

LESSONS LEARNT FROM FITTING AN INERT GAS BLANKETING FACILITY TO AN EXISTING STORAGE SILO

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SYNOPSIS

The decommissioning of redundant plant at BNFL Sellafield is proceeding as a priority.

One of the major activities is to remove metallic and organic Intermediate Level Wastes (ILW) from a large reinforced concrete storage silo. The waste has been stored in an air-based atmosphere.

It was decided to fill the silo with inert gas, prior to beginning the retrieval process. The silo had not been designed to retain inert gas. The inerting was completed successfully in early 2002.

This paper outlines how the silo was prepared for inerting and compares the predictions of performance, including anticipated problems, with the actual outcome.

INTRODUCTION

The decommissioning of redundant plant at BNFL Sellafield is proceeding as a priority. One of the major current activities is to improve the waste storage conditions of a large reinforced concrete storage silo located in a congested area of the site. This is being undertaken in advance of waste retrieval operations that will require the construction of new waste retrieval and processing capabilities at a cost of >£100 M.

The silo was built just after World War II at the start of the Cold War to provide waste storage facilities for the cladding from spent nuclear fuel initially arising from the military programme and later from the early civil nuclear programme. Radioactive wastes, generated from 1952 to 1968, were loaded and stored inside the silo within an air atmosphere. More recently, a programme has been initiated to systematically reduce the potential fire risk presented by the waste before waste retrieval can commence.

This paper primarily concentrates on presenting the technical challenges faced in developing a pragmatic solution to reducing the fire hazard by fully inerting the silo, as it was not designed to retain inert gas. Details are provided of the various options assessed, the development work conducted in support of the chosen option, site preparatory works and the plant commissioning carried out to prove the design. Safety and the reduction of risk to a level that is as low as is reasonably practicable (ALARP) has been paramount throughout the works programme and has had a major influence on the design and modification programme.

Substantial improvements of the silo structure and containment have now been achieved and the waste contents were successfully inerted with argon in early 2002. Further work in preparation for retrieval is now underway.

STORAGE PLANT DESCRIPTION

The silo (Figure 1) is a 300 mm thick reinforced concrete structure having external dimensions of approximately 29.5 m x 10 m overall and rising to a height of 18 m above local ground level. It consists of six equal compartments that are full or near to capacity.

Each compartment is divided into two equal sections by a 13 m high longitudinal division wall rising from a height of 1.5 m above the bottom of the silo. The silo is supported on cellular foundations (voids), to elevate the storage compartments above local ground level, with the compartment floors being covered by a layer of gravel and sloping towards a drain located in the corner. A charge hole is positioned at the top of each compartment above an inverted 'V' shaped divider plate, used to divert the tipped waste to the compartment sides. The charge holes connect the silo to a common overhead transfer tunnel running centrally along the silo and through which waste was transported and tipped. Some waste rests on the divider plate and protrudes up into the lower section of the transfer tunnel. Tunnel clearance operations are currently underway to dislodge this waste back into the silo, before sealing the chargeholes to isolate the tunnel from the silo compartments.

REDUCTION OF PLANT RISK (1 & 2)[1]

The key hazard was the potential for a silo fire to be initiated within the bulk waste material. Significant quantities of combustible waste material were sentenced to the silo; principally aluminium, magnox (an alloy of magnesium), uranium, graphite, and organic materials. Due to the reactive nature and degradation products of some of the constituents, there was a small possibility of spontaneous ignition occurring and a fire developing in an air atmosphere if the waste was disturbed. Temperatures and pressures generated during such a fire might, in extreme circumstances, have compromised the silo containment resulting in unacceptable consequences.

The approach taken to reduce the risk posed by the plant is summarised in a FAST diagram (Functional Analysis Systems Technique) (Figure 2). The challenge was to provide a robust means of managing any potential silo fire hazard. Any selected scheme had to be rigorous, satisfy BNFL Company and Regulator safety requirements and represent a solution that ensures the overall risk posed by the plant is ALARP.

Option studies were initiated, but it soon became apparent that only a limited number of options were available to manage the fire risk. It was rapidly concluded that there was a clear requirement to inert the silo contents with an appropriate medium to drive out the air and maintain oxygen levels at a safe limit. Further studies concluded that gas inerting was the best option for providing an inert atmosphere that will not support ignition of the waste and fire propagation.

SELECTION OF INERT GAS (3)

A comparison of the properties for various gases (Table 1) concluded that argon represented the best option for meeting the process, engineering and safety requirements, recognising that the asphyxiation hazard to plant operatives would need to be controlled by engineered and managerial means. Argon was selected over two other cheaper alternatives, carbon dioxide and nitrogen, because it is the only gas available on an industrial scale that could extinguish a burning metal fire. It also has the inert properties to enable permanent blanketing without chemical reaction with the waste mass that might later prove disadvantageous for waste treatment. Nitrogen is less dense than argon making it unsuitable

[1]The number(s) in brackets refer to the risk reduction step on the FAST diagram presented in Figure 2.

for dispersing air from within the silo and furthermore, reacts with burning uranium and magnesium. Carbon dioxide on the other hand is heavier than both argon and nitrogen and represents a suitable gas for displacing air. However, it both permits ignition and sustains metal combustion once ignition has occurred preventing it from being selected as a suitable inerting and extinguishing agent.

Other liquid and solid extinguishants were considered, but were rejected for several reasons including inability to ensure rapid delivery to the seat of the fire, and disposal problems once the extinguishant became radioactive.

ASSESSMENT OF ARGON ASPHYXIATION RISK (4)

Argon is a colourless, tasteless, odourless gas that becomes a hazard when present in sufficient concentrations to act as an asphyxiant at oxygen concentrations <18%. The silo compartments would be filled with large volumes of argon gas. There would then be the potential for fugitive argon to seep from the silo into other working areas. Furthermore, the advanced works to prepare for waste retrieval and subsequent processing of waste would require breaking through the silo containment, whilst retaining a fully inert atmosphere within the silo, thereby also presenting a potential asphyxiation hazard. BNFL have therefore developed a robust argon hazard management strategy for the silo that endeavoured to engineer out the hazard wherever possible as a first principle.

Immediately under the structural concrete of the cellular base of the silo is a 75 mm layer of blinding concrete. The ground directly beneath has been well compacted with very few air voids present. The site surrounding the silo has a covering of man made ground between 0.5 m and 8.0 m thickness and comprising of a 0.5 m layer of concrete and hardcore below which is a layer of sand and gravel containing bricks, clay etc. It was expected that this adjacent ground was also well compacted, but might be disturbed in the future during construction work to prepare for waste retrieval operations.

Computational Fluid Dynamic (CFD) modelling of the silo structure was carried out to simulate the leakage of argon from the silo into the atmosphere and surrounding area. The objective was to determine the magnitude of the asphyxiation hazard and to identify the optimum siting for oxygen monitors. A gas dispersion code was used to model the silo and its surrounds to address the dispersion of argon below ground, through the silo walls and from breached argon pipework.

The CFD model indicated that argon concentrations around the silo at ground level and below could present a potential hazard to personnel working in the local area. A second study modelled argon diffusion rates through the concrete silo containment walls and the combined diffusion/convection flows through small cracks in the silo walls. Once again the study revealed that there was a potential argon asphyxiation hazard to personnel that may be located below ground close by the silo. These two studies also demonstrated that concentrations rapidly fell a very short distance from the release site and would therefore, pose no hazard to personnel located outside the immediate vicinity of the silo building. Similar results were obtained from a third study that demonstrated severing the argon distribution pipework running along the north side of the silo could also result in significant argon concentrations. However, this was restricted to a small region local to the breach and the gas was rapidly dispersed as distance from the release site increases.

The conclusion from the CFD modelling work clearly indicated that there might be an argon asphyxiation hazard present within a few metres of the silo once it was inerted. It was clear that the optimum position for locating the oxygen monitors was external to the silo within a service trench that runs alongside the silo. Therefore, the most significant hazard would be from slow seepage into confined spaces, rather than gross leaks from high pressure pipework, the latter release being dispersed quickly and capable of being rapidly detected.

MANAGEMENT OF ARGON ASPHYXIATION RISK (5)

To complement the modelling work, a world-wide review of asphyxiation incidents was attempted. Unfortunately, very few countries made their data available in the public domain. Information was available mostly from the UK and USA process and nuclear industries. It was found that there were not many argon fatalities per se, but in the period 1995–2000, one person died in the UK (Ref. 1) and 23 persons died in the USA (Ref. 2) from Oxygen deficiency due to the presence of argon in work areas. However, there were many asphyxiation fatalities from other causes, some 98 in the UK (Ref. 3) and 195 in the USA (Ref. 2). The vast majority resulted from access to confined spaces such as vessels. The root causes of the argon incidents usually involved inadequate precautions, or safety management arrangements (risk assessment, safe systems of work, training etc.) or emergency procedures. Lessons learnt from these previous incidents and investigations are incorporated into the strategy developed for managing the silo argon hazard. The multi-legged approach to controlling safety in different areas of the plant is summarised in Table 2. It was recognised that these precautions were extensive and exceeded those usually found in most process industry plants. However, this was considered prudent at the time given that the silo represented the largest inerting application to an existing concrete structure on the Sellafield site and possibly the UK.

Management of the argon asphyxiation risk over a period of more than 6 months of active commissioning has resulted in no significant argon leakage being detected outside the operating envelope of the silo. This has been substantiated by an extensive external monitoring regime.

PROVISION OF ARGON SUPPLY SYSTEM (6)

A new modern argon inerting and fire fighting system was designed to provide the silo inerting and fire fighting requirements. Two liquid-argon storage and vaporisation plants are located remotely from each other on the site and are connected to the silo by diverse pipe-routes. The plants comprise of two double skinned liquid argon tanks that provide sufficient quantities of argon to ensure that all compartments and the transfer tunnel remain fully inerted, with sufficient capacity always being available for fire fighting duties. Gas is injected into the compartments at the bottom of the silo and is drawn through each compartment by the silo ventilation system maintaining the oxygen composition of the atmosphere at less than 2% (v/v) oxygen. In the unlikely event of the argon supply failing or during deliberate de-inerting, which may be required to support the pre-retrievals works programme, a segregated argon fire fighting supply is also provided by the argon plants. This injects large quantities of argon into the top of the compartments at such a high rate (capable of delivering 800 Sm^3/hr of gaseous argon for 30 hours) that it would rapidly extinguish any fire detected by the silo sensing instruments.

A supply line from each vaporisation plant feeds argon at its storage pressure of approximately 10 Bar to a pressure-reducing station located on the west wall of the silo. Four sets of regulators facilitate the passage of low-pressure argon to three headers. Each header is capable of serving all six silo compartments, one carrying inerting argon (controlled flow) to low-level connections, one carrying fire-fighting argon to the same low-level connections and one carrying fire-fighting argon to connections on the roof of the silo.

The vaporisation plants ensure an uninterrupted availability of argon for all duties, thereby maximising the reliability of the system. Both plants are on-line continuously supplying the inerting header whilst, normally, each plant serves one fire-fighting header. Thus, there will be two independent fire-fighting supplies available in normal operating circumstances.

The argon plants were installed and commissioned in late 2001, providing all of the silo inerting and fire fighting requirements. Argon is injected into the silo at a rate of 3 to 12 m^3/h per compartment through the single sump located at the base of each compartment.

There were concerns that the argon gas might not rapidly fill and disperse throughout each compartment if the injection points were partially blocked by the gravel/screed covering the silo floor or if the gap between the bottom of the central wall and silo floor was blocked by waste. This concern was investigated in development trials on an inactive model of the silo. It was shown that the forces of gaseous diffusion were dominant within the waste mass, for example, argon rapidly dispersed the trapped air inside an upturned container. Also, it was predicted that the argon would plug flow. The plant results are discussed later in this paper.

The silo ventilation system draws argon from each compartment via the charge hole and transfer tunnel and is set up to maintain the tunnel at a slight negative pressure. This maintains a very small air in-bleed in the upper sections of the silo rather than an egress of contaminated argon out to the environment.

It is worth noting that the existing silo structure and existing argon delivery system (pipework etc.) are capable of meeting the 0.125 g seismic design standard required for existing plants with substantial nuclear inventories. At completion of a current upgrade, the new argon storage plants will be capable of meeting the higher 0.25 g (10^{-4}/y return frequency) standard to cater for potentially better performance by the silo, and to be consistent with internal hazards standards for new plants.

ENSURING DELIVERIES AND QUALITY OF ARGON (7)

The volume of liquid argon required to ensure the full availability of the fire fighting system is approximately 70% of the maximum working volume for a single tank. This volume is maintained in both tanks at all times. Tanker deliveries are required every 6 to 19 days, based on the maximum and minimum injection rates respectively.

The liquid argon purity is <2 ppm (v/v) oxygen. This standard industry grade argon is delivered ‘on demand’ to the facilities by road tanker from a major UK supplier. Argon is routinely sampled and analysed for oxygen content at the production facility and certified in accordance with the bulk liquid supplier’s QA systems, with the road tanker being sampled before and after filling.

The design of couplings on the two argon storage tanks is unique to this particular plant on the site preventing an incorrect tanker load being delivered to the argon tanks. Furthermore, the filling process is performed by the road tanker driver under the supervision of a qualified BNFL operator.

ENSURING SILO CONTAINMENT (8)

A set of R&D trials and supporting test work was performed in support of the silo inerting programme and prior to commissioning the argon inerting system on site. The behaviour of argon gas inside a silo compartment was assessed using a scale model filled with pieces of polystyrene to simulate the waste. Oxygen monitoring equipment distributed throughout the waste measured the oxygen depletion as argon gas was fed into the bottom of the rig and drawn out at the top simulating conditions within the silo. The overall aim was to determine whether the inerting option was viable by:

- Establishing the optimum argon flow rate for inerting the silo and minimising the potential for air retention 'pockets' between the waste.
- Predicting the total volume of argon required to fully inert the silo.
- Determining the optimum location for oxygen monitors in the silo.

A series of tests were conducted in which the argon flow rate was varied and the oxygen concentrations recorded by monitors distributed at various levels throughout the test rig. It was concluded that:

- The minimum argon flow rate required to inert the entire silo to a level <2% oxygen would be 23 m^3/hr, or approximately 4 m^3/hr per compartment.
- Based on this flow rate, the time to inert the silo would be approximately 15 days.
- The argon would behave similar to a liquid when filling the silo from bottom to top similar to a bath filling with water and thus, is better represented by a plug flow rather than a mixed flow model. This important result was the first indication that argon injection at the bottom of the silo was an efficient means of displacing air from the silo and that no pockets of oxygen rich gas would remain. The assertion that argon filling was by plug flow was later verified by two-dimensional CFD modelling of the silo and confirmed during the silo commissioning trials.
- The top section of the silo would be the last to reach the target oxygen concentration and so the top of the silo would be the optimum location for any oxygen monitors.

Concrete porosity tests were performed on actual core samples taken from the silo to investigate the permeation of argon through the concrete silo walls. The results from these tests measured diffusion coefficient in the range 1×10^{-4} to 5×10^{-4} m^2/hr for a non-coated concrete surface. This inferred that argon leakage rates through the 300 mm walls of the silo would be in the range 3.5×10^{-4} to 1.25×10^{-3} m^3/hr per square metre of concrete. The diffusion coefficient and leak rate was reduced to 3×10^{-8} m^2/hr and 2.5×10^{-5} m^3/hr per square metre of concrete respectively when a nominal 1 mm layer of sealant was applied to the concrete surface. It was thus concluded that diffusion through the concrete would be very small and any cracks or through wall penetrations would dominate. These results initiated a programme of wall surveys and repairs, culminating in the coating of all external surfaces to enhance argon retention and minimise losses to levels that would support a safety case.

Because of surface cracking of the concrete, other tests were conducted to identify and assess the suitability of surface repair, preparation and sealant materials that could be applied to the external surface of the silo to reduce argon losses through the containment walls. They identified the best primer as a moisture curing urethane, because of its ability to significantly improve the cohesive strength of the concrete substrate. A urethane mastic was the better of two fillers tested, because it was easier to spread over a concrete surface, and a MTM Acothane proved to be the best top coat for filling in minor concrete defects.

The results from these R&D trials increased general confidence in the overall inerting proposal demonstrating that the proposal was practicable and further development of the scheme was worthwhile. They indicated for the first time that full inerting of the silo could be successfully achieved, providing key input information and data utilised during the subsequent design, installation and commissioning of the argon delivery and silo ventilation system.

STRUCTURAL IMPROVEMENTS (9)

A survey and inspection of the external surface condition of the silo walls was carried out in 1994/1995. The walls were washed down and areas of defective concrete and cracks repaired using a high strength polymer modified repair mortar. Following surface preparation, horizontal carbon fibre strips (nominally 100 mm wide by 1 mm thick) were then bonded to the external faces of the silo (1000 mm centre to centre) to strengthen the walls. Once the structural repairs, strengthening and surface repairs were completed, a 2 mm thick coating of mortar was applied before finally sealing the walls with a 1 mm coat of hot applied polyurethane sealant to minimise argon permeability. These measures, augmented by other civil and structural improvements to reduce loads on the silo and strengthen the roof, significantly reduced one of the key project risks.

OXYGEN MONITORING AND CONTROL (10)

Independent oxygen monitoring and argon flow control systems have been installed. There are 20 oxygen analysers. Sample points are distributed throughout the silo and at three levels along the length of the transfer tunnel. These monitors continuously record oxygen levels by extracting gas samples, with the sampled gas being returned back to the silo. Each monitor is set to alarm when oxygen concentrations in a compartment or in the tunnel reach an upper limit of 1.8% by volume.

COMMISSIONING (11)

There were a series of commissioning trials on the silo prior to full and continuous argon inerting. The principal aims were to:

1. Confirm that an inert atmosphere could be established within the silo and tunnel i.e. oxygen levels maintained at <2%. This target was pessimistically based on the minimum oxygen content required to sustain a metal fines fire.
2. Measure and record information and data that would allow the silo to be characterised in terms of argon retention, leakage and oxygen gain.

To achieve this purpose, initially a single compartment (Compartment 2) was inerted. This minimised the potential hazards, while providing sufficient data to determine how best to proceed with inerting the remaining silo compartments. Subsequently, the other five compartments were inerted and the overall objective of fully inerting the silo was achieved.

COMPARTMENT 2 INERTING TRIALS

The expectation, based on the previous R&D Trials and CFD modelling work, was that filling of the silo compartment would be by plug flow. It was predicted that there would be a rapid drop off in oxygen concentration, observed as a sudden fall on the oxygen analysers at the top of the compartment, once the compartment was full. This would imply that there was a narrow interface between the air and argon within the compartment. It was also anticipated that leakage rates through the compartment walls would be low, but there were concerns that the base of the compartment and construction joints might not be well sealed allowing significant argon leakage into the voids.

Inerting of compartment 2 commenced at the maximum design flow rate of 12 m^3/hr of argon. Subsequent analyses of the plant recordings showed that oxygen readings initially remained constant at the instrument full scale deflection (fsd) of 5%, but fell rapidly to 2% approximately 40 hours after inerting commenced. This rapid fall corroborated predictions that the filling regime was more akin to a plug flow rather than a mixed flow model, and that the argon was penetrating throughout the waste. The oxygen concentration continued to fall, reaching 1% after approximately 110 hours.

During the inerting of Compartment 2, the oxygen content of the voids was regularly monitored and no appreciable depletion occurred implying that no argon leaked out. Furthermore, monitoring around the silo has confirmed that no detectable leakage of argon occurred from Compartment 2.

COMPARTMENT 2 DE-INERTING AND RE-INERTING TRIALS

A series of further trials were conducted following the successful completion of the inerting trials to provide further important data in support of the safety case. These involved firstly isolating the argon supply and observing the instruments to determine how quickly oxygen levels in the compartment would recover. The oxygen concentration steadily rose from the base line of 1% in a near linear trend over the next 24 hours to approximately 2%, reaching 3% after 40 hours and 5% after 100 hours before exceeding the fsd of the instruments.

A further de-inerting trial assessed what impact the ventilation system had on inerting. It was established that it would take several hours before oxygen concentrations exceeded 2% with the ventilation system operational and more than 24 hours with the ventilation fan stopped.

Finally, the compartment was re-inerted by injecting the argon again at the full flow rate of 12 m^3/hr. There was a rapid decrease in the oxygen concentration to <2%, with levels continuing to fall and reaching 1% after approximately 30 hours.

FULL SILO INERTING TRIALS

Full commissioning trials were performed once the Compartment 2 trials had been successfully completed. These effectively repeated the trials performed for Compartment 2.

The results and outcome of the initial inerting trial generally reflected those recorded and observed for Compartment 2. All compartments attained the 2% oxygen concentration level approximately 60 hours after inerting commenced and then continued to fall to 0.5% after 70 hours. Recorded oxygen concentrations from the oxygen analysers located within the silo and tunnel are summarised in a diagram presented as Figure 3. Pressures in the tunnel extract were maintained between –10 and –50 Pa relative to atmosphere. Strong winds did affect maintenance of the pressures and caused the oxygen concentration at the top of the tunnel near to the extract to fluctuate by less than 1%.

CONCLUSIONS

1. Commissioning of the argon inerting system was successfully completed with the structural integrity of the silo and its argon retention capabilities proving to be better than was envisaged, prior to structural improvements. This means that in the event of an argon inerting system failure, the silo would remain in an inerted state (oxygen concentration less than 2%) for a several hours in the vicinity of the waste, even with the ventilation system operative. Argon can be retained for even longer periods of time (days) by switching off the ventilation system. This has enabled simplification of future inerting upgrade requirements, because a less rapid response is required following inert gas failure than was originally envisaged.
2. Commissioning established that atmospheric conditions (pressure fluctuations and wind speed) make fine-tuning of the silo depression to minimise the air in-leakage difficult to achieve. A compromise was implemented that balanced silo inflow, ventilation extract and atmospheric variations by maintaining the silo depression in the range –10 to –50 Pa.
3. Plug flow inerting of the silo compartments occurs during filling.
4. The maximum argon injection rate can be achieved with no sign of any restrictions to flow through the sumps and filter bed through which the argon is injected. It also suggests that there is no bulk free liquid at the base of the compartment as this would act as a resistance to argon flow.
5. No significant leakage of argon via diffusion or through construction joints has been detected into the voids under the silo. Nevertheless, area monitoring will continue to be provided.
6. The low-lying areas outside the silo, where argon could gather, were carefully monitored and no oxygen depletion was detected at any point. This is a function of the good argon retention of the silo and sealing. Whilst vigilance must continue in hazardous areas, it has been demonstrated that the hazard is less onerous than originally envisaged.

REFERENCES

1. Health and Safety Executive (Liverpool) January 2001
2. Occupational Health and Safety Administration. Department of Labor February 2001
3. Annual Report of the Health and Safety Executive 1998

Table 1. Comparison of argon, nitrogen and carbon dioxide properties

Property	Argon	Nitrogen	Carbon dioxide
Density (kg/m^3)	1.78	1.25 Diffusion rate is comparable with air. Would therefore need to change many compartment volumes to displace air and require large purge volumes.	1.98
Reactivity	Very non-reactive	Reacts with Mg, U & Zr at elevated temperatures.	Decomposed by Na, Mg, Li, K. Zr & metal hydrides. Forms weak acid in presence of water vapour that could attack the silo walls and structures.
Prevention of metal fires	Yes - due to oxygen depletion	No	No
Capability for extinguishing metal fires	Yes – any metal	No – once ignited Mg will continue to burn forming nitrides	No – Mg will burn forming oxides, CO & C.
Use as fire fighting system	Yes	No	No
Fulfils compartment inerting requirements	Yes	Yes	Yes
Cost (£/100 m^3)	39	7	17

Table 2. Safety legs providing the hazard management strategy for the silo argon asphyxiation hazard

Activities/Areas	Safety legs							
	Engineered		Engineered and ops, management & procedural				Ops, management & procedural	
	1	2	3	4	5	6	7	8
	Minimisation of argon flowrates	Containment	Access control	Safe working distance	Ventilation (forced)	Detection	Operational procedures	Respiratory protection
Argon delivery/ offloading to tanker	Y	y	Y	y			y	
Argon storage & let down plant		y	Y	y		y	y	
Argon supply to silo		y	Y	y		y	y	
Adjacent to silo	Y	y	Y	y		y	y	
Silo/tunnel roof	Y	y	Y	y		y	y	
Instrument cubicles		y	Y	y		y	y	
Control room		y	Y	y		y	y	
Vent & stacks	Y		Y	y		y	y	
Confined spaces (including tunnel and trenches)	Y	y	Y	y	y	y	y	*

* = As required, but only as a last resort.

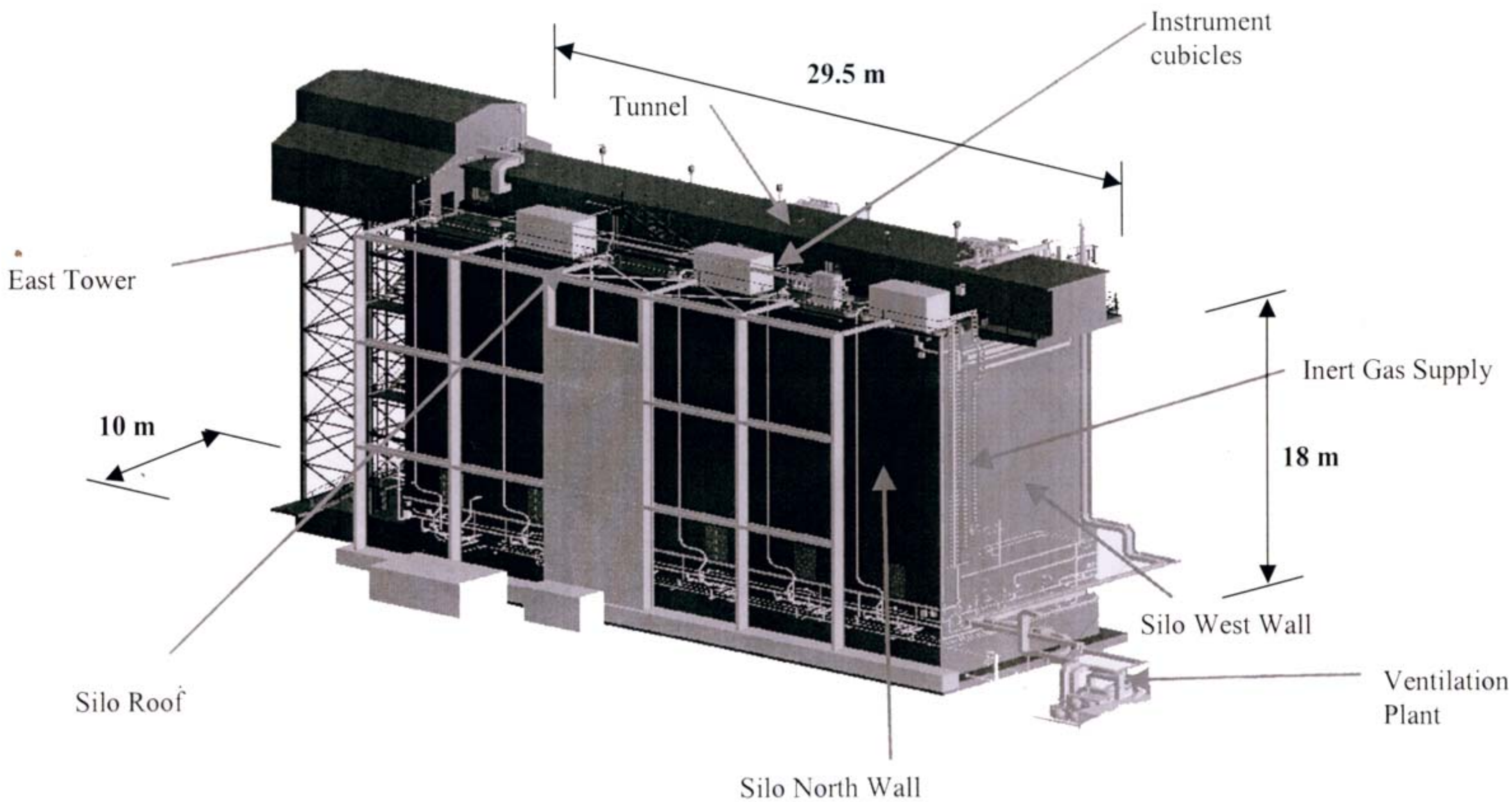

Figure 1. Silo isometric

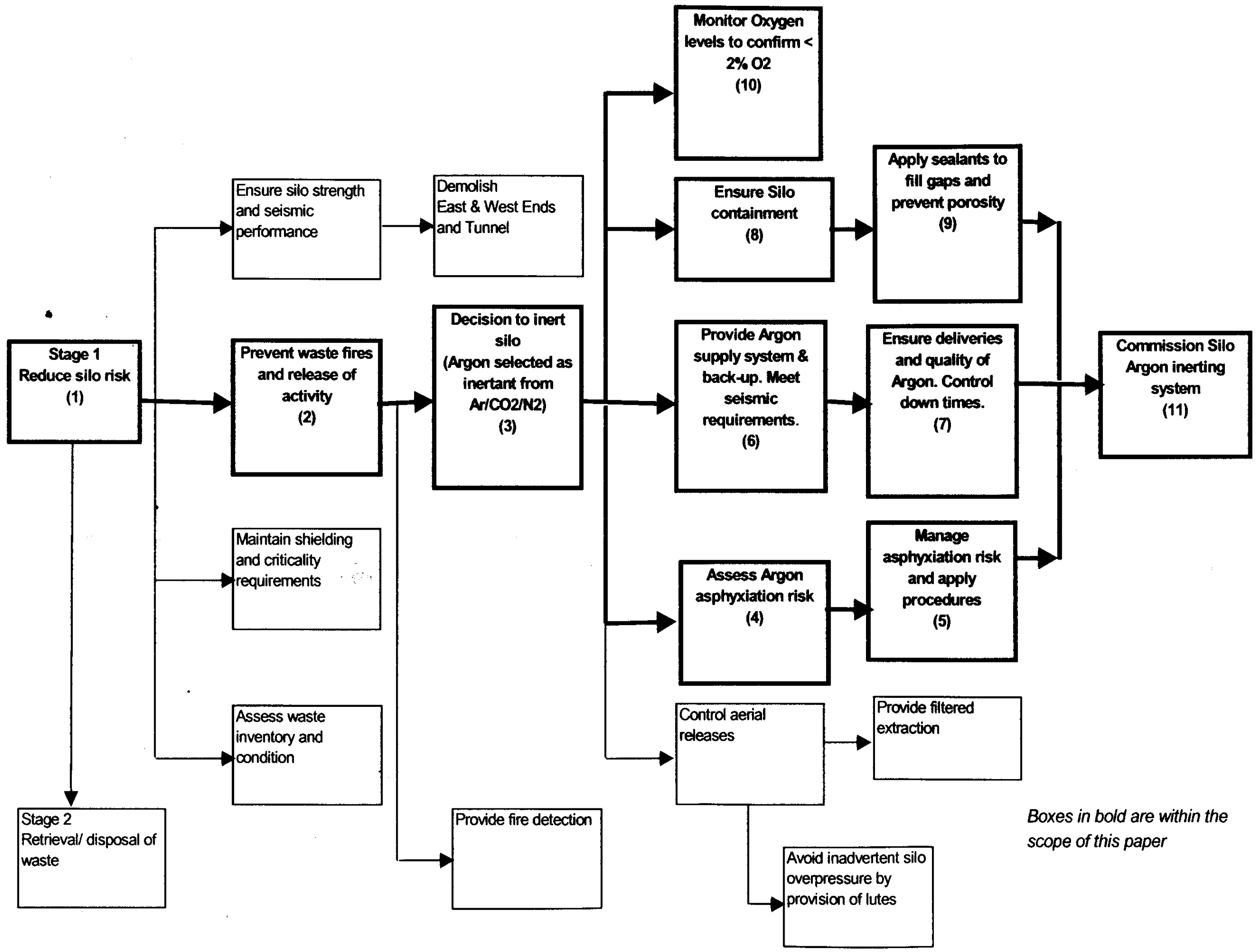

Figure 2. Fast diagram for silo risk reduction philosophy

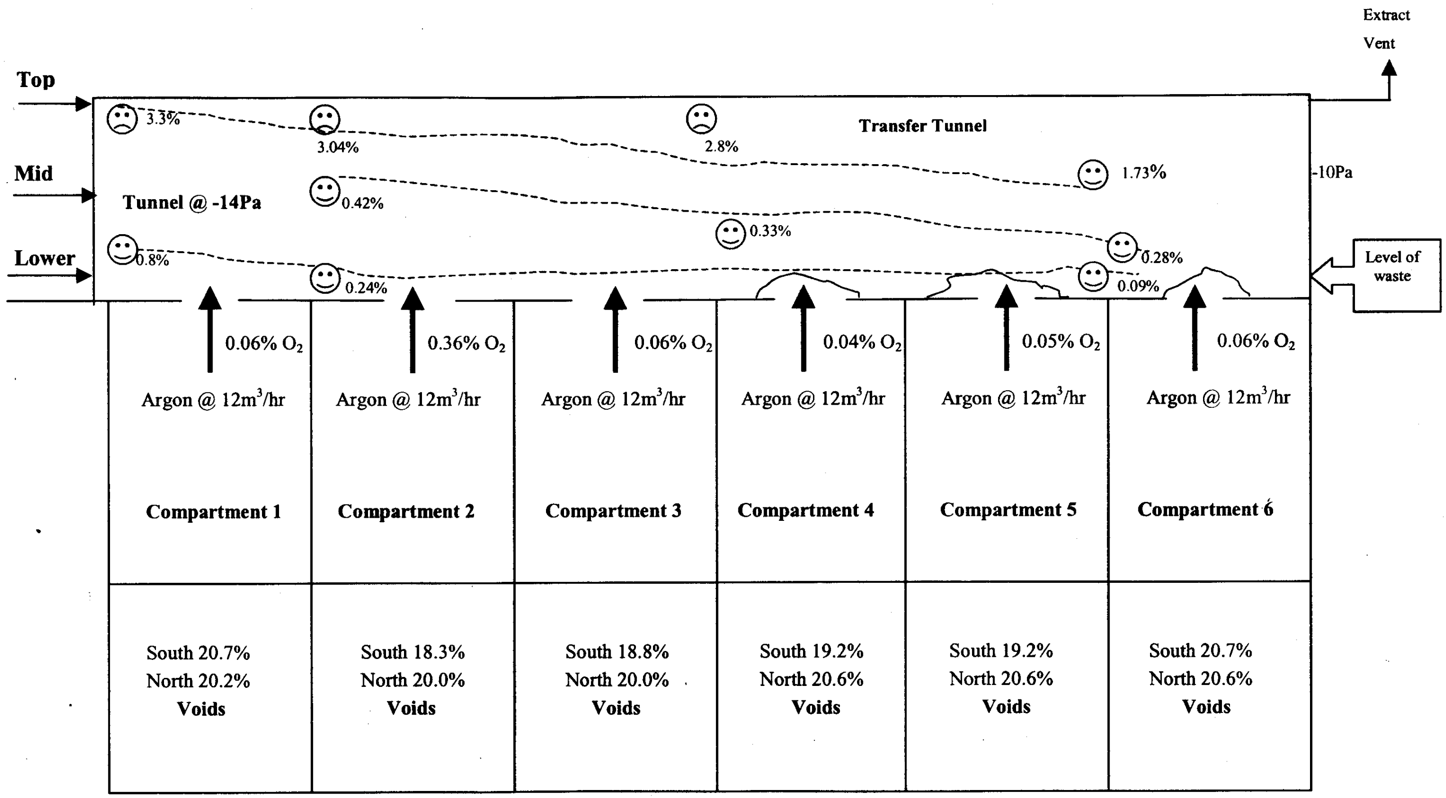

Figure 3. Oxygen concentrations measured during commissioning trials