protecting against loss of containment so same safeguards are relevant as 1.01. Need to conduct confined space risk assessment to enter confined space areas.	No agreed actions	
		1.04	Spontaneous Failure	Oxygen plant defect which could fail leading to a loss of containment. Vibration could lead to a fatigue crack	Risk is release of oxygen and escalation to any of the points mentioned in 1.01-1.03.	System design would need to specify seals which are appropriate for pure oxygen. Certain parts of the network which are prone to vibration have a level of monitoring.	Review suitability of vibration monitoring in line with industry best practice (Energy Institute AVIFF guideline) as part of next phase of work.	
		1.05	Abnormal Operation	Upstream process upset leading to overpressure in oxygen plant.	Loss of containment of oxygen and associated risks as discussed above. Rupture leading to fragment missiles.	Design to include pressure monitoring. National Gas monitor the pressure of all equipment anyway so there shouldn't be a significant procedural change from existing system. Design to include relief valves as part of PSSR.	No agreed actions	Seems unlikely to have oxygen piped in if it's a remote facility, would need long lines to be installed. Liquid oxygen considered due to likely infeasibility of piping gaseous oxygen in which is covered in Node 3.

Node	Process Description	Ref.	Event	Hazardous Event	Consequence	Safeguards	Action	Workshop Notes
		1.06	Operating Modes	Hazards associated with not following correct start up /shutdown procedures. Need security of supply for the oxygen production source.	Interrupted oxygen supply not tolerable - leads to unprotected pipeline and potential for hydrogen induced cracking.	During planned outages would still potentially need a supply of oxygen. May need additional plan to produce oxygen or ship it in.	Consider Pressure Swing Adsorption (PSA) or membrane technologies for separating gases or oxygen. May not need as much compression duty if PSA is used as oxygen produced will be pressurised (around 10 bar). Consider the possibility of Injecting it straight into the pipeline without storing it. Could even use multiples types of oxygen generation.	If there are planned outages would still need to provide oxygen to the network. If oxygen is produced alongside hydrogen in an electrolysis process there will be more than enough oxygen to support hydrogen cracking inhibition as oxygen is produced at half the rate of hydrogen. If oxygen is not produced on site would need backup oxygen storage if supply is disrupted as the system can't tolerate not injecting oxygen due to hydrogen cracking threat. Would need kilometres of pipe volumes for a days oxygen supply even if compressed.
		1.07	Ignition Sources	Static electricity which could ignite in the presence of any impurities in the oxygen stream	Fire Explosion	Careful consideration to risks in construction and operation	Look into potential commissioning hazards regarding impurities in oxygen stream which could ignite.	Pure oxygen is not ignitable so leaks might not have as great of a consequence as in co-mingled section. However, metals can get hot enough to combust in pure oxygen. Could be other impurities in the oxygen stream which could ignite if there is a loss of containment.
		1.08	Natural Events	Damage associated with extreme weather.	Plant damage	Current risk management for gas pipelines considered appropriate in gaseous oxygen system.	No agreed actions	
		1.09	Impact Damage	Dropped objects as a result of a site lifting operation.	Plant damage	Current risk management for gas pipelines considered appropriate in gaseous oxygen system.	No agreed actions	
		1.10	Human Factors	Human error in maintenance and/or operation. Lack of training leading to incorrect application of safety procedures.	Gaseous oxygen release Insufficient oxygen injected	Tool box talks prior to maintenance/intervention. Operator training Assumed that control system is fully automated so human factors are minimal.	No agreed actions	Currently NG don't handle pipelines with different products. Would need to introduce more training/management to protect against human factors.
		1.11	Adjacent Plant/Buildings	Hazardous event with staff in adjacent site office nearby	Presence of oxygen has potential to escalate safety consequences.	To be further considered in next phase of the project when design is better defined.		
2	Oxygen Injection Process and Control System	2.01	Loss of containment	Through wall corrosion. Fatigue crack. Hydrogen embrittlement	Asphyxiation Toxicity Gas cloud	Oxygen detectors to detect leaks in critical areas. Could use secondary enclosures around equipment most likely to leak.	No agreed actions	Control system malfunction, high integrity duty standby facility required (SIL rated) Effective mixing of oxygen with hydrogen/methane. Availability of suitable oxygen measuring instruments. 500ppm is below the flammability limit so wouldn't be much different from the standard methane or hydrogen mixture.

Node	Process Description	Ref.	Event	Hazardous Event	Consequence	Safeguards	Action	Workshop Notes
								Need to make sure there are several levels of protection.
		2.02	Fire	Combustion of flammable gas mixtures which have accumulated as a result of loss of containment/accident.	Damage to surrounding equipment and possible escalation	Gas detection. Smoke/flame detection Effective gas mixing.	No agreed actions	Consequence of fire not significantly altered from current case but likelihood increased due to increased flammability of hydrogen and increase in likelihood of flammable gas formation.
		2.03	Explosion	Ignition of oxygen/flammable gas mixture in a confined area.	Damage to surrounding equipment and possible escalation	Blast protection if appropriate Inspection program	No agreed actions	NG have confined spaces in network for example around valve pits.
		2.04	Spontaneous Failure	Defects present in system. Flow induced vibration. Seals in valves and compressors compatibility with new gas composition. Oxygen will impact the aging of the seals, it can accelerate the ageing process. Failed compressor metal bearings generating high temperature.	Loss of containment as a result of worn hoses/seals. Any problem with failed metal compressor bearings could reach the autoignition temperature of the hydrogen oxygen mixture.	Effective inspection program. Condition monitoring program. Effective maintenance programme	Further investigation required on the effects of Oxygen on the aging of seals/hoses.	Some testing done by NG to investigate the impact of hydrogen on seal material but not the effect of oxygen. Even at [redacted]r, the partial pressure of the oxygen will be lower than the outside of the pipe due to the low oxygen concentration. Therefore, this is unlikely to increase the aging effect on the seals
		2.05	Abnormal Operation	No flow or reverse flow in main gas/hydrogen line. Over or under dosing gas with oxygen.	Underdosing of oxygen would a more critical safety issue due to hydrogen induced cracking. work done suggests there is an immediate risk of hydrogen induced cracking (HIC) if underdosing oxygen. If there was a significant overdose of oxygen into the gas the main problem would be a potential flammable mixture in the pipeline. At 500ppm oxygen we are magnitude of 10 below the flammability level. Worst case is a catastrophic failure of oxygen injection which could lead to flammable mixture in the network. This would only be an issue if there is an ignition source in the pipeline.	A high integrity control system with appropriate redundancy to be designed to mitigate operational risks. An emergency shutdown facility likely required e.g. Emergency safety valve (ESV). Adequate detection/alarms in place if the oxygen is added at too high of a concentration. Downstream analyser to check that the concentration is appropriate.	Further work needed to determine if there is an acceptable timeframe for over/under dosing oxygen in the line to clarify if a short duration out of spec oxygen dose is a concern? Look into mechanical properties and how long after oxygen underdose does HIC occur.	Could be a risk of reverse flow based on NG previous experiences.
		2.06	Operating Modes	Ensuring ppm oxygen is maintained in the gas mix during startup/shutdown. Gas locked in a section of the network for an extended period - oxygen consumed.	Insufficient oxygen in the system	Is there a tolerable period of time that low levels of oxygen in the gas mix is acceptable? Purge system (may not be possible)	Discussion suggested there might be a potential safeguard to lower the pressure in low flow scenarios but might not be viable needs further investigation. Find more detailed information on how often there are trips in the network.	Potentially parts of the network which may have no flow at times for inspection purposes. Even after a significant pressure reduction, the system will still likely be at a large enough pressure for HIC to be a concern. Hydrogen pipelines are designed to operate at 30%/40% of MAOP but since these were not designed for hydrogen they likely operate much closer to MAOP. Hydrogen producers will want to be producing a constant flow of hydrogen so they will want an increased pressure during low flow situations to increase hydrogen storage in the line.

Node	Process Description	Ref.	Event	Hazardous Event	Consequence	Safeguards	Action	Workshop Notes
		2.07	Human Factors	Human error in maintenance and/or operation. Lack of training leading to incorrect application of safety procedures.	Gas release Insufficient oxygen injected	Tool box talks prior to maintenance/intervention. Operator training Assumed that control system is fully automated so human factors are minimal.	No agreed actions	Currently NG don't handle pipelines with different products. Would need to introduce more training/management to protect against human factors.
		2.08	Ignition Sources	Static electricity which could ignite any potential gas leaks. Also think of ignition potential in the gas network.	Fire Explosion	Safety zones at key areas of the plant.	No agreed actions	Low ignition energies (see TOR), more important to avoid flammable mixtures.
		2.09	Natural Events	Damage associated with extreme weather.	Plant damage	Current risk management	Consider if these risks require reassessed.	Once the oxygen is mixed in the stream, natural events are unlikely to have much of an impact on current risk profile.
		2.10	Impact Damage	Dropped objects as a result of a site lifting operation.	Plant damage	Current risk management	No agreed actions	There wasn't deemed to be much of an additional risk by adding oxygen.
		2.11	Adjacent Plant/Buildings	Hazardous event with staff in adjacent site office nearby	Potential to lead to larger safety consequences.	Adequate separation distances from adjacent plants or buildings.	No agreed actions	Does the addition of oxygen increase this threat. More risk to adjacent buildings. Need to account for the presence of oxygen in the area. Could lead to escalation.
3	Liquid Oxygen Storage (Oxygen top-up station)	3.01	General Node 3 Discussion	Liquid oxygen is stored at low temperatures (-160C) and National Gas likely not used to managing the operation so could be significant threat. Pressure is normally not high if stored at low temperature. Pooling of liquid oxygen and vapor cloud formation if suffer a loss of containment.	Cold burns or frostbite upon contact with skin. Cold could lead to brittle fracture of materials. Large risk of escalation if oxygen is released, could have ignition of dust/debris/hydrogen leading to fire/explosion and potential catastrophic damage and/or loss of life.	Should have training and procedures in place to handle liquid oxygen safety. Control system safeguards to monitor and prevent loss of containment including pressure relief.	Further consider the viability of using liquid oxygen in future work.	For a station like [redacted] would need a lot of oxygen to be stored on site. Is it economic to introduce an oxygen pipeline from an oxygen source? Top up stations will be smaller with top up quantities easier to store as liquid. Potential significant financial impact if not required to inject the stored oxygen? Storage likely expensive due to the cold temperatures.

4.4 Appendix E – Workshop Minutes of Meeting

Table 4-4: Workshop Minutes of Meeting

Workshop Minutes of Meeting

Location & Date:	ROSEN Aberdeen + Online, 23rd July 2025
Meeting Subject:	Workshop (WP2)
Project Ref.	ROSEN Ref. 19878
Attendees:	**ROSEN** David Phelps, Gareth Smith, Justin Sheppard, Neil Gallon, Dave Anderson (chair), Karl Dahlgren (scribe) **National Gas** Robert Best, Kousseyla Hamadi, Justin George, Steven Johnstone, Simon Kidd, Matthew Hammond, Mick Jarvis, Daniel Knowles

Wednesday 23rd July

AGENDA

- Goal/objective of Workshop
- Introductions
- Process overview
- Node 2 Hazard open discussion
- Node 1 Hazard open discussion
- Node 3 Hazard open discussion (if time permits)

Introductory Discussion

Introductions made for ROSEN and National Gas Parties.

Steven Johnstone wanted to confirm if his comments on the workshop TOR were received, agreed we can talk through these at some point in the meeting if there is time.

This study is not compliant to the HAZID methodology. National Gas requested it to be called a high level risk assessment from now on.

David Phelps gives an introduction to the scope of the HAZID workshop. This work should be used to flush out major concerns which can be of use in later stages of this project as there is not currently a detailed process design to properly assess risks on.

Justin Sheppard gave an overview of the phases of the project using previous slideshow.

Dave Anderson gave an overview of the block diagram sketches and worksheet used for the workshop.

Discussion about if the introduction of oxygen to the stream has the same risks/hazards as the introduction of hydrogen to the methane mix. National Gas have done some work on the hydrogen side and found that stratification was the main concern. Also when injecting biomethane with oxygen, the oxygen was distributed in the main stream within a couple meters.

Robert Best comfortable with the current approach, no reason why it cant be adapted to be more aligned to the HAZID methodology later at the conceptual design stage.

National Gas question: Are we assuming there are no other inhibitors that can be used? Were there other inhibitors which don't involve adding oxygen to a flammable gas? – Rosen confirmed this was part of phase 1 work. The scope of this workshop is specifically for oxygen as laid out in the terms of reference document.

Node 2 Discussion

	Confirmed with everyone that Node 2 is concerned with the co-mingled gas stream. Worksheet has been partially populated but looking for National Gas comments. Trying to get a homogeneous oxygen mixture at the low oxygen concentration is difficult. Might have to premix before adding to main stream so would be above 500ppm but still below flammability level, this could increase risk. **National Gas current network oxygen limits:** Above 38 bar they have a 0.2% limit on oxygen but typically levels are much lower than that. Up to 1% oxygen with biomethane. This is not a materials/integrity reason its more for end users. ROSEN Question: During existing safety work regarding oxygen injection, did they assume there was any oxygen already in the methane stream? – National Gas response: They didn't consider oxygen in the pipeline as a risk. **Metering:** Does the metering system or EOS needing to be modified if there is oxygen in the system [Action 1]. There is an allowable range for metering system: 500ppm likely will not be outwith the range, but regions operating towards the upper limit of 1000ppm could be a concern. **Biomethane:** If biomethane (and associated oxygen) is present, could oxygen concentrations be even higher than 1000ppm? ROSEN Question: Is there biomethane already injected in the network? - Biomethane is in one part of the network. Biomethane that is added is at a very low concentration so likely has a very little effect on oxygen levels. **Injection Process:** National Gas Question: Would oxygen be directly injected into the pipeline or the premixing in a previous chamber? - If try to mix two very different flowrates its difficult to get a homogeneous mixture so there are some benefits to a premixed system but there are greater risks as it gets closer to the flammability limit of the mixture. This would also lead to more process equipment being on site and therefore more expense. Look more into this outside of the meeting [Action 2]. National Gas Question: Do we know what injection process will be used? Would it be retractable probes which could bring rise to leaks? - High level view was that mixing would be through a tee piece. Pipe length for homogeneous mixture would be several diameters not very different to a normal above ground installation. Static mixer would bring about complications around pigging so might need to be in some sort of side stream or bypass loop [Action 3].
2.01	**Loss of containment:** Here we are considering the impact of introduction of oxygen into the fuel mix. National Gas Question: Does the loss of containment guideword cover leaks through fittings/seals? - this covered in 'Spontaneous Failure' guideword. National Gas Question: are we looking at the loss of containment risks which are different for the newly proposed system compared to general methane pipelines? – ROSEN Response: that is correct. 500ppm is below the flammability limit so wouldn't be much different from the standard methane or hydrogen mixture. So we aren't always considering a flammable mixture. But would need to consider the risk of overdosing oxygen in the pipeline. National Gas: we should focus on the actual injection of oxygen process Safeguards: main safeguard would be adequate detection/alarms in place if the oxygen is added at too high of a concentration. Downstream analyser to check that the concentration is appropriate. Reference made back to how there isn't a design in place so difficult to accurately determine risk. The design of the oxygen injection system would need to be a high integrity system with several levels of protection. Consequences: At what point is there a risk of internal pipeline combustion risks (much higher than the operating levels of 500-1000 ppm). This is covered in the terms of reference document.

	After its been mixed successfully, the loss of containment doesn't pose many other risks than with their standard gas operation. National Gas Question: Could leaking gas separate to create problems? – ROSEN Response: No, this has been assessed in the phase 2 study. Once the oxygen was mixed there is not a risk of the oxygen being unmixed. National Gas Question: Could hydrogen leak out preferentially over other molecules? – ROSEN Response: Due to the smaller molecule size of hydrogen in comparison to natural gas (CH4), there is a chance a pressure system that is leak-tight in natural gas service could leak in hydrogen service at flange joints or non-welded joints. However, there are some materials which hydrogen can preferentially diffuse through. Palladium is an example of this. Therefore, there is a chance that hydrogen can leak through any palladium components which are present in the network. This is considered extremely unlikely due to palladium being a rarely used material but more investigation regarding potential hydrogen leaks is required [Action 4]. To date, oxygen concentrations have been considered in relation to the total pressure in the system and not the partial pressure of hydrogen. Significantly less oxygen may be required if the oxygen is dosed based on the partial pressure of hydrogen in a natural gas and hydrogen blend. This is being considered in Phase 3 of this project but further work will be required to see if a homogeneous mixture can be achieved with lower oxygen concentrations [Action 5].
2.02	No comments.
2.03	No comments.
2.04	**Spontaneous Failure (Seals):** National Gas have done some testing to see the impact of hydrogen on the seals but not oxygen. Oxygen can accelerate the rate of aging of the seals. Oxygen partial pressure is an important parameter for investigating this. Even at 70 bar, the partial pressure of the oxygen will be lower than the outside of the pipe due to the low oxygen concentration. Therefore, this is unlikely to increase the aging effect on the seals but further investigation on this matter is required to validate this [Action 6]. Effect of hydrogen on fittings/seals - confirm this has already been assessed as part of other studies [Action 7]. Any problem with failed compressor bearings could reach the autoignition temperature of the hydrogen oxygen mixture and ignite any potential flammable gas leaks [Action 8].
2.05	**Abnormal flow effects:** The scenario of an overdose of oxygen needs to be carefully considered in the next stage of the project. National Gas have had previous injection problems with the control of the odorant systems but an engineering solution has been developed for this. 5 ppm of odorant was used. There was an outage and it wasn't isolated correctly. Odorisation is done at distribution level so its not as issue with transmission level. The learning points was around flow control and these should be considered in future oxygen injection work. Oxygen will only introduced at transmission level. Some parts of the network don't require odorant injection. National Gas can provide some documents about odorization [Action 9]. Could be a risk of reverse flow based on NG previous experiences. This could lead to an over injection of oxygen into the line, an appropriate control system would need to be in place to manage this. This needs to be carefully considered in future scopes [Action 10]. Want to expand the consequences on overdosing with oxygen. Timeframe of over/under dosing oxygen in the line? Is a small blip a concern? The control system is the safeguard here. The need for an emergency shutdown situation/ESV function needs to be carefully considered in future scopes. This is definitely something that is needed to provide an additional layer of protection [Action 11]. Discussions regarding over and under dosing oxygen should be separated. **Underdosing:** Underdosing oxygen would a more critical safety issue due to the risk of hydrogen induced cracking. There is limited scientific literature detailing the mechanisms associated with hydrogen cracking inhibition using oxygen but there seems to be an immediate risk of hydrogen induced cracking if oxygen is acutely underdosed. Some

	alarming studies shows embrittlement in a matter of minutes therefore there could be immediate risk. Therefore the inhibition effect will be assumed to require a constant supply of oxygen in the hydrogen. **Overdosing:** If there was a significant overdose of oxygen, the main problem could be a potential flammable mixture in the pipeline. Other thing would be the consumer side where you would have a reduce calorific level of the gas. Overdosing is less of a concern as the operating conditions are a magnitude of ten below the flammability limits of combustion. However, a catastrophic failure of oxygen injection system leading to a large oxygen overdose could lead to flammable mixture. This would only be an issue if there is an ignition source in the pipeline but the ignition energy of hydrogen mixtures are very low so any flammable mixtures should be avoided. These threats should be taken forward to the next phase of the project [Action 12].
2.06	**Operating modes:** ROSEN Question: How often are there trips in the network? – no definitive answer [Action 13]. There is potential that parts of the network may have no flow at times for inspection purposes. Pipelines specifically designed for hydrogen operate at 30% or 40% of MAOP. **Reduce Pressure as a safeguard?** Low flow situation: would the system pressure be dropped during low flow operations? - Not typically. Discussion around potentially reducing the consumption of oxygen by reducing the pipeline pressure. The lower pipeline pressure would reduce the chance of fracture in the event of a reduced oxygen concentration. This could be a potential safeguard? How would this work in terms of control system or physical implementation? Might be difficult to practically achieve. According to National Gas low flow situations are associated with increased pressures so this may not be a viable safeguard if it would change the National Gas procedures drastically. Even at a reduced pressure there would still be an integrity risk at lower oxygen levels. More work into looking into this is required, dropping by 15 bar for example might not be significant in terms of integrity risks. Hydrogen producers will want a steady state process so for hydrogen storage will want to increase pressure during low flow. Overall, this safeguard seems impractical but should be investigated [Action 14].
2.07	**Human Factors:** Could human factors increase the risk associated with the oxygen injection. Assume the control system would be fully automated. Not any further comments.
2.08	**Ignition sources:** Rotating equipment like compressors could fail leading to autoignition of combustible gases. Safeguards would be to keep the 500ppm concentration to avoid flammable mixtures. Not any further comments.
2.09	**Natural Events:** ROSEN Question: Is this assessed as part of the network's typical safety work anyway? – no definitive response. Once the gases are mixed, cant see any natural events having much of an effect. Not any further comments.
2.10	**Impact Damage:** Not any significant change to the risk by adding oxygen. Not any further comments.
2.11	No comments.

2.12	No comments.
2.13	No comments.
1	**Node 1 Discussion**

Oxygen production process:
Possible options are:

- Oxygen produced from water alongside the hydrogen if electrolysis.
- membrane or PSA (Pressure Swing Adsorption) separation of oxygen from air.

Treatment:
Pure hydrogen system could premix the oxygen at low pressure and compress and dry everything together.

If looking at a system where oxygen is added to natural gas likely need to treat oxygen separately.

Might be too early of a stage to consider the risks with the treatment, might be better to assess the risks at a later stage once the design is more established [Action 15].

1.01	**Loss of containment:** Will any leaking oxygen just mix into the air? This was decided to be more of a concern with liquid oxygen. ROSEN Question: Are there any contained/confined areas buildings in the network where you could get a high oxygen concentration if there was a loss of containment? - They do have confined spaces around the network around valve pits. Would have confined space risk assessment to enter those areas (safeguard). Less of a concern for gaseous oxygen in comparison to liquid oxygen but still a consideration. To be considered at next stage of the project [Action 16]. **Asphyxiation:** 25% oxygen is toxic if exposed long term. Medical grade oxygen is a higher concentration but for shorter durations.
1.02	**Fire:** Oils and greases on threads are prohibited on lines with oxygen. Enhanced risk of fire with higher concentrations of oxygen. Safeguards would be leak prevention through inspections. They have VSA2 and VF4 inspections for external corrosion. National Gas do PSSR inspections as a baseline visual inspection. ROSEN Question: Does National Gas do any vibration testing? - Certain parts of the network which are prone to vibration have a level of monitoring.
1.03	**Explosion**: There are some scenarios which could lead to explosion. These should be further considered once design is more mature [Action 17].
1.04	**Spontaneous Failure:** Risk is a release of oxygen. Seals/hoses impacts in pure oxygen? Would need seals which are appropriate for pure oxygen. Review suitability of vibration monitoring in line with industry best practice (Energy Institute AVIFF guideline) as part of next phase of work [Action 18].
1.05	**Abnormal Operation:** With the big quantities required, unsure if oxygen supply is feasible if there are no oxygen pipelines. Seems unlikely to have oxygen piped in if it's a remote facility, this would require long lines to be installed. National Gas don't currently use oxygen on their facilities therefore needs careful consideration [Action 19]. Overpressure scenario is a risk if storing oxygen need to monitor pressures. Need to monitor pressure of all equipment anyway so this wouldn't be any different. Idea of liquid oxygen use was brought up because it is likely not feasible to pipe in gaseous oxygen to remote top up facilities.

	Safeguard: Relief valves as part of the PSSR.
1.06	**Operating modes:** Need security of supply for the oxygen production source, if there are planned outages in oxygen source would still need to provide oxygen to the network due to hydrogen cracking risk. Likely would need a backup oxygen supply or ship it in. During electrolysis of water oxygen is produced at half the rate of hydrogen. Therefore, the system can rely on the oxygen generated as part of the electrolysis plant to be sufficient in relation to the hydrogen throughput. Would need kilometres of pipe needed for a day's oxygen supply, even if compressed. Could membrane technologies be used to produce oxygen? Inject it straight into the pipeline without storing it? Consider Pressure Swing Adsorption (PSA) or membrane technologies for separating gases or oxygen. May not need as much compression duty if PSA is used as oxygen produced will be pressurised (around 10 bar) [Action 20]. Consider the possibility of injecting oxygen straight into the pipeline without storing it [Action 21]. Would still need compression? Could even use multiple types of oxygen generation in tandem.
1.07	**Ignition Sources:** Pure oxygen is not ignitable, it is an oxidiser. Metals can get hot enough to self combust in pure oxygen. Other impurities in the oxygen stream that can catch fire? Commissioning hazard [Action 22].
1.08	No comments.
1.09	No comments.
1.10	**Human factors:** Right now National Gas don't handle different pipelines with different gases. Would need to introduce training/management procedures to protect against human factors if starting to operate with oxygen.
1.11	No comments.
1.12	**Adjacent Plant/Buildings:** Would likely be more risk to adjacent buildings. Need to account for the presence of oxygen in the surround area. Could escalate an incident if oxygen sources are nearby. No further comments.
1.13	No comments.
3	**Node 3 Discussion**

Liquid supply of oxygen was deemed to be the more feasible option in a National Gas cost benefit analysis meeting over gaseous oxygen supply.

Oxygen Storage:
For a station like [redacted] would need a lot of oxygen to be stored on site. Is it economic to introduce an oxygen pipeline from an oxygen source?

Top up stations will be smaller with top up quantities easier to store as liquid.

Liquid oxygen is stored at extremely low temperatures (-160C), National Gas likely not used to managing the operation so could be significant threat.

Long term exposure of workforce to oxygen, long term health risks? Want to guard against any leaks of oxygen. However, the greater hazard would be the fire risk.

Rupture of tank and projectiles would be a major hazard but tank likely stored at atmospheric pressure so maybe not as great of a risk as gaseous storage at pressure.

Escalation is a big risk if have a large release of oxygen e.g. fire/explosion.

Potential significant financial impact if not required to inject the stored oxygen? Storage likely expensive due to the cold temperatures.

Need to further consider the viability of using liquid oxygen option in future work [Action 23].

4 General Discussion

This section will contain discussion which does not directly relate to any of the nodes.

Current State of Line:
Safety risks will likely be affected by the current state of the line. Investigate current state of the line. Any defects present that will alter safety considerations of new oxygen system should be known [Action 24].

Low Ground Leakage:
National Gas Question: If there is some low ground leakage, are there any additional risks (external corrosion) of the mixture under the wrapping of the pipeline? - Only possible risk would be where there is oxygen present with the odorant but this is only at the low pressure distribution level. Gareth cant think of any issues associated with oxygen and pipe covers. Air has 20% oxygen anyway so risks are more relevant to the inside the pipeline as they are typically not subjected to oxygen. If the pipe is dry internally it is not considered to be much of a risk.

Hydrogen Sulphide:
ROSEN don't consider there will be increased risk of hydrogen sulphide formation due to the transfer of hydrogen through the network. There is a risk of this at the distribution level due to odorization. This should be further investigated as part of next phase of work [Action 25].

Oxygen Consumption Rates:
The consumption of oxygen is one of the main uncertainties with this work, ROSEN could only made assumptions in previous calcs investigating this. Could be that the inhibition effect consumes oxygen in addition to the oxygen consumed by the pipe wall. This is the main unknown to determine in order to adequately determine how top up stations should be distributed across the network. Top up may not even be required at all as there is a possibility that oxygen consumption is negligible.

There could be other components in the system which may consume oxygen. This shouldn't be an issue with the typical components in the gas. But there may be some unknown low level components which should be investigated. Would need to do field tests with a experimental model [Action 26].

Oxygen depletion rates were brought up by National Gas but ROSEN explained that phase 2 work looked into the time taken for oxygen to be depleted based on various consumption rates.

Gas turbine fuel:
Fuel for gas turbines for compression: Will the oxygen have an affect on the fuel used for gas turbines. Some users have expressed that concern. The 500ppm wont have any large concern but will slightly lower the calorific value of the fuel [Action 27].

ROSEN Question: If National Gas allow 0.2% oxygen already, have they already considered the compressor effect? - National Gas response: this is not likely the case. National Gas operate far below the 0.2%/1% limits, closer to 0.02% (200 ppm) which is the European specification.

Cracking risk at lower hydrogen volumes:
Even at low volumes of hydrogen need to assume there is the same risk of cracking as pure hydrogen. Might be a slightly reduced hydrogen cracking risk at 2-5% hydrogen than at 100% hydrogen but there is likely only a minimal difference so assume blends are as bad as 100%.

Oxygen Inhibition Mechanism:
Only have ideas on how the oxygen inhibits, not an accepted mechanism. Either oxygen immediately bonds to the surface creating an oxide scale which acts as a barrier, delaying it. Second is that the oxygen absorbs preferentially, which stops the hydrogen getting in those sites.

Until proven otherwise, it should be assumed 250ppm is to be used for all grades of hydrogen (hydrogen and pressure effects to be validated).

Further work required to see how much less oxygen would be required if using a blend of hydrogen [Action 28].

National Gas Question: typical spacing on the injection into the system? - Depends so much on the consumption rate.

We haven't got a lowest possible flow case to work out. So the top up stages may not even be required but this is yet to be proved.

Need pilot test program to physically test how everything would come together (injection storage top up, etc) [Action 29].

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Need pilot test program to physically test how everything would come together (injection storage top up, etc) [Action 29].

APPENDIX D – WP2: INTEGRITY MANAGEMENT

OXYGEN INHIBITION FEASIBILITY
ROSEN POSITION

National Gas Oxygen Inhibition

ROSEN
empowered by technology

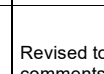
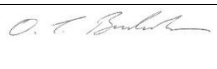
1	22/08/2025	19	Revised to address client comments.			
				Neil Gallon	Ollie Burkinshaw	David Phelps
0	02/07/2025	18	First Issue	Neil Gallon	Angel Izquierdo Sanchez	Ollie Burkinshaw
Rev.	**Date**	**Pages**	**Description**	**Prepared by**	**Reviewed by**	**Approved by**

TABLE OF CONTENTS

1 INTRODUCTION

ROSEN have recently completed work for National Gas looking at the inhibition of hydrogen embrittlement effects in pipeline steels, this work was performed under National Gas project number NIA_NGGT0183. The main technical deliverables of this work were a technical review and benchmarking report which looked at available literature on the mechanisms of inhibition (primarily by oxygen) and a test programme which investigated these effects in the laboratory.

The ROSEN report [1] concluded that, based on the laboratory results, oxygen was an effective inhibitor of hydrogen embrittlement at levels of 250 ppm or greater. Additional work was recommended looking at the time-dependence of this inhibition effect, and its performance under realistic loading scenarios. In addition a couple of anomalous results were noted during testing whereby, if testing was performed consecutively in the same environment without refreshing the test gas, the final test in the sequence appeared to show significantly worse results than the initial test. The reasons behind this were unclear although hypotheses were presented looking at potential stratification, consumption of the oxygen or a time-dependent effect.

Since the completion of this work, SANDIA National Laboratories have published various webinars and reports questioning the long-term efficacy of oxygen inhibition [2], [3]. National Gas have requested that ROSEN review the SANDIA work and recommend whether oxygen inhibition remains a viable technology to mitigate against the long term effects of hydrogen embrittlement.

In addition National Gas have posed some specific questions regarding project scope prioritisation for future work. The questions related to integrity management are addressed in this report.

2 SUMMARY OF SANDIA WORK

The SANDIA work poses two potential challenges to the mechanisms that underpin oxygen inhibition:

1. Short term effects of oxygen observed in laboratory tests in hydrogen gas may not translate to long-term benefits over the life of the component
2. Steel surfaces are 'dirty' and/or native oxides will prevent absorption thereby removing risk of hydrogen embrittlement.

2.1 Time Dependency

With respect to the time dependence, SANDIA performed some work using high strength steels (SA372 Grades J and L, and X100) subject to an instrumented ASTM E1681 constant displacement test at a very high hydrogen pressure (1030 bar) in nominally pure hydrogen and with additions of 100 and 1000 ppm oxygen. For all three materials tested, the fracture arrest threshold (K_{tha}) was reported to be similar for all three oxygen levels, although the "incubation time", the time required for the crack to start to extend, was longer when oxygen was present.

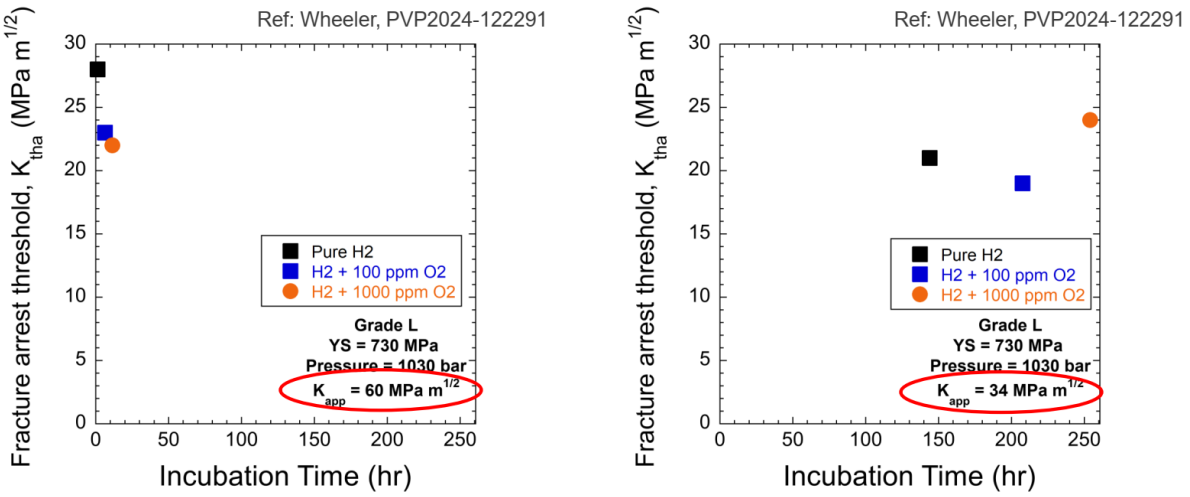


Figure 1 - Oxygen Inhibition Effects on SA372 Grade L – from [2]

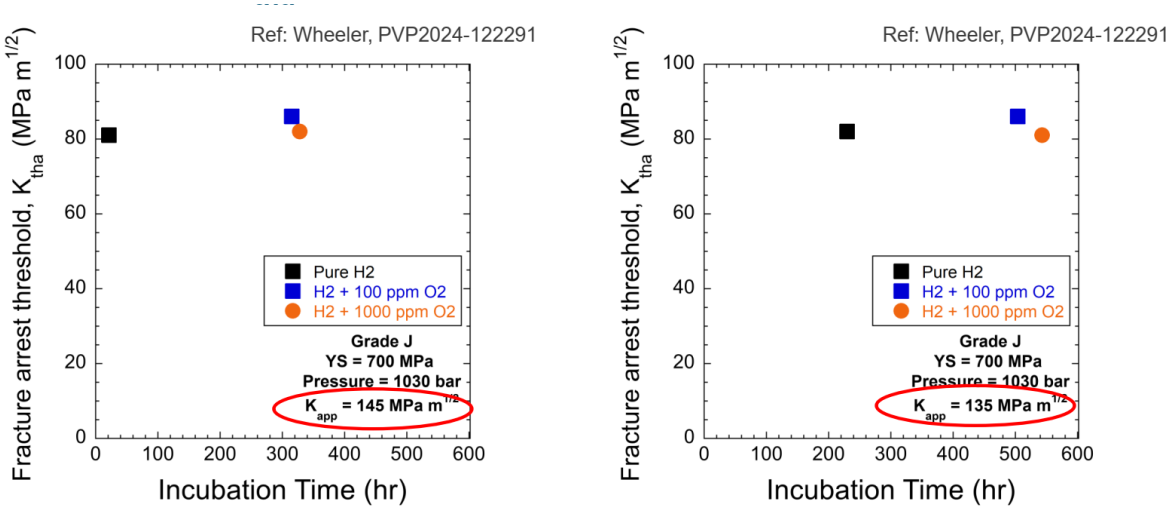


Figure 2 - Oxygen Inhibition Effects on SA372 Grade J – from [2]

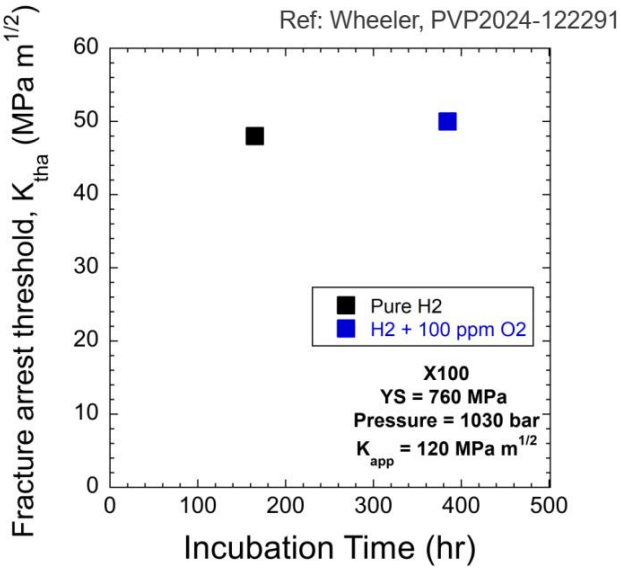


Figure 3 - Oxygen Inhibition Effects on X100 – from [2]

Based on these results SANDIA suggest that oxygen does not change the fracture resistance of steel, but only delays the onset of cracking.

2.2 Influence of Oxides

SANDIA have performed some sub-scale pipe testing using NPS 2 Sch 40 pipe (nominal 60.3 mm OD, 3.9 mm WT). The test involved introducing EDM notches of a nominal depth of 2 mm to both the internal and external pipe surfaces, then pressure cycling the pipes to failure in both hydrogen and nitrogen environments. The pipe surfaces were not modified except for the introduction of the EDM notch, and therefore SANDIA postulate that, for the external notch, the internal oxide layer should be present. The

results of the tests showed that the number of cycles to failure was reduced significantly for both internal and external notches in hydrogen compared to nitrogen.

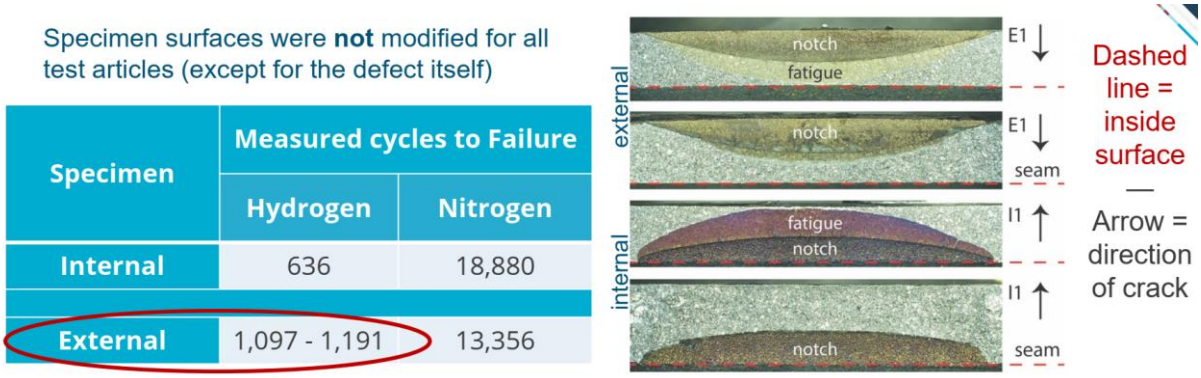


Figure 4 - Sub-Scale Pipe Fatigue Testing – From [2]

SANDIA also presented some X-ray Photoelectron Spectroscopy (XPS) results which claimed to demonstrate that oxides formed on clean X65 steel surfaces even in a high vacuum.

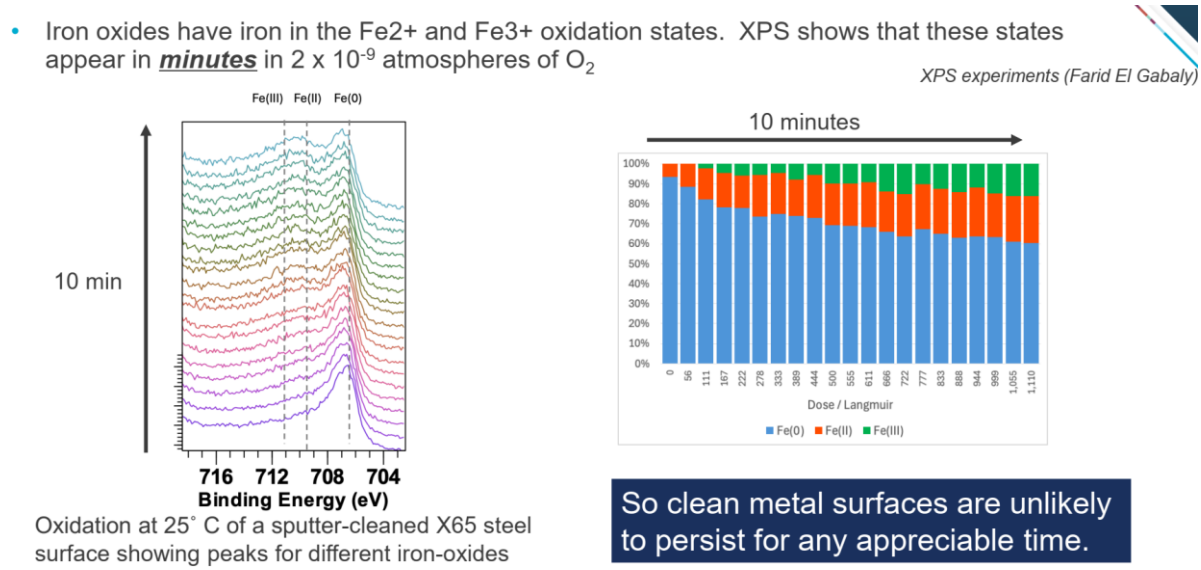


Figure 5 - XPS Results from [2]

2.3 Influence of Oxygen on Test Results

Related to the potential time dependence of oxygen inhibition, there is significant ongoing research looking at rate effects in testing and the potential interaction between trace levels of oxygen and the required rate for testing in hydrogen. This potential time dependence is summarised in Figure 6.

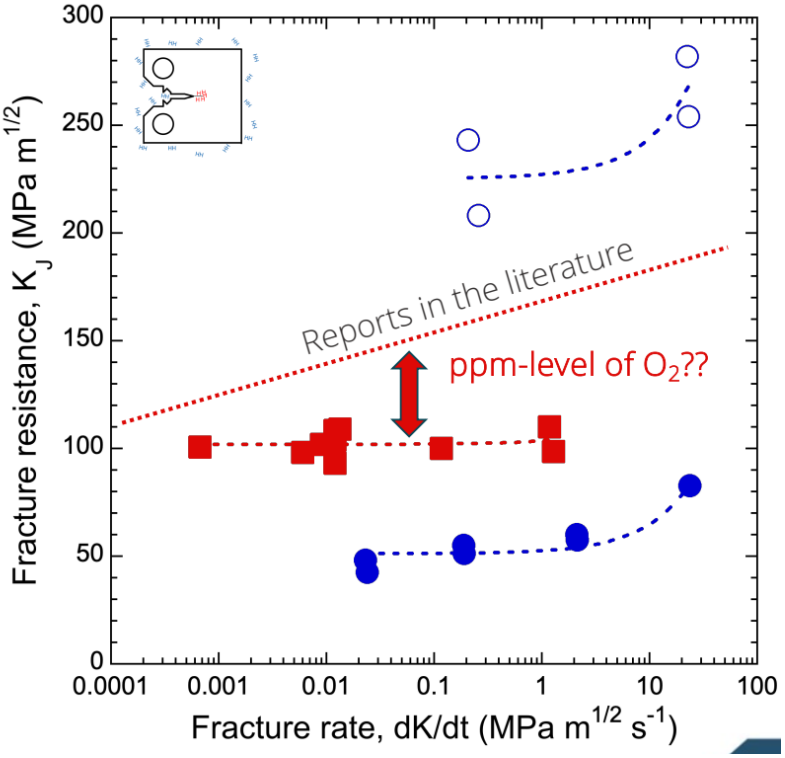


Figure 6 - Potential Interaction Between Oxygen and Testing Speed from [3]

The hypothesis is that hydrogen embrittlement itself is effectively rate-independent over the range of testing rates characterised (~0.001 - ~2 MPa.$m^{1/2}$.s^{-1}), however trace amounts of oxygen can introduce an apparent rate sensitivity due to the time-dependence inherent in absorption through the oxide layer.

This hypothesis has not been fully explored, but is gaining increasing attention within the industry with the latest draft edition of ANSI/CSA CHMC-1 [4] considering allowing faster testing speeds but with tighter controls (~0.1 ppm maximum) on oxygen content. There is no consensus on the implications of this, for example the DVGW SyWeSt dataset [5] reported neither testing rate nor oxygen content so cannot be demonstrated to have complied with the latest draft CHMC-1, however DVGW codes still reference this dataset as being suitable for use in engineering assessments.

3 DISCUSSION

3.1 Time Dependency

The SANDIA work demonstrates that, for the materials they have tested, there is a clear time dependence in terms of time for the fracture arrest threshold (K_{tha}) to manifest. The implications of these results for real pipes are discussed below.

The SANDIA results demonstrate that small amounts of oxygen in high pressure hydrogen gas can delay the onset of K_{tha} by some hundreds of hours, however there is no conclusive proof that this is due to a delayed incubation time. In theory the delay could have been due to oxygen consumption or stratification within the test environment, post-test measurements of the oxygen content are not reported.

It is noted that neither the materials nor the pressure of the tests are representative of pipeline steels, the materials were specifically chosen to support test validity (linear elastic fracture mechanics) while the test pressure was presumably chosen to ensure the tests finished in a reasonable time. For the K applied, real pipeline materials may be in the elastic-plastic region with the mechanism of fracture therefore being different. The impact of oxygen on this different mechanism at lower test pressures can therefore be reasonably extrapolated to be similar, but has not been proven. In particular, the extrapolation may not be linear and it is conceivable that, even if oxygen does just delay rather than stop hydrogen embrittlement, this delay may be long enough in a real pipeline to significantly extend the pipeline's expected lifetime.

As discussed in ROSEN's original technical literature review [6], there are various different measurands which can be chosen to represent "fracture toughness". The ROSEN review concluded that K_{THi} (crack extension under rising displacement) was more conservative and representative than K_{THa} (fracture arrest threshold). The relative effects of oxygen on K_{tha} and K_{THi} therefore need to be considered. Based on the results, it appears that small amounts of oxygen in high pressure hydrogen gas can delay the onset of K_{tha} by some hundreds of hours, whereas even the slowest rising displacement fracture toughness tests to measure K_{THi} will last for a shorter period of time, and are thought to represent the "true" hydrogen affected material toughness. The quantitative relationship between oxygen, time and fracture toughness is therefore unclear.

The test data presented is restricted to K_{THi}, and is therefore representative of a pre-existing crack subject to a constant displacement. No test data is available to demonstrate the effect of oxygen on crack initiation, and this presentation does not address the behaviour of the crack post-initiation. The ROSEN test data presented as part of this project indicated that oxygen had an effect on the slope of the J-R curve as well as the reported $KJ_{0.2}$. Although current assessment methods do not generally take account of the full J-R curve, if oxygen does have an effect on curve shape then this will increase the resilience and durability of a real pipe and may enable higher fracture toughness assumptions to be made in engineering assessments.

3.2 Influence of Oxides

The statement by SANDIA that the sub-scale tests prove that oxide scales do not stop hydrogen embrittlement is not considered to be proven. For the tests with the external notches, the remaining ligament below the notch would only be ~1.9 mm (3.9 mm WT with a 2 mm notch). When heavily fatigue cycled, it is possible if not probable that this entire ligament would have been plasticised. If this was the case, then any previous oxide scale on the internal pipe surface would likely have been disrupted

exposing bare metal surface. The inference that the subscale test demonstrated that oxide scale was largely ineffective in stopping hydrogen absorption is therefore not considered robust.

The original ROSEN literature review [6] concluded that the main inhibition mechanism was due to a layer of chemisorbed oxygen on the steel surface, although it was also recognised that some sources stated that oxides could form. Previous work by SANDIA referenced in the original ROSEN report determined using a Density Function Theory (DFT) model that “much fewer” than six monolayers of oxygen were necessary to block chemisorption of hydrogen, however the recent SANDIA work has also used DFT to demonstrate that hydrogen can dissociate on oxide surfaces and diffuse into the bulk steel. It is therefore considered that the new SANDIA modelling work does not conclusively invalidate the findings of the original ROSEN review. The new work appears to demonstrate that a coherent oxide layer cannot be relied upon to act as a permanent barrier to hydrogen absorption although the migration barrier is significantly greater than for a clean surface, which would be expected to result in slower hydrogen uptake. If this retardation is significant enough, then it is possible that the pipeline’s expected lifetime could be extended. The latest SANDIA work does not explicitly address chemisorbed oxygen, and can be read to imply that there is no chemisorbed oxygen, only oxide. This statement contradicts earlier research cited in [6] and would benefit from greater investigation.

In laboratory tests (including the ones reported by SANDIA) the test specimens are normally entirely immersed in gaseous hydrogen, there is therefore no concentration gradient of flux between surfaces. In a real pipe, gaseous hydrogen will only be present at the internal surface and could escape at the external surface. This may lead to an equilibrium situation with a higher concentration of hydrogen at the internal surface and a lower concentration at the external surface. An inhibitor that affects kinetics of hydrogen ingress at the internal surface could therefore permanently shift the equilibrium concentration of hydrogen in the lattice. The implications of specimen geometry compared to pipe geometry, any resulting effects on concentration gradient or equilibrium hydrogen concentration are therefore unclear.

3.3 Integrity Management Project Scope Prioritisation

Specific topics raised by National Gas with respect to prioritising future integrity management work, and the ROSEN view on these topics, are discussed below.

3.3.1 Effectiveness of Inhibition Over Industrially Relevant Timescales

This topic is discussed in Section 3.1. In summary, the SANDIA work does not appear to be definitive enough to demonstrate the effectiveness or otherwise of inhibition over an industrially relevant timescale (assumed to be years or decades).

3.3.2 Applicability of SANDIA Work to Fatigue Crack Growth

As discussed in Section 3.1. the test data provided by SANDIA refers only to K_{THi}, and is therefore representative of a pre-existing crack subject to a ‘static’ constant displacement. It follows that there is no new empirical data regarding the time dependence on fatigue crack growth rate (FCGR) since the mechanisms and kinetic factors involved with fatigue are fundamentally different from fracture under static loads.

Some potential implications can, however, be considered based on extrapolation and interpretation from the mechanistic point of view. The SANDIA argument is that the presence of oxide scale only delays the dissociation and absorption of hydrogen. The implication of this for fatigue crack growth is unclear, since fatigue is by definition a dynamic effect. In a fatigue scenario, there will be multiple kinetic mechanisms happening and competing. Mechanically the crack will be extending, exposing fresh metal surface. As

this bare metal surface is exposed, hydrogen will be dissociating at the surface however simultaneously fresh oxides will be formed and oxygen will potentially be chemisorbed (see Section 3.2 for discussion of chemisorption).

At a minimum, the formation of oxide scales will slow the rate of hydrogen embrittlement, the overall effect of this will be dependent on the different kinetic reactions and rates however a qualitative argument can be made that FCGR will be slowed in the presence of oxygen considering cyclic loading frequencies of the order of hours or days, if considering the mechanism of hydrogen embrittlement to be dominated by the availability of hydrogen from the environment (pipe bore) to adsorb on the crack surfaces and diffuse to the crack tip region.

An unknown factor is the relative importance of bulk hydrogen concentration in the steel lattice, compared to that diffusing from crack surfaces to the crack tip region, and the time effects suggested by the SANDIA data would affect this. Some data exists suggesting that availability of hydrogen to adsorb from the gaseous environment drives fatigue crack growth, for example as included in [6] showing that the growth rate for an actively growing fatigue crack in hydrogen is immediately suppressed by the introduction of oxygen, and immediately accelerates again on removal of the oxygen. However, this data did not purposefully explore pre-exposure to pure hydrogen for several hundreds of hours such as in the SANDIA data, so does not rule out time effects.

As part of ROSEN's original scope of work frequency scans were performed to quantify any dependence of FCGR on test frequency as reported in [1]. As discussed in the earlier ROSEN report, results of the frequency scans were dependent on the K_{max} applied, however for a K_{max} of 38 ksi.in$^{1/2}$ the FCGR appeared to be relatively frequency independent below a test frequency of 0.1 Hz. The conclusion made in [1] was that a test frequency of 0.1 Hz was sufficiently slow to demonstrate the "true" oxygen affected FCGR, and therefore there were no additional time dependencies. This conclusion remains valid based on the test data presented, however it should be noted that the minimum test frequency was 0.0001 Hz (1 cycle per 10,000 seconds, which equates to ~8 cycles per day), which may not be representative of the diurnal or longer swings typically expected in a gas pipeline.

It should also be noted that the laboratory tests (both frequency scans and Paris law curve generation) were time-limited, and therefore may not have lasted long enough to reflect industrial timescales. This argument is impossible to completely refute without tests lasting for decades, however ROSEN's judgement is that the empirical data is sufficient to show that oxygen inhibition will have some beneficial effect on FCGR.

As discussed in Section 3.1, the SANDIA work does not directly address fatigue crack initiation. The implication is that, if there is an effect, it will only be a temporary delay however again as discussed this is not quantified and may be long enough to have some industrial relevance.

It is possible that the anomalous results noted in ROSEN's experimental FCGR tests, whereby some tests performed at the end of a sequence showed lower results than equivalent tests performed at the start of a sequence, may be a function of this time dependence and / or geometry effects. The relationship between this apparent time dependence and any consumption of oxygen, as reported in the earlier work, is unclear and would benefit from further investigation.

3.3.3 Applicability of SANDIA Work to Alternative Inhibitors

In addition to oxygen, various alternative gases have been shown in the laboratory to potentially have some benefit, for example carbon monoxide (CO) and various sulphur compounds. The applicability of the latest SANDIA work to these alternative gases is unclear. Mechanistically the chemisorption of CO

or sulphur compounds are comparable to oxygen, with different strengths or affinities for adsorption. However, the argument that hydrogen can dissociate and diffuse through oxides (i.e. iron oxides rather than physisorbed atoms at the surface bonded only by Van der Waals forces) is not directly applicable to alternative inhibitors, for example sulphur compounds may form iron sulphides. Equally the experimental work demonstrating the time dependence of K_{THi} can only be strictly applied to oxygen, not another gas.

Following from the above, ROSEN do not believe that the SANDIA work applies to all gas inhibitors, however it is conceivable that similar mechanisms and results may apply. If alternative gas inhibitors are of interest then a significant amount of work is likely to be necessary to quantify the potential benefits, time dependence and mechanisms.

3.3.4 Integrity Issues (Corrosion)

National Gas have questioned whether it is possible for oxygen to react with hydrogen to form water in the pipe. As reported in [6], the original ROSEN literature review found that mixtures of H_2 and O_2 were chemically stable at pipeline temperatures and pressures, therefore no risk of water generation was identified. This conclusion is considered to remain valid unless new data becomes available.

3.3.5 Design Philosophy

National Gas have requested some clarification on how to practically take advantage of oxygen inhibition. In particular, they have raised the question about whether in-air fracture toughness and fatigue properties can be assumed for design purposes, and how to account for a potential loss of inhibitor supply in terms of design and integrity management.

It is recommended that consideration on the practical implementation of oxygen inhibition be made a focus of future work. Specific areas which would benefit from consideration are discussed below.

As identified in [6] there is some evidence that oxygen inhibition is only effective while oxygen is present, if the oxygen level decreases then the effectiveness of inhibition also decreases. As an initial step, it is recommended that the circumstances under which this could happen be established. Example scenarios are as follows:

1. Lack of effective inhibition immediately adjacent to mixing points due to initial inhomogeneity in the gas.
2. Lack of effective inhibition remote from mixing points due to oxygen consumption.
3. Lack of effective inhibition in areas of low or no-flow (dead legs etc.) due to gas separation or stratification.
4. Lack of effective inhibition due to preferential leakage / release of oxygen.
5. Lack of effective inhibition due to process upsets, for example issues with oxygen supply or the injection / mixing mechanism.

The implications of each scenario should then be investigated, looking at both the extent of the network affected, for example is the effect likely to be localised or general, the potential timescale associated with the lack of inhibition, and the potential failure modes (see below).

Laboratory data indicates that removal of oxygen will lead to a decrease in fracture toughness and an increase in fatigue crack growth rate, however the implications of these effects for a real pipeline are unclear and are related to the failure mechanisms which may be associated with hydrogen pipelines.

Conventionally, the risk of fracture is assessed using failure assessment diagrams. Simplistically fracture is considered to be a risk if the applied stress intensity factor at a crack tip is greater than the material's fracture toughness ($K_r > 1$). The choice of measurand to represent the material's fracture toughness is therefore key when assessing the risk of fracture. As discussed in [6], multiple measurands are available and more recent research has concentrated on the definition of KJ_{th} (the stress intensity factor at the point of crack initiation) rather than the more conventional $KJ_{0.2}$ (stress intensity factor at a 0.2 mm offset) from a rising load fracture toughness test. The work reported in [1] looked purely at $KJ_{0.2}$ since the measurement of KJ_{th} requires the use of potential drop equipment and is not fully standardised. A recent EPRG full scale fatigue test in pure hydrogen, designed to quantify the risk of fracture, failed by leak rather than rupture (effectively the crack fatigued through-wall). This result was despite small scale tests indicating that $K_r > 1$ using either the hydrogen affected $KJ_{0.2}$ or the hydrogen affected KJ_{th} value as the material's fracture toughness in an FAD [7]. The implication of these results is that the definition of acceptable defect size based on an FAD using hydrogen-affected fracture toughness may be over-conservative and inaccurate. Using oxygen to increase the apparent material fracture toughness may aid in achieving a positive outcome from an engineering assessment, but the translation of this into a real world effect at full scale, and the need for this, is therefore uncertain.

The EPRG full scale test also exhibited some anomalous features, which may have been due to crack growth under a static load however this was not confirmed. Based on these results there are therefore outstanding questions relating to how to assess the risk of fracture in hydrogen pipelines generally, with related questions regarding how to assess the impact of oxygen on this risk. Answering these questions is likely to require additional full scale testing, for example triplicate tests using test media of water / air, pure hydrogen and hydrogen with a deliberate oxygen addition. Such tests would help to validate or challenge the EPRG test results, and also quantify the effects of oxygen on a full scale basis, but would require careful design and would likely to be relatively expensive and time consuming.

Fatigue, and the related design requirements, are in principle easier to address. Assuming that the data reported in [6] is valid then FCGR differs depending whether oxygen is present or not. Elapsed fatigue life or fatigue crack growth can be calculated based on pressure data in time periods with or without inhibitor being present (or assumed to be effective) and summed, either using the S-N curve approach or fracture mechanics based approach, without much additional work. This approach would benefit from some additional small scale tests to validate the results previously reported, and potentially also from an additional full scale test although this could probably be combined with the full scale tests proposed above.

In summary, the effect of hydrogen on the risk of fracture in a real pipeline is unclear with a recent EPRG test indicating that conventional assessment methods using laboratory data may be over-conservative. The inclusion of any beneficial oxygen effect into these assessments is therefore difficult to implement. Further work, including full scale testing, is likely to be necessary before a definitive position can be reached.

The effect of oxygen on fatigue crack growth rate appears to be clearer, although see Section 3.3.2 for more discussion. Subject to this discussion, it appears that different FCGR curves can be applied depending on the environment.

In terms of the practical implications of oxygen inhibition, some example critical curves are included in [1]. These show that the critical crack size is very dependent on the material fracture toughness in hydrogen. If operation at 72% SMYS is desired for the pipe size in question (generally aligned with natural gas operation) then if "worst case" fracture toughness values are assumed the critical crack size is below EMAT detection thresholds and may be below the original mill NDT detection thresholds.

Justification of operation at these higher pressures is therefore challenging unless a higher fracture toughness (e.g. using oxygen) can be justified.

If the oxygen effect must be relied on for safe operation at the MOP or MIP then a pipeline integrity management plan should include measures to ensure that the oxygen level is maintained throughout the network during operation. Contingency plans in case the oxygen level drops, for example reducing the operating pressure (e.g. from a design factor of 0.72 to an equivalent hoop stress of 180 MPa) could be required.

3.4 Review of CPChem Alternative Inhibitors

National Gas have requested that ROSEN review a presentation supplied by Chevron Phillips Chemical (CPChem) [8] regarding hydrogen odorization and hydrogen embrittlement inhibitors and assess whether the candidate inhibitors were worth considering.

3.4.1 Summary of CPChem Findings

CPChem have performed a programme of testing and evaluation to assess nine separate inhibitors for their effectiveness in inhibiting the effects of hydrogen embrittlement. Four[1] of these inhibitors (S1 – S4) were sulphur based, while five (N1-N5) were non-sulphur based. The testing programme involved fracture toughness and fatigue crack growth rate testing, and was compared against baseline reference properties in air, “100%” hydrogen, hydrogen with 10 ppm oxygen and hydrogen with 40 ppm oxygen. For the fracture toughness testing, results were reported at “KJ_0” (assumed to represent KJ_{th}), $KJ_{0.2}$ and KJ_1. FCGR results were compared to in-air reference results and the standard B31.12 curve. All testing was performed on AISI 4617 steel (i.e. a low alloy steel not typically used in pipeline applications), baseline mechanical properties were not reported and the number of tests per condition was not reported.

For the sulphur based inhibitors fracture toughness results are reproduced in Figure 7.

[1] Only three individual chemicals were tested (S1-S3), inhibitor S4 was a blend of S1 and S2

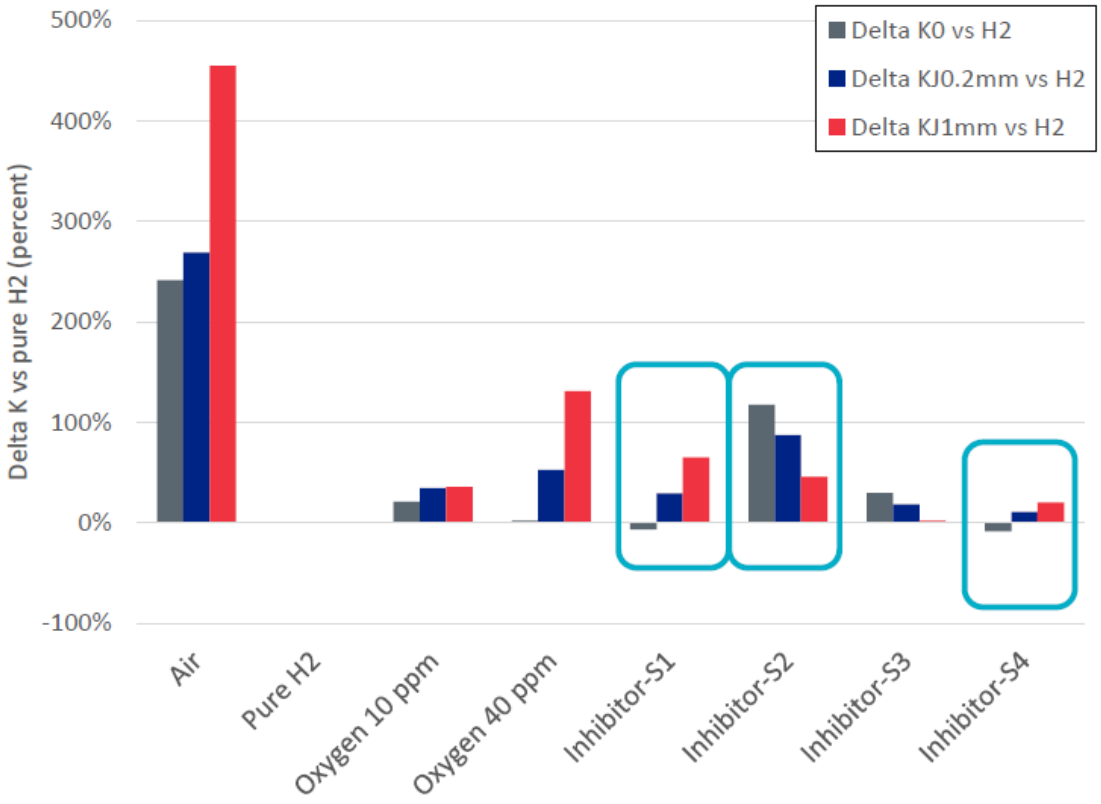


Figure 7 - Fracture Toughness in various sulphur based inhibitors compared to hydrogen from [8]

CPChem conclude that inhibitor S1 gave better crack propagation protection while inhibitor S2 gave better crack initiation protection. They also concluded that inhibitor S4 (blend of S1 and S2) did not increase overall performance.

Fracture toughness results for the non-sulphur inhibitors are included in Figure 8.

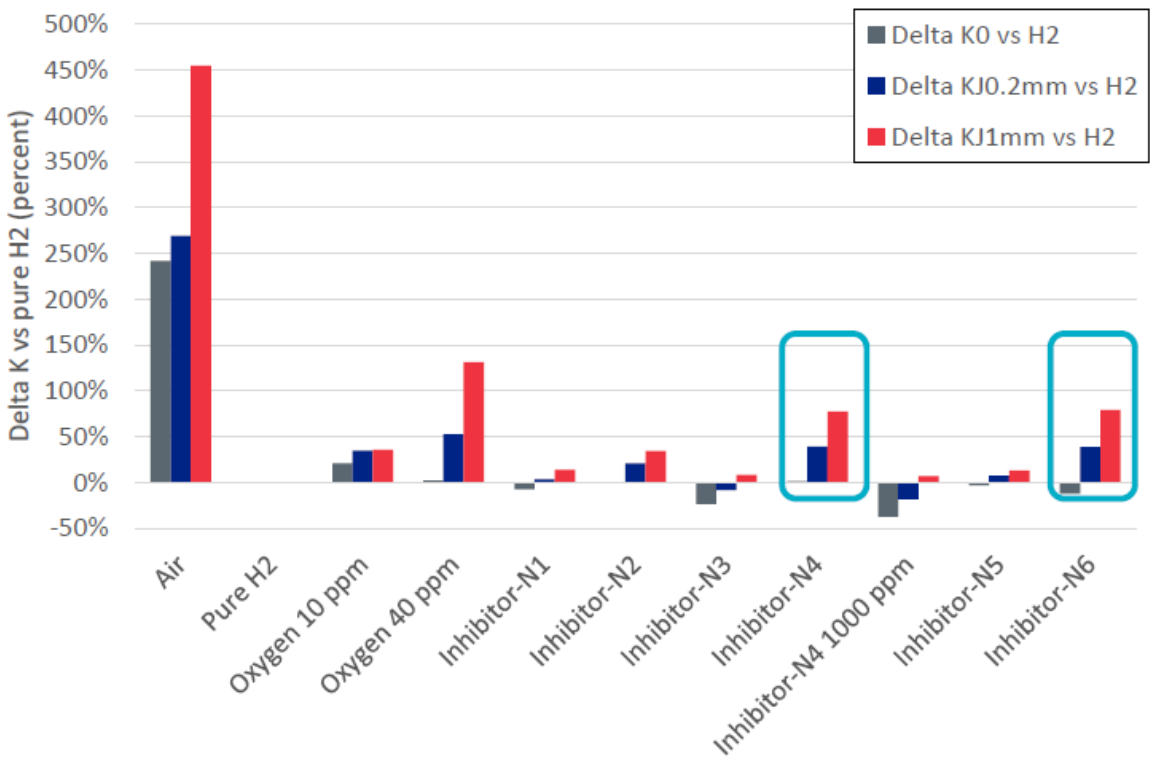


Figure 8 - Fracture Toughness in various non-sulphur based inhibitors compared to hydrogen from [8]

CPChem concluded that inhibitors N4 and N6 significantly outperformed all non-sulphur inhibitors tested, that there was no clear structure property relationship and that the “concentration response was not as expected”.

Finally CPChem performed some FCGR tests comparing inhibitors S2, N4 and N6 against reference curves in hydrogen and air. Results are shown in Figure 9.

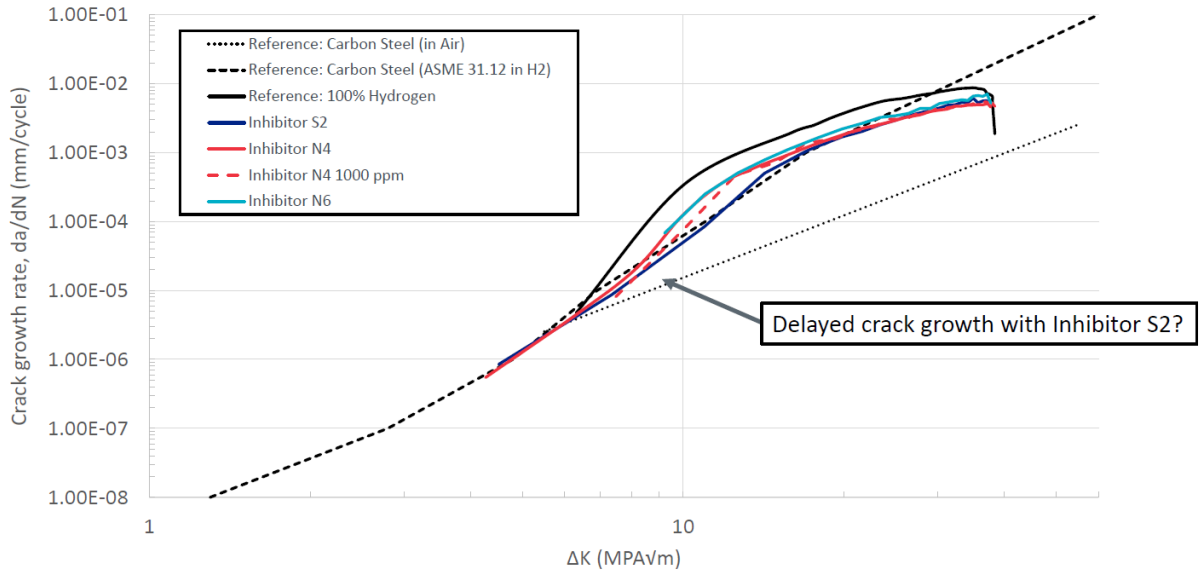


Figure 9 - FCGR Curves in various environments from [8]

CPChem concluded that inhibitor S2 showed the lowest crack growth rate, confirming its superior resistance. They also concluded that the effect of S2 was possibly due to affecting hydrogen diffusion, while inhibitors N4 and N6 likely affected surface adsorption or offered a shielding effect.

3.4.2 Discussion of CPChem Findings

Most of the test results presented by CPChem imply that the inhibitors were less effective than 40 ppm oxygen, and by implication would be significantly less effective than higher amounts of oxygen. This is consistent with the literature reviewed by ROSEN in this project, which found oxygen to be the most potent inhibitor, above CO and significantly above sulphur compounds.

The mechanism of inhibition for the different chemicals is not discussed in detail, however assuming that most of them affect surface adsorption then this appears to be similar to oxygen, with the same caveats therefore applying with respect to long term exposure and the potential for the inhibitors to merely delay rather than prevent hydrogen embrittlement. Notwithstanding this, the delay is unquantified so, similar to oxygen, may be long enough to be useful for industrial applications. The delay time compared to oxygen has not been investigated.

The most interesting result reported by CPChem is the apparent effect of inhibitor S2 (a 10 ppm bulky and sterically hindered alkyl mercaptan) on KJ_0 / KJ_{th}. According to the CPChem results oxygen had basically no effect on KJ_0 / KJ_{th}, although this was limited to 40 ppm oxygen (the effect of higher oxygen levels on KJ_{th} was not investigated as part of the original ROSEN test scope), whereas the S2 effectively doubled the reported KJ_0/ KJ_{th}. Equally the KJ_0 / KJ_{th}, $KJ_{0.2}$ and KJ_1 values were all close together for inhibitor S2 (closer than for any other condition tested). This implies that the resulting J-R curve was flatter, and may imply a change in fracture morphology. This result appears to warrant further investigation to determine its repeatability, and also to determine whether there was any time dependence. It is also noted that when S1 and S2 were blended to form S4 they appeared to interact antagonistically rather than synergically (i.e. the reported fracture toughness values in S4 were lower than either S1 or S2 individually). The implications of this result in terms of inhibition mechanisms and repeatability of results should be investigated.

In conclusion, based on the data provided none of the inhibitors tested by CPChem present significant additional inhibition benefits compared with 40 ppm oxygen, and by implication would be significantly less effective than 250 or 500 ppm oxygen. The exception to this is inhibitor S2, which appears to increase KJ_{th}, this may be worth further investigation particularly if there are other benefits such as lack of reactivity / consumption with steel surfaces, flammability or other safety aspects, and effects on end users.

4 CONCLUSIONS

The recent SANDIA work is informative, deserves close consideration and does raise data that is potentially consistent with the argument that oxygen inhibition only delays onset of cracking under static loads. However, it should be noted that it is based on much higher strength steels and much higher hydrogen pressures than are relevant for the NTS. It is ROSEN's position that it does not conclusively disprove the potential for oxygen inhibition for long-term inhibition of hydrogen embrittlement, but does warrant further testing using representative materials and test parameters, if the inhibition is to be relied upon.

It should also be strongly considered that even if the effect is only to delay embrittlement, the time scales indicated by the SANDIA data may still mean there is the potential for a complete or significant reduction of fatigue crack growth rates under cyclic loading in hydrogen. There could still, therefore, be valuable applications for oxygen inhibition where there are concerns over fatigue life. Again, further testing may be necessary to prove that the inhibiting effect can still be relied upon following pre-exposure to hydrogen over longer time periods, or considering low frequencies of cyclic stress.

The time dependence of hydrogen embrittlement per se, together with the potential for time-dependent crack growth under a static load, is currently unquantified. Given this uncertainty, it is therefore very difficult to ascertain the time dependency of oxygen inhibition and to an extent the two mechanisms must be considered together. This is already being done within CHMC-1 with the relationship between oxygen concentration and testing rate.

To address the concerns raised though SANDIA, future work is recommended to follow two approaches. A more detailed fundamental understanding of the mechanisms of hydrogen embrittlement and oxygen inhibition is obviously desirable, but would also involve some fundamental academic research. In parallel some empirical studies are recommended to try to demonstrate the effects of oxygen in a real pipe. Examples that could be considered are comparative full scale long-term tests in an inert environment, in "pure" hydrogen, and in hydrogen with oxygen inhibition.

Further work is recommended looking at how any beneficial effect of oxygen inhibition can practically be taken into account during design and integrity management. This work should look at both the mechanisms where oxygen could become depleted, and the effects of the presence or otherwise of oxygen on fracture and fatigue.

In terms of alternative inhibitors presented by CPChem, inhibitor S2 appears to warrant further investigation however the other inhibitors appear to be less effective than 250 ppm oxygen, but may warrant further consideration if the use of oxygen is found not to be viable for safety or practical reasons.

5 REFERENCES

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APPENDIX E – WP2: HIGH LEVEL CBA

OXYGEN INHIBITION COST BENEFIT ANALYSIS TOOL

CLIENT: National Gas Transmission

PROJECT NUMBER: 19878

REVISION: 2

DATE: 03/09/2025

ROSEN
empowered by technology

Rev.	Date	Description	Prepared by	Reviewed by	Approved by
1-0	22/08/2025	Revision 1	I Martin	J Sheppard	D Phelps
2-0	03/09/2025	Revision 2	I Martin	J Sheppard	D Phelps

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1 COST BENEFIT TOOL

This document provides detail on each worksheet within the cost benefit analysis spreadsheet model "*19878 O2 Inhibition Cost Benefit Model rev 1-0.xlsx*" [1]. This spreadsheet has been provided to National Gas Transmission (NG) and provides a high level cost benefit assessment comparing the following three scenarios:

1. Maintaining current operating parameters for all feeder pipelines while transporting 100% Hydrogen. This scenario requires the introduction of an Oxygen inhibitor at each inlet on the national transmission system (NTS) to a concentration of 500 ppm.
2. Maintaining current operating parameters for all feeder pipelines while transporting a 20% Hydrogen, 80% Natural Gas blend. This scenario requires the introduction of an Oxygen inhibitor at each inlet on the NTS to a concentration of 500 ppm.
3. Reducing the design factor and therefore, the operating parameters for all pipelines on the NTS when used to transport Hydrogen in any concentration. This option would not require Oxygen inhibition, as the reduced operating pressure would be sufficient to mitigate against Hydrogen induced cracking within the pipeline materials. In addition, in order to provide a similar energy delivery capacity as the network today, network reinforcement may be required for some pipelines.

The Cost Benefit Model consist of the following worksheets:

- Feeder Details
- Reinforcement Required
- NTS Inputs
- O2 Requirements
- O2 Injection Sites
- CBA Results

For each worksheet within the cost benefit model spreadsheet; a short summary is provide in each of the following sections.

1.1 Feeder Details

The "Feeder Details" worksheet includes information for all pipeline sections on the NTS. This data was extracted from the National Gas Pipeline data book [2]. This data provides the inputs for other worksheets.

A number of pipeline sections have been identified as having erroneous data in the data book and these will require review. However, for the purposes of the cost benefit, the data has not been corrected.

This data includes the following extracted from the pipeline data book:

- FDR No – Feeder Number
- FROMASSETL – AGI at start of pipeline section
- TOASSETLOC – AGI at end of pipeline section
- LENGTH_KM – Pipeline section length, km
- NOMINALDIA – Nominal diameter of pipeline section, mm
- MOP_BAR – current MOP of pipeline section, bar
- GRADE – Material grade of the pipeline section
- WALLTHICKN – Nominal wall thickness of the pipeline section, mm

The following columns and calculations have been included in this sheet for the analysis:

- SMYS – the specified minimum yield strength of the material grade listed, N/mm^2
- Minimum WT – minimum wall thickness possible using manufacturing tolerances, mm
- Diameter – Actual diameter of the pipeline, mm
- DF – Design factor of the pipeline under current operating conditions
- Reduced DF – the required design factor for pipelines for the specific material grade when used for transporting Hydrogen, as specified by IGEM/TD/1 Edition 6 Supplement 2 [3]
- ROP (Reduced operating pressure) – the equivalent operating pressure for the reduced design factor when transporting Hydrogen, bar
- ZEM – Zone effective MOP as determined by DNV Report 10524402 [4], bar
- ROP or ZEM < MOP? – A logic check to identify if the pipeline operating pressure needs to be reduced if it were used to transport Hydrogen (in any concentration).

The ZEM is the maximum MOP for Hydrogen service of a pipeline, limited by network operation and design of all connected pipelines, for example, if one pipeline is limited to a maximum operating pressure of [redacted] all other connected pipelines shall also be limited to that MOP. Currently, no pipeline specific ZEM has been provided for each of the pipeline sections, with the DNV report only providing ZEMs for pipeline regions across the NTS. It is unknown where the boundaries are for each region and therefore, which pipe sections fall into each region. It is therefore recommended that further detail is provided on the pipelines within each region so the ZEM can be applied to each pipeline section. This can then be updated in this worksheet.

It is recommended that NG should review the pipeline data book in detail, and complete any missing pipeline data or update any erroneous data identified as highlighted above. This review might include completing missing information, and also a review of the calculated design factor, as this would offer guidance of where the pipeline information currently in the data book is not correct, for example where the pipelines are calculated to be operating with a design factor over 1.

1.2 Reinforcement Required

The “Reinforcement Required” worksheet determines the total length of pipelines that require reinforcement for Scenario 3.

Reinforcement is assumed to be required where the current operating pressure of the pipeline (MOP) cannot be maintained when transporting Hydrogen i.e. the ROP or ZEM are lower than the current MOP. Due to requiring a lower operating pressure, the pipeline capacity is reduced and therefore, a reinforcement pipeline is required.

No network analysis has been carried out for the proposed reinforcement, therefore for this analysis, a reinforcement pipeline is considered to be an identical pipeline with the same pipeline parameters such as diameter, wall thickness, and length.

This worksheet includes a summation of all pipeline lengths by nominal diameter where the ROP or ZEM are lower than the current MOP. The total number of pipeline sections requiring reinforcement has also been calculated.

The calculations assume a single pipe laying set up cost per pipeline section requiring reinforcement, and then an incremental cost for pipe laying per metre. The pipe laying set up cost is intended to cover activities such as pipeline design, procurement, and all activities required for constructing a new

pipeline. The incremental cost per metre is for the activities on site while constructing the pipeline. Based on these numbers, it is possible to calculate a total cost for reinforcing all the pipeline sections with duplicate pipelines where their operating pressure must be reduced when transporting Hydrogen and or Hydrogen / Natural Gas blends.

It is recommended that the average costs for all stages of pipeline design and construction should be reviewed, with any updated values then input into this cost benefit model.

In order to improve the reinforcement costings, network analysis should be carried out for each offtake, considering the required flow rates for 100% Hydrogen and the 20% Hydrogen 80% Natural Gas blend, and whether the pipeline(s) feeding that offtake can provide that flow at the reduced operating parameters. Where the pipeline(s) cannot provide the required throughput, reinforcement options would need to be considered by network analysis, considering all alternative supply points, as well as duplicating the same pipeline feeding the offtake.

1.3 NTS Inputs

In order to determine the costs for oxygen inhibition, two main considerations are the quantity of Oxygen required and the location where the Oxygen will be required.

The “NTS Inputs” worksheet include a list of all inputs into the NTS provided by NG, including all terminals, storage sites, and interconnector pipelines. It is currently assumed that, if oxygen was to be used to inhibit Hydrogen induced cracking, injection points would be situated at these locations.

NG provided a record of the daily Natural Gas flows for these sites [5] for the period of 01/01/2024 to 06/06/2025, and the average and maximum flows for the 1-year period of 07/06/2024 to 06/06/2025 have been extracted and included in this worksheet for each site / input.

In order to assist in determining where Oxygen is required on the NTS, these site names have been simplified into common sites, for example [redacted] have all been simplified to “[redacted]

It is recommended that the gas flow data is reviewed for a greater period of time, to identify the worst case scenario in terms of daily Oxygen use and also to confirm the average from 2024-2025 is typical for a year.

1.4 O2 Requirements

The “O2 Requirements” worksheet calculates the number of Oxygen tankers that would be required at each of the NTS input sites. Using the simplified site names assigned on the “NTS Inputs” worksheet, a summation of all the gas flows through each site is calculated based on the average daily flow.

It is assumed that the energy of 100% Hydrogen or Blended gas is required to be the same as Natural Gas. Using parameters provided, the yearly flow of Natural Gas is converted into equivalent flows of Hydrogen (or Blend) with the same energy output using a flow factor determined as a ratio of the calorific value and density of the gas of Hydrogen (or Blend) compared to that of Natural Gas. From this, the worksheet then calculates the amount of Oxygen required to maintain 500 ppm in the flow for both 100% Hydrogen service 20% Blended service, and hence the number of tankers of liquified Oxygen that are required each day at each site can be calculated.

This number of tankers are then summed up to provide a number of tankers required per day across the entire NTS. This number is then multiplied by the price per tanker of liquified Oxygen based on the price per tonne of liquid Oxygen, and that is then used to calculate the cost of liquified Oxygen across the NTS every year. The price per tonne of liquid Oxygen is taken as an average cost based on various internet sources, and will need to be validated by a supplier of liquid Oxygen, as this may have a significant impact the outcome of the model.

1.5 O2 Injection Sites

The “O2 Injection Sites” worksheet includes information and costs for designing, procuring, and constructing the injection systems for the Oxygen across the NTS. The current list of equipment is not complete, but an estimation based on the known information at this low technology readiness level. It is recommended that the design of an Oxygen injection system should be carried out and fully costed, along with the surrounding installation pipework required for incorporating this system. Gas analysis, monitoring, and recording should also be determined and any variation in cost added to the list of costs within this cost benefit model. Cost currently used in the model are based on quotes for similar equipment in 2021.

It is assumed that all the NTS input sites will require an injection system, and these shall be supported by injection systems at NTS compressor stations. These compressor stations are intended as back up if the levels of Oxygen are found to be below the target concentration in the gas being transported. It is also assumed that a single back up system will be required at all NTS inputs and compressor sites to protect the NTS in the event of an injection system failing. With the number of NTS inputs and compressors known, and assuming a single backup system is sufficient, the cost for these injections systems/sites are calculated.

Additional monitoring points have also been considered at the outlets of the NTS to the local distribution zones. It is assumed that the gas must be analysed at these offtakes to ensure the appropriate quality and Oxygen content before the gas exits to other Networks. For these offtakes, the cost of an analyser and installation cost has been considered. These can be updated once further costs are known.

1.6 CBA Results

The “CBA Results” worksheet brings the final results together onto one sheet.

For the two options requiring Oxygen inhibition, the estimated costs for the installation of the injections sites, and monitoring sites, have been included, as well as the annual cost for the Oxygen required.

For the third scenario not requiring Oxygen inhibition, the cost for reinforcing the pipelines with reduced design factor is also included.

2 ASSUMPTIONS

The assumptions made in the cost benefit analysis model, as described in Section 1, have been summarised in Table 1.

Worksheet	Assumption(s)
Feeder Details	• All information contained within the 2024 pipeline data book is correct
Reinforcement Required	• If the required design factor for transporting Hydrogen results in a lower operating pressure than the current MOP, or the ZEM is lower than the current MOP then the pipeline will require reinforcement • The reinforcement pipeline is a duplicate pipeline, assuming an identical route / pipeline length • The pipe laying setup cost and the incremental cost per metre
NTS Inputs	• The maximum flow rates for the 1-year period of 07/06/2024 to 06/06/2025 have been used in this model.
O2 Requirements	• It is assumed that the energy of 100% Hydrogen or Blended gas is required to be the same as Natural Gas, therefore, the flow rates of these gases have been calculated for an equivalent energy throughput. • The cost for liquid Oxygen has been assumed to be [redacted] per tonne, based on an average value from a number of internet sources.
O2 Injection Sites	• Prices for injection systems and associated equipment, including the gas analysers required at both injection and monitoring sites, were based on quotes for similar equipment in 2021. • The cost for installing all equipment at both the injections sites and monitoring sites • Number of monitoring points across the NTS, currently assumed to be at every offtake from the NTS • Number of back up systems required per injection and compressor site
CBA Results	None

Table 1: Cost Benefit Model Assumptions

3 FINDINGS

Based on the costings and assumptions used and described in Section 1 and Section 2, the costs for the three scenarios have been calculated.

The cost for the installation of the injection and monitoring stations remains the same whether the intention is to transport 100% Hydrogen or a blend of 20% Hydrogen and 80% Natural Gas.

A significant factor in this model is the volume of Oxygen required, and its cost. When assuming an equivalent energy throughput, when transporting 100% Hydrogen, the cost for this Oxygen is approximately 3 times higher than that of the cost of Oxygen required if transporting a blend of 20% Hydrogen 80% Natural Gas. This is due to the energy capacity and density of Hydrogen when compared

to the proportion of Natural Gas within the Blend. This cost of Oxygen is a recurring cost every year that the inhibitor is deployed.

When considering the option to reduce the operating parameters of the pipelines to eliminate the need for Oxygen inhibition, based on the assumptions made for the required pipeline reinforcements, a cost for reinforcing the NTS can be provided. The costs used in the model need to be validated by NG and network analysis could be carried out to further refine reinforcement options.

4 RECOMMENDATIONS

The following recommendations are made for future consideration:

1. The ZEM for the individual pipeline sections should be requested from DNV.
2. NG should review the pipeline data book in detail, and complete any missing pipeline data or update any erroneous data identified.
3. The average costs for all stages of pipeline design and construction should be reviewed, with the updated values used in this cost benefit model.
4. Network analysis should be carried out for each offtake, considering the required flow rates for 100% Hydrogen and the 20% Hydrogen 80% Natural Gas blend, and whether the pipeline(s) feeding that offtake can provide that flow at the reduced operating parameters. Where the pipeline(s) cannot provide the required throughput, reinforcement options would need to be considered by network analysis.
5. Gas flow data is reviewed for a greater period of time, to identify the worst case scenario in terms of daily Oxygen use and also to confirm the average from 2024-2025 is typical for a year.
6. The cost of liquid Oxygen should be validated by a supplier of liquid Oxygen, as this may have a significant impact the outcome of the model.
7. The design of an Oxygen injection system should be carried out and fully costed, along with the surrounding installation pipework required for incorporating this system. Gas analysis, monitoring, and recording should also be determined and any costs added to this cost benefit model.

5 FURTHER CONSIDERATIONS

Further to the costings and recommendations provided in the above sections, the further consideration should be given to the following:

1. The model does not include ongoing operational costs (OPEX) other than the yearly Oxygen use. OPEX costs may include additional activities such as injection system maintenance and periodic fatigue assessments.
2. The model does not include any cost for Oxygen storage on installations. This may require cryogenic storage facilities for liquid Oxygen storage. Depending on the final solution for Oxygen provision, storage facilities will need to be costed and considered.
3. Expected flow patterns will need to be reviewed, with expected Oxygen requirements and the logistics planned in, as the number of tankers required per day will change depending on the flow rates through each input. During the Winter/peak months, these required tanker numbers may be significantly higher than the Summer months.
4. The number of tankers based on the maximum flow rate has been calculated in this model to allow planning at each NTS input, however, these numbers are based on flow data from 07/06/2024 to 06/06/2025. Flow data from a much longer time span should be reviewed to ensure that the planning and logistics is carried out effectively.

6 REFERENCES

[1] ROSEN(UK), "*19878 O2 Inhibition Cost Benefit Model rev 1-0.xlsx* ", Ian Martin, 22/08/2025

[2] Pipeline Data Book, National Gas Transmission, Issue 41, Version: Final

[3] IGEM/TD/1 Edition 6 Supplement 2, Communication 1849, High Pressure Hydrogen Pipelines, Institute of Gas Engineers and Managers, 2021

[4] Network Impact for Hydrogen - Natural Gas Blends, DNV, Report Number 10524402_RP-02, Revision 0, 10/04/2025

[5] National Gas Transmission, "*Copy of SupplyData_CameronCoogan.xlsx*", 06/08/2025.