THE CIRCUMSTANCES SURROUNDING THE FLOODING OF THE LONGANNET COMPLEX MINE, FIFE, SCOTLAND

23 MARCH 2002

A report by

HM Inspectorate of Mines
Health and Safety Executive

11 SEPTEMBER 2002
EXECUTIVE SUMMARY

Part of the Longannet Complex mine flooded on 23 March 2002 interrupting ventilation and causing the cessation of all activities other than the installation of pumping systems and associated work to recover the mine. The mine subsequently closed after the owner, Scottish Coal (Deep Mine) Ltd, entered administration. Pumping ceased on 3 April, and at the current time the workings are flooding progressively.

A mining engineering inspector from the Health and Safety Executive’s Mines Inspectorate (MI) began an investigation into the circumstances surrounding the incident within a few days of it occurring. Because of remaining uncertainties as to the cause of the flood, MI subsequently asked another of its inspectors, Steve Denton, BSc(Hons), CEng, FIMM, also a mining engineer, to examine all potential failure mechanisms and to determine as far as possible the likelihood of them occurring. That investigation is now complete and this report details its findings. Within the text it deals with the various allegations made by ex-employees and questions raised by their representatives.

Findings

There is very little hard evidence that relates to the actual incident. What there is, is limited to:

- Pressure readings taken at a dam site from which we can deduce the water levels in the sealed off part of the mine and estimate the rate of inflow to that part before the flood;
- A body of water within part of the working area rising at a certain rate and flooding the mine, from which we can estimate current inflow rates into the working part of the mine;
- An alarm sequence recorded by the mine monitoring system, which if accurate enables us to make some broad estimates of initial inflow rates into the working part of the mine.

What little evidence we have tends to point to a rapid inrush into the mine of around 3.6 million gallons of water within 20 minutes of the incident starting and 17 million gallons within 2.5 hours.

The findings that relate to possible failure scenarios are little more than informed guesswork based on an analysis of that evidence and of information obtained during investigation of the circumstances leading up to the flood. They therefore need to be treated with caution. All of the potential causes appear to be extremely unlikely or inconceivable, and none reasonably foreseeable. Specific findings are as follows:

- We consider the most likely source of the water to have come from behind one of the dams built in 2001 to seal off the worked-out Castlebridge and Solsgirth parts of the mine complex, the water having passed through or around the dam.
- We consider that failure of the surrounding strata is more likely than failure of a dam.
The dams appear to have been designed and constructed to a standard and strength well in excess of those required by an industry code of practice.

While the code of practice could be strengthened in some areas the design elements within it are based on engineering first principles and both dams appear to have been more than adequate to resist the pressures exerted on them by the maximum possible heads of water.

The Castlehill/Solsgirth dam had been reduced from its original design length (10.8m plus a 10.8m explosion-proof stopping) to 7.32m in its final form, but only because a much higher strength grout was used to build it than originally specified and a separate explosion-proof stopping was first constructed.

An engineering consultancy’s water report anticipated there would be some leakage around the Castlehill/Solsgirth dam. However, with hindsight the rate of flow around the dam at a relatively low head may have been a precursor to failure, but not necessarily of the dam. We could not determine whether the water flowed wholly through the solid geology or whether there were some undetected fractures within the strata.

There was no evidence of sabotage as a cause of the flooding.

Breaching the Piperpool pumping borehole from the surface will determine whether or not there is a connection between the body of water north of the dams and that south of the dams.

The only way to determine beyond doubt the cause of the incident would be to pump out the mine (including the Castlebridge/Solsgirth side of the dam). The cost of doing so would be substantial, and any gain in health and safety benefits marginal, so this course of action is difficult to justify.

Recommendations

Detailed recommendations appear close to the end of this report.

While there are no recommendations specific to the mine, MI has already stimulated other mine owners to look again at inrush potentials in their mines in light of some of the findings that have emerged from this investigation. A Mines Inspector has followed-up with a number of inspections targeted at large mines.

All but one of the remaining recommendations relate to the production of guidance to supplement an existing industry code of practice, part of which relates to the construction of underground water dams.

THE INCIDENT

Just after 17:00 hours on Saturday 23 March 2002 a number of roadways (mine tunnels) close to the bottom of the Castlehill Mines at the Longannet Complex Colliery,
near Kincardine-on-Forth, Fife, flooded very quickly with water. The 15 people below ground at the time were in another part of the mine remote from this area and all were evacuated to the surface via the Longannet Mine. The water overwhelmed the pumps and it took less than 20 minutes from the first indication that something might be wrong to the level rising far enough to flood the 5th cross cut (connecting roadway) between the Castlehill Mines. It interrupted the ventilation circuit causing the ventilation pressure to fluctuate and the surface fan to trip out.

Management on duty at the mine quickly organised two teams to enter the mine, one from Castlehill and one from Longannet. They subsequently determined that part of the mine had flooded and that the water was still rising. The mine manager put into place the mine emergency scheme and called out all key personnel. As a matter of expediency he also called out the Mines Rescue Service (MRS) whose part-time brigade men were Longannet workers. When the teams arrived one of the officials exploring the Longannet Mine was slightly late contacting the surface. MRS had just started to prepare a team to go below ground to locate him when he called from the Bogside telephone.

Based on the information on water levels supplied by the exploration teams it appears that within no more than two and a half hours over 80,000m$^3$ (17 million gallons) of water flowed into the mine at an average rate of over 110,000gpm. Subsequently, based on the time the main fan took to trip out, the surveyor calculated the volume of the roadways flooded in the first 19 minutes at over 16,000m$^3$ indicating an initial inflow into the mine workings of some 3.6 million gallons at a rate of 175,000gpm (13.5m$^3$/s = 13.5 tonnes/s).

Over the next 12 hours or so, the rate of rise continued to reduce until at a point 214m below ordnance datum (BOD) it assumed a constant rate of rise. The initial water level prior to the flood had been 252m BOD at the pumps.

It took nearly five days to establish auxiliary ventilation systems and then pumping systems. When pumping commenced at a measured rate of 900gpm to the Castlehill surface, unexpectedly the water level hardly fell.

On the same day, the mine owner, Scottish Coal (Deep Mine) Limited, entered receivership and shortly afterwards, when it became clear that no new operator was prepared to take over the mine, all the pumps were switched off. These included pumps controlling other inflows, including the 650gpm inflow into the Longannet Mine, and switching these off allowed that water to flow further into the mine workings. The water has continued to rise up both the Castlehill Mines and the Longannet Mine flooding the Kincardine area workings, the coal producing part of the mine, in the

2 ‘Mine’ is the term used in Scotland to describe sloping tunnels driven from the surface to access coal seams. The ‘Castlehill Mines’ are two parallel sloping tunnels driven from the surface at Castlehill to gain access to the Upper Hirst coal seam. There was a third mine, the ‘Longannet Mine’ at the Longannet site that connected with the Castlehill Mine approximately 300m vertically below the surface (245m BOD).

3 For the purposes of this report the ordnance datum can be taken as the mean sea level. Anything below ordnance datum (BOD) therefore has the same meaning as below mean sea level and is a convenient reference point from which to define the depth of mine workings.
process. On 18 June 2002 the water level in both the Longannet and Castlehill Mines stood at 180m BOD.

THE HSE INVESTIGATION

A mines inspector from the Health and Safety Executive’s Mines Inspectorate (MI) started an investigation into the circumstances surrounding the flooding within a few days of it occurring. Initial findings based on the limited knowledge available at that time concluded that it was impossible to determine with any degree of certainty where the water came from, but that the most probable source was old Castlehill workings some 50m higher than the bottom of the Castlehill Mines.

MI alerted other mine operators to the circumstances surrounding the incident requesting they review the situations at their mines and identify any places that might be similarly at risk. Subsequently MI followed up by visits targeted at a number of large mines.

While this process was going on, there emerged from a few ex-employees and their representatives a steady stream of allegations that, if they could be substantiated, might have had a bearing on the cause of the flooding. Because of this and the uncertainties surrounding the cause, MI decided to carry out a more detailed investigation than originally envisaged. The HSE investigation aimed to:

- Examine all potential inrush mechanisms;
- Assess the relative likelihood of each mechanism occurring;
- Deal with the various allegations made by ex-employees and the questions raised by their representatives insofar as they related to health and safety.

Mr S P Wing, HM Principal District Inspector of Mines (MI’s senior field officer), asked me to carry out a detailed investigation and to prepare this report. I examined relevant documentation and interviewed those identified to me who might be able to assist the investigation. A list of the functions of the people I spoke to is at Appendix 1, and a list of colleagues who provided help and support at various stages of the investigation is at Appendix 2.

BACKGROUND TO THE LONGANNET COMPLEX

The Longannet Complex came into being in the 1960’s when the then National Coal Board (latterly British Coal) decided to drive the Longannet Mine from a site near to Longannet Power Station on the northern side of the Forth, about a mile to the east of Kincardine on Forth. From the bottom of the Longannet Mine a roadway was then driven straight on to connect with new roadways driven at the same time from the Bogside, Castlehill and Solsgirth Collieries to form a single, straight but undulating tunnel over five miles long and at about 245m BOD.
They then installed a single cable-type conveyor belt from the surface at Longannet running for over five miles to the Solsgirth Colliery workings. The new roadway became known as the ‘Cable Belt Mine’, and it meant that all of the coal produced from the Upper Hirst seam at the Bogside, Castlehill and Solsgirth collieries could be brought to the surface at Longannet and conveyed straight into the adjacent power station. See Appendix 3, Plan 1.

Two new roadways were driven west from the Cable Belt Mine, between Castlehill and Solsgirth to connect with roadways driven from a new shaft at Castlebridge, to open up millions of tonnes of coal reserves for mining to the north and north-east of Castlebridge.

The Bogside Colliery closed in the 1980s and the Bogside mines were sealed at the top and bottom. By the early 1990s the remaining Castlehill and Solsgirth coal reserves had been exhausted with production now concentrated in the Castlebridge area. This was the situation when the coal industry was privatised in 1994 and the Longannet Complex passed from British Coal into the ownership of Mining Scotland and subsequently to its subsidiary company Scottish Coal (Deep Mine) Ltd.

The new owners continued with plans drawn up by British Coal to flood the old Castlehill west workings. The initial plan was to let the water level build up from below 400m BOD in the old Castlehill west workings to 252m BOD at which point it would overflow at a controlled rate from an old roadway near to the bottom of the Castlehill Mines where it could be collected and piped to the Castlehill pump lodge for pumping to the surface.

However, the Castlebridge pit bottom was 340m BOD, 90m lower than Castlehill, and to stop water reaching the Castlebridge shaft a dam was designed and constructed at the top of the Castlehill-Castlebridge New Mine, a roadway connecting the Castlebridge shaft with the Castlehill west workings, about 300m to the south of the shaft (‘DAM NO.1’ on Plan 1). The dam was 345m BOD and was designed to withstand a head of 90m (345-252=93m). In the event the mine decided to let the water flow through a 300mm pipe through the dam and pipe it to the Castlebridge pit bottom pumps, thus controlling the water level in the old Castlehill west workings to around 340m BOD.

The geology of the Castlebridge area and the adjacent Aberdona area worked from Castlebridge was more difficult than predicted with extensive faulting making much of the remaining coal very difficult and uneconomic to extract. In the late 1990s the mine started to develop two roadways from the Longannet Mine to access millions of tonnes of coal in the Upper Hirst seam in the Dewar Zone, an area beneath the Forth downstream of the Kincardine Bridge.

Production from the Kincardine area started in 2000 with production from Castlebridge ceasing at that time. There being no further prospect of mining coal in the northern (Castlebridge/Solsgirth) side of the complex the company took the decision to seal off

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4 A ‘dam’ in a mine is the term used to describe a concrete plug used to completely seal a tunnel and prevent the flow of water. In strict engineering terms it is a ‘bulkhead’ or ‘plug’ rather than a dam.

5 ‘Head’ is a term used to describe the height of water above a reference point and is directly proportional to pressure (1m head ~ 10kN/m² ~ 14lb/in²). Hence a head of 435m would exert about 4,350kN/m² (~ 609lb/in²) on the face of the dam.
all workings to the north of Castlehill. This involved strengthening the Castlebridge water dam (‘DAM NO.1’ - Plans 1 & 2) and building a new water dam in the Cable Belt Mine at a suitable point north of its intersection with the Castlehill Mines between Castlehill and Solsgirth (‘DAM NO.2’ - Plans 1 & 2).

In mid-2000 the owner brought in International Mining Consultants (IMC) to conduct a mine water study and to make recommendations on dam sites, design and construction. These dams would isolate the old Castlebridge and Solsgirth workings from the current Kincardine working area, access to which could be gained via either the Longannet or Castlehill mines.

The consultant’s report concluded that this was a viable option for managing mine water make in the long term and made recommendations for the dams and the treatment of the Castlebridge shaft. IMC concluded that the existing (1995) dam at Castlebridge should be up rated and that a new dam should be constructed in ‘the Castlehill – Solsgirth drivage’ (the Cable Belt Mine). The report also anticipated some seepage through the sandstone around the new dam.

A contractor, Amalgamated Construction (AMCO), built the new Castlebridge dam between January and April 2001, and the Castlehill/Solsgirth dam between August and September 2001.

The building of the new Castlebridge dam stopped the mine pumping water through the pipe in the original dam, as planned, allowing water in the old Castlehill west workings to rise steadily from 330m BOD. As expected, a few months later it reached 252m BOD and started to overflow into the S5 roadway and from there was piped to the Castlehill pump lodge and pumped to the surface.

On completion of the Castlehill/Solsgirth dam all remaining pumps to the north of the dams were turned off allowing water to start to accumulate and progressively flood the sealed off workings. As the water reached the Castlehill/Solsgirth dam and the level started to increase behind it, water started to seep through the strata emerging from the roof on the left hand side in front of the dam. Scottish Coal asked AMCO to do some further curtain grouting to control the flow, but it only succeeded in transferring the seepage further out. The flow steadily increased and before the flood was estimated at around 30-40gpm by both the mine manager and by the command supervisors responsible for that area of the mine. While the water caused some difficulties underfoot, because seepage had been anticipated, it was considered a nuisance rather than an indication of a potential threat to the mine.

By 02:00 on the morning of 23 March 2002 a mine official read the water pressure gauge monitoring the pressure of water behind the Castlehill/Solsgirth dam at 67lb/in\(^2\) indicating that the water level was nearly 48m above the dam. The flood occurred 15 hours later at which time the level would have been around 400mm higher, at around 197m BOD, and the pressure on the north side of the dam no more than 48kN/m\(^2\) or 68lb/in\(^2\).

At the time of the flood the water levels at the Castlebridge dam would have been 197m BOD on the north side (the same as that behind (north of) the Castlehill/Solsgirth dam) and 252m BOD on the south side (the same as at the Castlehill pump lodge), giving a

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6 IMC report 4042 ‘Report on Longannet Water Management for Scottish Coal’
net head of 55m on the north side and a net pressure of around 76lbs/in$^2$ from the north side.

Appendix 3, Plan 2 is an isometric sketch of the Longannet Complex to illustrate the flood location and show how it interrupted the ventilation path. Appendix 3, Plan 3 is a copy of part of a mine plan coloured to show the water level prior to the flood in the roadways around the Castlehill pit bottom area. Appendix 3, Plan 4 shows the assumed water levels in the Castlehill pit bottom area at 17:20 when the main fan tripped out as the water interrupted the main ventilation circuit.

**POTENTIAL WATER SOURCES**

The rate of inflow of water to the bottom of the Castlehill Mines during the early stages of the incident appears to have been around 175,000gpm (~13.5m$^3$/s). There is some doubt as to what were the normal water flows into this area as the mine did not keep a systematic record of pumping times or rates, but it seems unlikely to have been more than 400gpm (~0.03m$^3$/s). Such a high flow must therefore have resulted from a sudden, catastrophic release rather than failure to control existing water flows. Pump failure can therefore be ruled out as the cause of the flooding.

The investigation considered five potential sources that might have provided the amount of water that flowed into the workings:

- Surface (including boreholes)
- Waterlogged strata (aquifers)
- Shafts (vertical accesses from the surface) and mines (sloping tunnels from the surface)
- Waterlogged old workings on the Longannet/Castlehill (south) side of the dams
- Flooded old workings on the Castlebridge/Solsgirth (north) side of the dams

The report now goes on to examine the mechanisms by which water from these various sources might have reached the mine workings.

Because of the lack of a systematic record of pump running times most of the water flow rates from various parts of the mine before the flood quoted in this report are best guesses based on the limited information available.

**Surface**

All of the longwall face workings to the south of the dams were generally deeper than 100m BOD with a minimum depth of cover of around 120m. Therefore, for surface water to enter the workings at the calculated rate of inflow, it would need both a long and large conduit to reach the workings. My calculations indicate that it would require a conduit with a cross sectional area of at least 0.75m$^2$ (equivalent to a one metre diameter pipe) to pass the 13.5m$^3$/s required to fill the workings at they rate they initially filled.

To the north of the dams the mine worked a number of faces within 100m of the surface in the Devonside district at Solsgirth. However, any water ingress from the surface into...
this part of the mine could not have reached Castlehill while the dam sites remained intact.

Exploratory boreholes and pumping boreholes drilled from the surface intersecting the mine workings were no more than 250mm diameter (~0.05m$^2$), and it would therefore need the simultaneous failure of about 15 of them to transfer water at the required rate. I consider this inconceivable, particularly as all exploratory boreholes were sealed after drilling.

A conduit of the size and length necessary is unlikely to occur naturally in the absence of major seismic activity, either natural or mining-induced. The British Geological Survey (BGS) in Edinburgh Seismic Monitoring and Information Service monitors seismic activity across the United Kingdom and when contacted by telephone reported that there was no significant seismic activity in Central Scotland on 23 March, or in the country as a whole.

There are four BGS seismometers (Aberfoyle, Auchinoon, Edinburgh and Corrie) within 26-45km of the mine$^7$.

The loss of at least 80,000m$^3$ of water from the surface in a few hours should have provided a visible effect. It is likely to have led to a lowering of the water table in the vicinity of the conduit and would probably have caused local watercourses to dry up and other effects such as the lowering or disappearance of any water in the bases of quarries.

On hearing that the mine had flooded, a concerned member of the public telephoned the mine and reported that a small stream had dried up. The reported location was above the old Castlebridge workings to the north of the Castlebridge shaft, which were at a depth below the surface of over 400m. Enquiries made by the mine survey staff were unable to confirm this. The mine surveyor also visited the Bath Moor and Burrowmine Moor sand quarries working above former Longannet Complex workings and found no evidence of any abnormal events.

**Strata water**

At section 3.5.1 the IMC report (see footnote 6) notes that the Upper Limestone Formation (ULF) of strata in which most of the mine is driven includes up to 35% vertical thickness of sandstones, and that these will be capable of storing and transmitting water (3.9).

The Passage Formation lies above the ULF and the report (3.6) notes that ‘...it is dominated by many thick sand bodies...’ and that ‘...these are the most important as reservoirs because of their thickness, lateral extent and connectivity, coarser grain sizes and generally poor cementation’ (3.9).

The Longannet, Bogside, Castlehill and Solsgirth Mines all penetrate these sandstone beds, as does the Castlebridge shaft. The Longannet Mine was by far the wettest of these accesses with a net inflow calculated at around 650gpm (~50 litres/s), all but 50gpm flowing in at the Plean 3 sandstone bed horizon in the 1 in 4 section. The other

$^7$ Locations taken from Annex E of ‘UK Earthquake Monitoring 2000/1’ the Twelfth Annual Report of the BGS Seismic Monitoring and Information Service
accesses had less significant inflows. The Castlebridge shaft was concrete lined and sealed against water ingress.

There is no history of significant water flows along fault planes, most of which were effectively sealed against measurable water flow by smearing from the clayey rocks in the succession. Neither were significant water flows associated with the igneous (volcanic) intrusions and the non-igneous tuff features encountered across the mine.

The mine was damp throughout and water flows into the mine increased as mining induced stresses caused fracturing of the strata above the coal seam to the overlying wet rocks. However, during the life of the mine there was no history of sudden inrushes and all water was routed to sumps from where it was pumped through pipe ranges to the surface.

As with the surface water scenario the failure of a sealed exploratory borehole does not provide a large enough diameter conduit to be able to transmit water into the workings at the rate seen at the time of the inrush. There were no active workings in the vicinity of the inrush, and had there been a sudden massive settlement of old workings such a seismic event should have registered on the closest BGS seismometers.

Even if there had been a connection of a sufficient size to pass the amount of water necessary, bearing in mind the permeability of the strata, it is unlikely that the inflow rate from the strata to the conduit would be more than a fraction of the rate of inflow seen during the early stages of the event.

Shafts and mines

Shafts and mines would have the potential to create the inflow rates but not the volume. To add to this there were no shafts connecting into the workings to the south of the dams.

Of the mines to the south of the dams the Bogside Mines were sealed top and bottom in 1990. However, the mine continued to drain water from behind the lower Bogside dam into the Bogside pump lodge so there were no significant amounts of water trapped behind the dam. Following the flooding, both the Longannet Mine exploration team and subsequently others were able to gain access beyond the Bogside pump lodge and found no evidence of any inflow from that point.

The other mines to the south of the dam, the two at Castlehill and the one at Longannet, remained open and were clearly not the source of the water.

To the north of the dam, water would have risen some 133m up the Castlebridge shaft and also about one third of the way up the Solsgirth Mines. However, this resulted from the general rise in water level to the north of the dams so there was no potential for an extra sudden inflow from these sources. Even if there had been such a sudden inflow anywhere to the north of the dams it should not have reached the Castlehill workings in the absence of some other failure around either of the dam sites.

Waterlogged old workings on the Longannet/Castlehill (south) side of the dams

There were waterlogged old Castlehill workings to the west of the Cable Belt Mine, and waterlogged old Bogside workings and Castlehill workings to the East.
Castlehill workings to the west

Following the sealing of the Castlebridge dam the water from the old Castlehill west workings had been allowed to rise by about 90m (from 340m to 252m BOD) until it overflowed at a controlled rate close to the Castlehill pit bottom and was piped to the Castlehill pump lodge from where it was pumped to the surface. While the absence of systematic pumping records leaves some room for speculation the net amount flowing from this area is likely to have been no more than about 250-350gpm.

All of the Castlehill west workings were deeper than the bottom of the Castlehill Mines and there were no structures that might have prevented the water from freely overflowing and building up within the workings to the extent that it alone could have caused such a catastrophic flood.

Bogside workings

These were known to be flooded and could have contained up to about 120,000m$^3$/s (~25 million gallons), depending on assumptions made about the ratio of void spaces in waste areas. However, water overflowing from these workings had been pumped from Bogside for many years and, as with the Castlehill west workings, there seems to be no potential for an uncontrolled sudden overflow at the rate seen at the time of the incident. Furthermore, mine personnel still had access after the flood to the Bogside pumps and to the roadways along which water from these workings would have flowed. There was no evidence of any flow from this source towards Castlehill.

Castlehill workings to the east

There were three waste areas from worked out faces to the east of the Cable Belt Mine:

- C07 worked 1974-5 at a depth of 250-285m BOD;
- C16 worked 1980-2 at a depth of 135-210m BOD;
- C19 worked 1985-6 at a depth of 95-170m BOD.

All three faces were damp when worked.

C07

When C07 was abandoned and the pumps turned off the water that built up within the waste flowed out via C07 Access, into S2 and eventually down to the pumps at N6, which was a main pumping station for Castlehill at that time. When the mine built the first Castlebridge dam in 1995 the N6 pumps were switched off and the water level in the Castlehill west workings was allowed to rise to 340m BOD. However, the water from C07 would continue to flow along the same route joining with the same body of water now being drained at the Castlebridge dam and pumped up the shaft.

On completion of the second Castlebridge dam and the Castlehill/Solsgirth dam in 2001, the water level in the Castlehill west workings was allowed to rise to 252m BOD before overflowing at a controlled rate (~250-350gpm) to the Castlehill pumps. As C07 is deeper than the bottom of the Castlehill Mines, and the flow from C07 has been

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8 The longwall face method of working used at the mine allows the rock above the coal seam to collapse after mining the coal. These caved areas of broken rock are known as wastes, and the amount of space in them as the voids ratio
under control, it is difficult to envisage any circumstances where sufficient water from C07 could build up above 252m BOD and then suddenly release. Appendix 3, Plan 5 shows the probable water levels in the C07 area and indicates the likely water flow paths to the Castlehill pumps.

**C16/C19 Area**

The C16/C19 area was a potential source as their waste areas are between 35m and 150m higher than the bottom of the Castlehill Mines, and therefore any water running from these wastes would ultimately end up in the Castlehill pit bottom.

Two former supervisory workers whose duties included pump maintenance estimated the total flow from the C16/C19 area at 200-250gpm during its working life, but this will have reduced considerably since the end of coal production in 1986.

For 17m gallons of water to accumulate there would have to be some physical barriers to hold it back and prevent it flowing to the pumps in the Castlehill pit bottom. The only obvious barriers to water flow were ventilation stoppings erected by the mine to prevent air from entering the C16/C19 and C07 areas of the mine when coal production ended there. To allow water to build up three of these stoppings, number 50 at 244m BOD, number 90 at 201m BOD, and number 89 at 233m BOD, would all have to have stopped water flowing from C16/C19 for a significant period.

Based on contours taken from the mine statutory working plans and other work done by the mine staff and IMC, I analysed the likely water flow paths and determined the necessary conditions for 17m gallons to have accumulated in the C16/C19 area. Appendix 3, Plan 5 also shows the probable water flow paths from this area.

If they were completely filled with water the combination of roadways and wastes in the C16/C19 area could potentially hold 32-80 million gallons, assuming 20%-50% void space in the waste areas, less if the voids ratio is less.

The mine surveyor calculated that at 50% voids the C16 waste would have to be flooded to the 180m BOD contour in order to store 17m gallons. This means that stopping number 50 at 244m BOD would have to withstand a head (the height of water above the stopping) of 64m, which is the difference between it and the water level. Put another way this equates to a force on the wall of 64 tonnes/m², or a total force of 1,300 tonnes, pushing against the stopping. Similarly, stopping number 89 at 233m BOD would have to resist a head of 53m, and stopping number 90 a head of 41m. See Appendix 3, Plan 6.

At 20% voids the level of water in the C16 and C19 wastes would need to be near to 160m BOD to hold back 17m gallons requiring stopping number 50 to withstand a head of 84m, which equates to a force on the wall of about 84 tonnes/m², or a total force of 1,700 tonnes, pushing against the stopping. Similarly, stopping number 89 at 233m BOD would have to resist a head of 73m, and stopping number 90 a head of 41m. See Appendix 3, Plan 7.

In order to assess the likelihood of them being able to withstand such pressures, it was therefore necessary to determine the construction of these stoppings and to calculate their strength.

In the Upper Hirst Seam the accumulation of explosive gas in wastes has never been a problem in shallower workings such as these, and consequently there was never a need
to build explosion-proof stoppings to seal off waste areas. Stoppings therefore have tended to be one, two or three fly ash block walls (the blocks being known as Siporex blocks after their manufacturer). It was not unusual for the mine to use rubble to seal off roadways not connected to waste areas.

The mine maintained a 'stoppings book' that contained some details of the stoppings erected. The book I saw dated from the early 1970's and included the stoppings in this area. It records stopping number 50 as being a single Siporex (fly ash) block wall with a (gas) sample tube through it but no drainage pipe. There is no record in the book of the date of building of this particular stopping but it seems to have been one of five stoppings (50-54) built around July 1980 to seal off the worked-out C07 area. Number 90 was another single wall stopping, and number 89 was three separate walls spaced at 12m intervals. The mine built both of these stoppings in late 1988 as part of the programme to seal off C16/C19 for ventilation purposes.

There was no record of stoppings being knocked down or otherwise breached prior to the area being abandoned, although some later ones were built with 150mm pipes through them to allow any water behind them to drain freely. However, two former command supervisors recollect stopping number 50 being breached at the bottom as part of the C16/C19 abandonment process, specifically to allow water to flow freely out of the area.

I asked Eur-Ing Mr S Cartney, BSc(Hons), CEng, FICE, MIOSH, one of HSE's specialist civil engineering inspectors, to undertake some calculations on the likely ability of walls, made of 620x215x280mm fly ash blocks with a compressive strength of 3.5N/mm$^2$ (manufacturer's data) and an average mortar, to resist water pressure on one side. The assumptions made in the calculations err to the conservative and indicate that if the wall could fail in bending, where the water pressure causes the middle of the wall to bulge out and collapse, at a head of only 4.6m of water, and that the highest conceivable head was around 16m.

The other potential failure mode is shear failure, where the water pressure forces blocks near the bottom of the wall (where the pressure is higher) to slide over each other or to slide along the floor or side of the roadway. The calculations indicate that the head would be around 10m.

The calculations make no allowance for any confining pressure that might have been exerted downwards on a wall by the roof of the roadway lowering over time as it deforms due to strata pressure. Any confining pressure would push the blocks in the wall together improving its ability to withstand force. However, the history of roadways in the Upper Hirst Seam at Longannet is that once driven they deform very little. Therefore, any confining pressure exerted on any of the walls is likely to be very low. Whatever the confining pressure Cartney found it 'inconceivable' that such a wall could resist a 32m head of water, which is still only half that which would be needed to hold back 17m gallons of water at the most optimistic voids ratio.

An undated (but probably mid-1990’s) technical paper posted on the US Department of Labor’s Mine Safety and Health Administration (MSHA) website reports on the

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9 ‘Technical considerations for the design and construction of mine seals to withstand hydraulic heads in underground mines’ – DT Kirkwood and KK Wu.
outcome of hydraulic tests on a double-thickness, buttressed concrete block bulkhead, which is substantially stronger than a single fly ash block wall, and notes that ‘...the maximum allowable pressure that the bulkhead can safely withstand is approximately 17.9kPa (6ft of water head)’.

It seems likely therefore that even if stopping number 50 were not breached deliberately when these workings were sealed in 1988, the increasing weight of water would cause it to collapse well before C16 and C19 wastes started to fill with water. Assuming that it failed at 20m head, it would have released water from about 400m of flooded roadways containing about 8,000m$^3$ (~1.75 million gallons) of water. This would have flowed into the old Castlehill west workings and percolated down to the N6 pumps, where had pump running times been monitored they would have shown an increase, probably over a period of several days.

Potential water inflows in the 13.5 years between the sealing off of these workings and the flood seem to indicate that water did flow freely from C16/C19, either because stopping number 50 was breached deliberately or collapsed quickly due to the build up of water pressure behind it following sealing. Had the average inflow rate to C16/C19 been only 10% of what it was when the faces were working, say 20gpm, the total make in 13.5 years would have been around 140 million gallons, about twice as much as the workings are capable of holding even at a relatively high voids ratio of 50%. To accumulate 17 million gallons would have required the average flow from this area to be less than 2.5gpm, which seems inconceivably low.

Assuming that there was a flow path I considered the possibility of the low point in that path, a length of S2 at 334m BOD, becoming progressively silted up over the years and causing a blockage in relatively recent times. This would have caused water from the C07 and C16/C19 areas to build from its 319m BOD free flow level but it would have found other potential routes through the old workings to the N6 pumps. Even if all of these routes had become silted up the water would have eventually appeared at stopping number 92 at 246m BOD, which remained accessible up until the time of the flood. It is therefore difficult to conceive how sufficient water could accumulate to produce the flood that occurred. See Appendix 3, Plan 8

The lack of conclusive evidence makes it impossible to rule out completely the retention of water either behind stoppings or by the blockage of flow paths, but it is almost inconceivable. In the first case, three separate fly ash block wall stoppings would have to withstand enormous pressures for which they were not designed, and in the second case there would have to be at least four simultaneous restrictions against large heads to generate the quantities required and some indication at stopping 92 that significant amounts of water had built up. The circumstances tend to indicate that water flowed steadily from these workings and continued to do so until the time the flood occurred and that the C16/C19 area was not the source of the floodwater.

**Flooded old workings on the Castlebridge/Solsgirth (north) side of the dams**

These workings were deliberately flooded following the closure of the Castlebridge and Castlehill/Solsgirth dams as part of the mine water recovery strategy for the Longannet Complex. By the time of the flood the water behind the Castlehill/Solsgirth dam had risen to 197m BOD, some 48m above it.
After the flood the water finally settled to a steady rate of rise in the Castlehill and Longannet Mines at 214m BOD, indicating that it was at the same level as that in the reservoir that had been the source of the floodwater and that both reservoirs were rising together as a result of further water inflow.

If there were there some connection between the water bodies to the north and south of the dams there would have been sufficient water in the old Solsgirth S67, S69, S84 and S86 wastes, between 197m and 214m BOD, to release the amounts seen. Working on a 20% voids ratio, it works out to be within about 20% of the amount of water that arrived at Castlehill in the first few hours.

The dams between these workings were engineered to have a minimum 4:1 safety factor at head of 435m and should therefore not have failed when the head on the Castlehill/Solsgirth dam was only 48m (~11% of the design head) and the net head on the Castlebridge dam 55m (~13% of the design head).

The alarm sequence

The first indication that something might be wrong was at 17:05 when an air velocity monitor sited at the end of the flexible ventilation duct delivering air to the face of the Castlehill/Solsgirth dam generated a critical (high-level) alarm in the surface control room.

Two minutes later, at 17:07, the same air velocity monitor generated an operational warning (one level down from a critical alarm), while at the same time the vibration monitor on the auxiliary fan generated two critical alarms in quick succession.

At 17:11 there was another critical alarm indicating that the No.2 pump at the Castlehill pump lodge had tripped out.

At 17:16 a critical alarm showed that the auxiliary fan had tripped out.

At 17:24 the surface main ventilating fan at Castlehill tripped out on low suction. The only reason this could have happened is that the water had now flooded to the roof all roadways in the Castlehill pit bottom area interrupting the main ventilation circuit.

Assuming that the alarms generated were accurate a possible explanation of the alarm sequence recorded by the Mine Operating System (MINOS) computers on the mine surface at the time of the incident might be of some failure in the vicinity of the Castlehill/Solsgirth dam. If water was pouring or spraying from the vicinity of the dam then it could have begun to interfere with the air velocity monitor sited in the end of the ventilation duct or restricted the duct itself.

A near total blockage of the ventilation duct, restricting the airflow and causing a higher back pressure on the auxiliary fan could have caused the fan to vibrate triggering the auxiliary fan vibration alarm two minutes later. The flow might have worsened to the extent that it caused the end of the duct to fall to the floor, the weight of falling water squashing it flat or tending to wash it away from the dam, doubling the end back on itself.

It is also conceivable that the pump tripped out a further four minutes later when the rising water reached its electric motor causing it to trip out, and that the auxiliary fan tripped out when the water reached either it or its associated electrical switchgear.
While this interpretation of the alarm timings is consistent with an extremely fast flood originating somewhere in the vicinity of the Castlehill/Solsgirth dam there are some unexplained anomalies in the alarm sequence and MINOS records.

First, there was no record of the pump switching on, so it appears to have run continuously for some hours prior to the flood. This was not uncommon as supervisory officials responsible for that area commented that the pumps had run much more since the Castlebridge dam was built and the water from the old Castlehill west workings had been allowed to rise and overflow to the Castlehill pump lodge.

Second, the high water level alarm in the Castlehill pump lodge failed to operate. This may have been because it was faulty or because it is just about conceivable that as the floodwater reached the pump lodge the flow past the float was sufficient to keep tension on the switch as the water level increased.

Last, it cannot be explained readily why the air velocity monitor close to the Castlehill/Solsgirth dam generated a warning two minutes after it generated an alarm, although one possibility is that it was a spurious signal generated as water seeped into the low voltage supply and data transmission systems feeding to and from the monitor.

This opens up the possibility that the whole alarm sequence, except the surface fan trip alarm, might have been spurious had water affected supply and transmission systems more widely. The MINOS records show that some monitoring circuits failed during the early stages of the flood, but it is impossible to determine with any degree of certainty whether or not all of the alarms generated by the monitoring devices prior to circuit failure were real.

Another scenario surrounding the air velocity and vibration alarms might be that following some failure in the vicinity of the Castlebridge dam the water flowing from the old west side workings to the Castlehill pumps had risen very quickly, overwhelmed the pumps and then obstructed the duct and then the fan. However, this does not explain the gaps of 11 minutes between the first air velocity alarm and the auxiliary fan tripping out and 9 minutes between the vibration alarms and fan trip. In such circumstances the water would have reached the fan soon after it reached the lowest point in the duct. Also, because the rapidly rising water would reach the pumps before the fan, it is reasonable to expect that the pumps would have been overwhelmed before an air velocity alarm was generated, even allowing for a ‘tidal swell’ effect.

**Sabotage?**

Soon after the flood there were some allegations that the owner had deliberately engineered the flood, or that there had been a deliberate act of sabotage by a third party, by opening the valve on the 300mm diameter pipe through the Castlehill/Solsgirth dam. Calculations to determine theoretical flow rates have been done by Weir Engineering Services for the mine owner, and by Mr M Williams, HM Inspector of Mechanical Engineering in Mines, for the purposes of this investigation.

Both indicate that it would have taken far longer than 20 minutes for the 3.6 million gallons of water needed to cut off the ventilation to flow through a 300mm pipe, and far longer than 2.5 hours for the 17 million gallons calculated to have flowed in through the pipe when mine personnel measured the water levels at that time.
The Weir calculation is based on the flow of water through a pipe between reservoirs\textsuperscript{10}. The details of the reservoir areas and initial heads provided to Weir by the mine surveyor seem reasonable and when entered into the equation they produce a time of around 32 hours for the 17 million gallon inflow.

The Williams calculation is based on a straightforward ‘worst-case’ application of Bernoulli’s equation\textsuperscript{11}, assuming no head loss, no friction loss and zero head at the receptor side. This idealised calculation results in a maximum flow rate of 29,419gpm giving a minimum time of 9.6 hours for 17 million gallons to flow through the pipe. Applying a 50mm reduction in radius to allow for frictional losses and head restriction reduces the theoretical flow to 13,039gpm and raises the time to 21.7 hours.

By interpolation, the corresponding times for 3.6 million gallons to flow through the pipe are 2 hours (idealised – 29,419gpm) and 4.6 hours (allowing for frictional losses and head restriction – 13,039gpm). All indications are that this amount of water flowed into the workings in 20 minutes at an initial rate of the order of 175,000gpm.

The last person to see the dam was the command supervisor who inspected it at around 02:00 on 23 March. There is no record of work being carried out in the vicinity of the Castlehill pumps between that time and the flood 15 hours later. Had someone opened the valve deliberately there would therefore have been ample time for the Castlehill pit bottom to flood as in theory the roadways could have flooded to the roof in 4.6 hours had the valve been fully opened. However, the average inflow rate calculated once the flood had been detected and the rate of rise of the water level determined appears to exceed the theoretical capacity of the pipe given the difference in water levels that existed in front of and behind the dam at that stage.

There was no gradual build up of resistance to the main fan, as would have occurred had the main ventilation roadways flooded more slowly. Furthermore, if the recorded alarms were genuine, the alarm sequence and the time between various alarms seem at odds with a slow flood scenario. What evidence there is seems to rule out any deliberate act of sabotage.

**Mine water recovery following the flood**

One of the few pieces of factual information available to the investigation has been the rate at which the water level has risen (recovered) in the mine workings since the flood occurred. There is also a record of the pressure behind the Castlehill/Solsgirth dam prior to the flood. Using this information and assumptions about the voids ratios in waste areas (net volume) it is possible to estimate the rates of inflow on either side of the dam.

Just before the flood occurred the rate of increase in head behind the Castlehill/Solsgirth dam indicated a net inflow into the workings to the north of the dam to be about 520gpm. This calculation is based on a net increase in head behind the dam of 12.5m in 21 days and assumes a 20% voids ratio in the wastes behind the dam.

\textsuperscript{10} From ‘Hydraulics’ (9\textsuperscript{th} edition), p161 – EH Lewett

\textsuperscript{11} Many authorities
To the south of the dams prior to the flood the mine estimated the net total inflow rate to be around 1,550gpm, of which 650gpm flowed from the Longannet Mine, 350gpm from the Bogside workings, 300gpm from the Kincardine Area (the actively producing area of the mine) and 250gpm from Castlehill. The mine shut off power to the Kincardine area following the initial flood and the water made in that area started to accumulate. When the remaining pumps were turned off on 3rd April (after the mine entered receivership) further water started to flood into the mine workings south of the dams.

Looking at the rate of rise of the water levels in both the Kincardine area (now completely flooded) and the Longannet and Castlehill Mines since the pumps stopped, it is possible to estimate the net rate of inflow south of the dams. Assuming that the Castlehill wastes (C16, C19 etc.) have a 20% voids ratio the average flow rate into the mine south of the dams appears to be in the region of 645gpm. This appears to be far too low as the Longannet Mine alone (still well above the rising water) continued to contribute 600gpm, leaving only 45gpm from other sources.

It was also well below the calculated rate for water flowing into the Kincardine area as that flooded. For a period of about a month commencing around the end of the first week in April the total water make would have flowed into the Kincardine Access Drifts and progressively filled the Kincardine Area and then the drifts themselves. During this time water flowed to the drifts from Castlehill, overflowing a high-point in the Cable Belt Mine at 206m BOD, and down the Longannet Mine to the Kincardine Access Drifts (roadways). While this happened the water level in the Castlehill Mines remained at 206m for a month before resuming its rise when the Kincardine Area was full.

On 4/5 May, the mine lost the signal from the battery-powered telephone at the No.1 Cross Cut in the Access Drifts, almost certainly as a result of the water reaching this level. This indicates a flow rate into the Kincardine Area of between about 1,650gpm and 1,875gpm for voids ratios of 20% and 25% respectively. In these much younger workings the higher figure is probably more appropriate, but crucially even the lower of these inflow rates is higher than the net estimated inflow of 1,550gpm to the south of the dams before the flood.

Even this figure should have reduced as the pressure head on the Kincardine workings increased by nearly 300m, and that on the Castlehill workings by almost 50m as the workings flooded, so it tends to indicate that there was a significant excess of water flowing into the mine south of the dams while the Kincardine Area filled. This excess was probably in the range 400-600gpm depending on actual relative voids ratios north and south of the dams. Discounting the surface, aquifers and old workings to the south of the dams, the only other place this extra water might of come from is behind the dams.

If there were some connection between the north and south water bodies, during the time the Kincardine Area filled and the surface level of both bodies remained at 206m BOD, the north area would contribute to the inflow at around 500gpm, which is within the target range for excess flow.

Once the Kincardine Area was full the water level would have started to rise throughout the mine. Assuming that there was a connection, mine water levels to the north of the dams would rise at the same rate as to the south, a faster rate of rise than observed behind the Castlehill/Solsgirth dam before the flood. The rate of inflow to the north of the dams to achieve this faster rate of rise would need to be about 850gpm, 330gpm
more than the 520gpm calculated just before the flood. Assuming the excess came from the south area, this would indicate a total flow into the south area of around 1,000gpm (645gpm if no connection + 330gpm) and around 1,500gpm into the mine as a whole (~1,000gpm South + ~500gpm North); much closer to pre-flood flows adjusted down for increased pressure head than if there was no connection.

While this is still only one possible scenario, the single water body theory seems to explain the observations of water levels far better than the two-body theory. If it is the case that there is a single water body, it seems to indicate some failure in the vicinity of one of the dams. Because of this, although the safety factors built into both dams should have precluded their failure, I have investigated in detail the design and construction process surrounding both of the dams.

The only other potential routes for water from the north to flow to the south would be via the strata between the waterlogged side of Cable Belt Mine and C07 Access and W9 roadways which pass beneath it and connect into the Castlehill workings on the south side of the dams. However, there are 55m of sandstones and clayey shale between C07 Access and the Cable Belt Mine and 61m between W9 and the Cable Belt Mine and it seems inconceivable that a conduit large enough could develop to transmit water at the inflow rates seen at the mine.

THE DESIGN AND CONSTRUCTION OF WATER DAMS IN MINES

The code of practice for dam design etc

Since 1982 water dams in coal mines have been constructed to an industry code of practice known colloquially as ‘The Brown Book’ (see footnote 1), which replaced a number of earlier, similar industry instructions. Although the code of practice concentrates in particular on disused mine shafts, it also applies to the construction of water dams in active mines. The design parameters set out in Appendix D to the code of practice mainly derive from engineering first principles. It indicates that concrete should be used to construct dams and provides a bibliography of relevant standards. The code of practice makes the reasonable assumption that provided a dam is of adequate length, any failure would be a shear failure at the dam/rock interface.

The code includes no requirements for the sampling and subsequently testing of fill materials to check that design parameters have been achieved.

While the code requires at Section 6 that ‘A study of the geology and hydrogeology…should include the engineering characteristics of soils and rocks… and the quantity, pressure and quality of water within them’, it does not set out any minimum requirements for how comprehensive this information needs to be, or how it should be obtained.

Appendix B covers geophysical methods of locating concealed mine entrances. Some of these could be applied below ground, but the code of practice makes no such requirement. Also, being 20 years old, it does not mention anything of newer geophysical techniques that allow a view of the bulk structure of the strata around a mine roadway or other excavation or opening.
Neither does the code address the treatment of the host roadway in front of or behind the dam, nor does it address monitoring the long-term stability of the host roadway and the measures to be taken to maintain it in a fit condition.

Having identified these omissions a search of available archives has so far not revealed any previous failures of water dams constructed to this standard.

Enquiries abroad and Internet searches have so far failed to uncover any other similar industry codes of practice in other countries, although there are indications that there might be at least one other in the USA. Authoritative papers on the subject of dam/bulkhead/plug design, like the NCB Code of Practice, approach the determination of minimum length based on design against punching shear failure at maximum expected pressure. We can therefore to conclude that the design basics of the code of practice are in line with internationally accepted practice. However, some of the papers cover the issues above that are absent from the NCB Code.

Geology

British Coal selected the site for the original Castlebridge dam following an inspection in 1994 by one of its mining geologists and a member of the mine survey staff, at which time they observed the rock exposed in three refuge holes near the top of the Castlehill-Castlebridge New Mine. The geologist also reviewed the geological notes made during the construction of the Castlehill-Castlebridge New Mine and submitted a report to the mine on his findings. The site recommended for the dam was in the footwall zone of the Alloa Fault (and about 120m from it) in reasonably strong, dune cross-bedded sandstone interlayered with ripple cross-bedded sandstones and interlaminated sandstones and siltstones.

During the examination the geologist acquired a large block of sandstone that he considered typical of Castlebridge and recommended to the mine manager that the sample be tested to determine its mechanical properties. There is however no record that the sample was ever tested or that British Coal asked contractors to acquire and test their own samples prior to building the 1995 dam. The geologist’s report notes that typical values for other sandstones in the Upper Hirst sequence were in the range 30-75MPa (Megapascals (= MN/m$^2$ = N/mm$^2$)). The report also recommends that the bulk strength needs to be assessed from the fracture incidence. I have not been able to determine whether or not this was done.

The report also notes that a full geological description of the site could only be made if all the wooden cladding boards used to cover the roof and sides of the roadway were removed. In the event this was not done until the dam site was prepared and there was no further geological examination. There are some safety issues associated with the removal of the cladding boards, principally the risk of falls from the exposed roof and sides. However it would have been possible to provide temporary support to allow a geologist to safely inspect most of the sides and roof of the dam site to obtain a more comprehensive view of its geological structure.

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Scottish Coal selected the site for the Castlehill/Solsgirth dam based on a recommendation in the IMC July 2000 report, made following a site visit to the Cable Belt Mine. The IMC geologist who wrote the relevant section (9.3) of that report was the same person who, as a British Coal employee, had written the earlier report for the original Castlebridge dam. The report notes that the site was selected because it:

- Minimised the length of roadway that would have to be maintained in the future;
- Is away from known faults lying further to the north
- Is in generally strong and unfaulted ground
- Is essentially unaffected by Upper Hirst mining.

As with the earlier report it is based on the examination of only a limited number of rock exposures in refuge holes and a review of the geological logs made as this section of the roadway was constructed in 1968. The geologist saw no indication that there was anything atypical about the strata but noted in the report that he could make a full geological description only if the cladding was removed. Again, this appears not to have happened and there was no further geological examination.

The site was in a section of the roadway where it passed through a 40m thick bed of massive, medium-grained sandstone known as the Glenbervie Sandstone. At the dam location the roadway was approximately in the middle of the bed and midway between the points where the Cable Belt Mine entered and exited the bed. There were two geological faults in the vicinity and while they did not know the precise position of one of them, they knew that it did not intersect the dam site. The geologist concluded that it was most likely that the two faults had run together to form what is known as a strike-slip feature such that only one main fracture was present in the Cable Belt Mine.

Assessment of subsidence effects on the Cable Belt Mine

The site for the Castlehill/Solsgirth dam was in a length of the Cable Belt Mine driven in the latter half of 1968. C07 face worked in the Upper Hirst seam 1974/75, its maingate running parallel to and 54m from (44m horizontally, 33m vertically below) the Cable Belt Mine. By reference to the former NCB Code of Practice ‘The Subsidence Engineers Handbook’\(^{13}\), still an authoritative source of guidance, I calculated both the subsidence profile and fracture limit plots for C07 waste based on the worst case seam inclination of 14\(^\circ\). The Cable Belt Mine falls at least 20m outside either zone of influence and it is therefore most unlikely that the working of this face subsided the Cable Belt Mine in the vicinity of the dam or had any significant effect on its strength or stability.

Dam design

Scottish Coal decided to proceed on these proposals and in November 2000 went out to tender for contractors to undertake the physical works. The mine awarded the fixed price contract for the dam construction to Amalgamated Construction Ltd (AMCO), a long-standing, experienced mining and civil engineering contractor.

As part of the tender AMCO submitted in December 2000 they included revised designs for both the Castlebridge and Castlehill dams, as its engineers felt that certain

\(^{13}\) National Coal Board Mining Department 1965, reprinted 1975
features of the IMC designs were impractical and gave rise to logistical problems. The AMCO designs were simpler to construct and had the same factor of safety as the IMC designs and were also based on a 5:1 pulverised fly ash (PFA)/cement grout, and designed to achieve at least the 4:1 factor of safety specified by the industry code of practice against a maximum head of 435m of water. Scottish Coal accepted the AMCO tender and formally awarded them the contract in January 2001. AMCO started site preparation work shortly thereafter.

Around the time the preparatory work commenced Scottish Coal began to doubt that they had the expertise in house to properly oversee the contractor, supervise the work, and in particular for them to assess the effectiveness of the contractor’s design and construction quality assurance and quality control regimes. In late January 2001 Scottish Coal engaged WS Atkins, a large engineering consultancy, to oversee the project. They provided a former British Coal Civil Engineer experienced in the design and construction of underground water dams.

The consultant engineer agreed with AMCO that the IMC dam designs would have been more difficult to construct than the AMCO designs. However, he expressed concerns that:

- the AMCO designs (contract ref.1076), like the IMC ones, were based on a relatively weak 5:1 PFA/cement grout mix rather than the concrete required by the code of practice;
- the existing dam was included in the design length of the new dam when the available information did not support such a course;
- there was no provision for high-pressure (HP) interface grouting between the completed dam and the surrounding strata, a requirement of the code of practice.

He accepted that a PFA/cement grout could be used instead of concrete, provided that it was a properly specified, high-strength grout with similar mechanical properties (strength, durability, permeability) to concrete. He anticipated that a 1:1 grout would have very low permeability.

Having made a site visit to the Castlebridge dam and commented on some inadequacies in the stripping and cleaning of the yet-to-complete site, he recommended a review of the design philosophy, changes to the detailed design specification and improved communications between design office and site staff to ensure that the design was realised in practice.

By early March AMCO, to the satisfaction of the consultant engineer, had revised the dam designs in line with these recommendations (contract ref.3011/38), choosing a 1:1 PFA/cement grout and making provision for HP interface grouting.

By the time the redesign started AMCO had been on site for several weeks and were well advanced with preparation work at Castlebridge, based on the design for a dam constructed from a 5:1 ratio grout. Now that AMCO were to use a grout over three times stronger at 90 days (manufacturer’s figures) to construct the dams the one at Castlebridge could have been considerably shorter than the 14.4m prepared length, but AMCO decided that it would be more cost effective to build the dam to the original design rather than start again with site preparation. The product would be a vastly over-
engineered structure with a safety factor far in excess of the Code of Practice requirements.

The situation for the Castlehill/Solsgirth dam was different. As the mine planned to construct the dams sequentially work had not started to prepare the site and AMCO therefore had the opportunity to redesign this dam to a length appropriate to the stronger grout.

The initial design for this dam (contract ref.1076) was for a 21.6m long, two-stage dam/stopping structure based on a 5:1 ratio grout. The first stage was a 10.8m long explosion-proof ventilation stopping with a 750mm diameter access tube, the second stage was a 10.8m long dam built against the stopping. A 300mm diameter pipe would run through the whole length of the dam and stopping.

The revised design, approved by the WS Atkins consultant, was for a ‘traditional’ 3.66m long explosion-proof ventilation stopping filled with the same 1:1 PFA/cement grout to prove the system to be used to construct the dam. The stopping was not part of the dam and not considered to contribute anything to the dam’s strength. The dam would be built against this sometime later.

Calculations done in line with the Code of Practice to determine the length of dam necessary to give a 4:1 safety factor at a 435m design head indicated that it should be at least 4.9m long. As this was less than the 5.5m width of the roadway and the Code of Practice indicates that the minimum dam length should be the greater of the two, the minimum acceptable design length was therefore 5.5m. However, the spacing (pitch) between arched roadway supports was 1.22m, and this increased the minimum practical length of the dam to 7.32m (six pitches).

If the workforce did not understand the engineering reasons for the design change this in turn may have led directly to allegations that the Castlehill dam had been reduced in length by two thirds, but from 21m to 7m and not from 15m to 5m as alleged. In the absence of such information workers and supervisors at the mine weren’t to know that the revised dam design was based on a much higher strength grout and that the overall safety factor for the dam alone was 6.33:1, over 50% in excess of the 4:1 required by the Code of Practice.

Overall the design process appeared to be secure with quality assurance based on a number of checks and balances within the system. Foremost among these was the power the consultant engineer had to approve or veto each stage of the design and specification process.

**Dam construction**

More or less the same small core of AMCO employees worked on both dams. I am satisfied that those directly involved with building both dams were very experienced, received adequate instruction in the method statements drawn up by AMCO and agreed by the consultant engineer, and received adequate supervision from both their own shift supervisors and command supervisors at the mine.

**Castlebridge**

Site preparation involved progressively stripping out the covering from between the steel arch supports and removing any loose or broken rock until reaching solid rock.
Most people involved with the Castlebridge site described the rock as ‘broken’ or ‘flaky’. The natural planes of weakness in the rock may have been opened close to the periphery of the roadway when it was driven by drill and blast methods some years before. However, the size and nature of these planes of weakness were such that the curtain grouting done as part of the site preparation would have controlled their effect. Having interviewed a number of command supervisors employed by Scottish Coal, as well as the men who built this dam, contract engineers, the consultant engineer and a number of others, I am satisfied that the standard of stripping, cleaning and curtain grouting at the site was adequate. The men encountered a number of small breaks while drilling the 1.8m long curtain-grouting holes but the curtain grouting should have sealed these within 2m of the roadway periphery.

At Castlebridge the availability of a spare shaft pipe range led to a decision to batch mix the grout on the surface and pump it down to site. This had a number of advantages:

- Larger mixing tanks could be used, so both the design PFA/cement and water/solids ratios were less vulnerable to error (miscounting by one bag would have a proportionately lesser effect);
- AMCO could use drillers from its AMCO Drilling subsidiary who were very experienced at mixing grouts to seal wells;
- No need to transport large quantities of equipment and materials below ground in small batches;
- Cube and cylinder samples for testing could be acquired on the surface.

The equipment was set up and commissioned on 17 April 2001 and pumping commenced on 18 April, the consultant engineer having checked and approved both the calculations for the PFA/cement/water ratios (630kg/630kg/505litres) for batch mixing and the method statement to ensure that this was achieved. The pour continued more or less continuously until complete 46 hours later on 20 April.

The first difficulty was that for the first two minutes or so, the grout was very thin, probably due to residual water in the shaft range from the commissioning process, but it then thickened to its expected sludgy consistency and there were no problems associated with the mix beyond that. The second problem was a make of 2-4gpm of roof water flowing into the chamber from above the original dam. Until the grout pour commenced the mine had used a small electric pump in a sump to collect it and pump it to the main pump lodge near the shaft bottom. During the grout pour the water collected on top of it and ran out through the numerous peripheral standpipes inserted ready for the HP interface grouting stage. As expected, it did not mix with the grout. The third difficulty was that the shuttering started to leak on one side late on 19 April, about 75% into the pour, and the pour stopped to allow the men to plug the leak. There is some doubt as to the exact duration of the gap but there is no suggestion that it was

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14 Curtain grouting is a technique where a number of holes are drilled into the rock around the periphery of a roadway and grout is then pumped into them under pressure and fills any small fractures or fissures, setting hard to cement the rock together. At both dams there were three rings of twelve 1.8m long holes.
over four hours, the initial set time of the grout, and so the likelihood of a ‘cold joint’ in
the dam is extremely low.

Both the men and command supervisor (who was on site when the dam was topped
out) confirmed that the dam was completely filled and that grout ran from the top
breather tubes, the open ends of which were in a small roof cavity deliberately
excavated above the general level of the roof to ensure full roof contact.

During this investigation the command supervisors expressed surprise at how quickly
and how hard the grout set. They said that excess grout run out of the pipes as part of
the cleaning process following completion of the pour set solidly within a shift.

In the following days, using a closely fitting scroll drill, AMCO reamed out the solid grout
from the standpipes in preparation for the first phase of the HP interface grouting
between the dam and the strata. The men reported that the grout in all of the
standpipes was solid, and that they encountered no voids and no water. One of the
command supervisors remembers a small amount of water flowing from one of the
standpipes but this was not corroborated.

On 30 April, 10 days after completing the pour, AMCO started the first phase of the HP
interface grouting using a hired-in HP pump to force grout into the 30 interface
standpipes at 45 bar (~650lb/in²). They completed the first phase on 5 May and when
the grout had set started to ream out the standpipes in preparation for the second
phase of grouting. Again they reported that all grout had set solidly and that there were
no void spaces. The 30 standpipe shut-off valves had to be removed and taken out of
the mine for total strip down and clean as it proved impossible to remove the hard grout
from them any other way.

AMCO commenced the second phase of interface grouting to 87 bar (~1,260lb/in²),
twice the maximum design head of the dam (as required by the Code of Practice), on 9
May and completed on 12 May. Grout usage on the first phase was low, indicating little
shrinkage of the highly specified bulk grout forming the mass of the dam, and the men
reported achieving target pressures on all holes. Grout usage on the second phase
was very low with target pressures being achieved quickly on all holes. This tends to
indicate that AMCO achieved a very strong and stiff seal between the dam and the
strata.

The men worked to a code of practice drawn up by AMCO and demonstrated good
knowledge and understanding of its contents. In particular they knew to shut off the
standpipe valves under pressure once the pressure had stabilised and held at the
target level.

**Castlehill/Solsgirth**

When AMCO removed the cladding from around the roadway to prepare the site they
found little in the way of loose rock and encountered no breaks when they drilled the
1.8m holes for curtain grouting. The independent consultant visited the prepared site
and noted that the strata conditions were good and appeared stronger than those at the
Castlebridge dam site.

However, command supervisors and two workmen who had worked in this part of the
mine reported poor roadway conditions in the Cable Belt Mine in the vicinity of the dam.
They said that the steel arch supports were not distorted but the wooden cladding
boards covering in the roof and sides between them were rotting and allowing small falls to occur, up to about 1m high and usually along the left hand shoulder of the roadway. The two men reporting this were occasionally deployed to repair these areas when they could be spared from other work.

They also reported a more significant fall, which they felt had occurred within 20-30m of the dam site. They said that this was up to 10m above the left shoulder in the form of an inverted groove about 1m wide at the bottom and stretching for 6-7m along the length of the roadway. They could not safely support it and so covered over the arches with fresh wooden cladding boards to make the roadway safe for travelling and working.

The former deputy manager, who deployed the repair workers, could also remember some minor falls, mainly in the left hand shoulder, in the section of the Cable Belt Mine leading to the dam, but nothing as large as that described by the men and nothing as close as that to the dam. Although he doubted it he did not rule out completely that such a fall might have occurred but recalled that the strata in the immediate vicinity of the dam appeared very strong with no significant breaks or weathering. He offered the reasonable explanation that the majority of falls occurred on the left hand side of the Cable Belt Mine because that was the side where the cable belt ran conveyor for over 30 years, and it was therefore more difficult to access to repair the covering.

The statutory reports completed by mine officials for this area of the mine often refer to falls and repairs. While the level of detail in these reports is generally sufficient for day-to-day safety management purposes, it has not been possible to relate specific falls to the repair work carried out.

The location of the dam presented the mine with some logistical problems, as it was over 600m from the bottom of Castlehill No.1 Mine with no proper transport system.

The construction sequence of this dam was essentially the same as at Castlehill, but here all of the grout had to be mixed below ground, as there was no spare pipe range from the surface down the Castlehill Mines. AMCO set up a mixing station at the bottom of the Castlehill No.1 Mine close to the end of the transport system. This had with two mixing tanks with a changeover facility to pump from either tank, a compressor, a pump and a spare. The grout delivery system was a 1¼” steel pipe range with a 1¼” hose as standby, both running nearly 700m from the mixing station to the dam.

AMCO had specified a bagged pre-mixed 1:1 PFA/cement grout so the only quality control required was to mix in the correct amount of water at the mixing station. The size of the tanks dictated that 700kg of grout powder be added to 280 litres of water. The measuring stick provided to measure the depth (and hence the amount) of water within a tank should have provided for accuracy to within about 1% for the water/solids ratio of 0.4. The consultant engineer approved both the quantities and the method.

AMCO started to pump the dam on 24 September and finished on 28 September. There were a few minor problems that led to about three, two-hour delays during the pour, but nothing more significant. Again, a command supervisor was on site when the dam topped out and was satisfied that it was full. Both phases of HP interface grouting progressed without difficulty with all holes achieving their target pressures. Grout usage was low on the first phase, indicating few voids and very low on the second phase. The men encountered no unset grout or voids during either of the reaming operations and no water.
Test sample acquisition procedure

Part of the quality assurance arrangements for both dams was to take three cube specimens of grout every eight hours and one cylinder specimen every 24 hours, and to have them tested at Weeks Laboratories Ltd, an independent laboratory, for strength and permeability at 28 days and 56 days in accordance with procedures laid down in British Standards BS1881 and BS1337 respectively.

The AMCO method statements set out the sampling regime but not the sample acquisition procedures. Practice at both dams was to acquire the samples at the mixing tanks, casting the cube specimens into polystyrene moulds and the cylinder specimens in a plastic mould. This is acceptable.

When tested at the independent laboratory the cube specimens from the Castlebridge dam failed by some margin to achieve the specified 28-day compressive strength. The senior technician who analysed the specimens confirmed to me that he reported signs of frost damage on some of the specimens, adversely affecting their strength. Apparently, this resulted from inadequate curing arrangements, specimens being stored adjacent to the point of sampling and manufacture, in “site cured” conditions. The cement supplier also confirmed in July that samples stored on site would achieve typically only 77% of the strength of cubes stored under BS1881 conditions. The AMCO code of practice for the construction of the Castlebridge dam did not cover in any detail BS1881 test sample storage arrangements.

Following a lengthy exchange of correspondence between the consultant, Scottish Coal and AMCO, three cylinder samples from the Castlebridge dam were sent for full analysis to a geomaterials research laboratory. They produced a report in September 2001 that showed that all samples had a better than 1:1 PFA/cement ratio (adding strength) and worse water/solids ratios (compromising strength). While the net effect of these variations tends to cancel out, it could indicate poor quality control over the mixing process, or sample acquisition, or both.

The test samples from the Castlehill/Solsgirth dam were the subject of allegations made by two ex-workers in the weeks following the flood, but apparently not at the time of building the dams. The workmen, who were made redundant from the mine in November 2001, had transported some of the bagged grout to the mixing tanks during the construction phase and alleged that the test cubes were not representative of the material being pumped into the dam. Specifically, they said that the AMCO workmen mixed the test samples in a bucket instead of acquiring grout from the mixing tanks, and that they did this because they were using more water than specified in the grout design to ease pumping and avoid pipe blockages. The water content was in fact the only thing that workers could do to vary the design mix; the use of ready mixed grout meant that the PFA/cement ratio was guaranteed to be constant.

I interviewed four of the AMCO employees who had been involved in building the dams, three of whom had been involved in sampling at the Castlehill/Solsgirth dams. AMCO’s senior contracts manager, whom I had interviewed before, was also present. I did not disclose in advance that one of the purposes of the interview was to explore these allegations.

In order to avoid repeating the mistakes made with the Castlebridge test samples cubes, AMCO’s senior contracts engineer and the mechanical engineer for the
Longannet dams contract went together to the testing laboratory to determine good practice for sample acquisition, handling and storage.

To acquire the grout for casting the test specimens, a senior technician at the testing laboratory confirmed to me that he advised them to put the grout pump into recirculation mode and then tap the grout from a valve in the relief hose into a bucket. If test specimen manufacture was to take place remotely from the point of sampling, the material should be agitated briskly before casting the test specimens. This was to ensure that there was no settlement within the sampled material, during transportation, prior to specimen casting.

Although AMCO did not include this sample acquisition procedure within the method statement for the Castlehill/Solsgirth dam, the AMCO dam construction workers confirmed that it was included as part of their prior teach-in. The men refuted vigorously the suggestion that the material in the samples was anything different from the material that had been pumped into the dam.

None of the Scottish Coal command supervisors in this area, who were responsible for supervising the health and safety of the workers at the mixing station, most of whom I interviewed, noted any discrepancies in the sampling procedure or were aware at the time of any concerns over the sampling procedure.

AMCO stored the samples acquired in this way much closer to BS1881 storage requirements and despatched them to the laboratory at a much earlier stage for controlled curing. Nevertheless, at around 27MN/m$^2$ the cube samples were an average of about 10% under strength at 28 days. By 56 days all samples from the Castlehill/Solsgirth dam had recovered to exceed the target strength, but by significantly variable amounts. As with Castlebridge this casts some doubt on the efficacy of either the mixing arrangements, or sample acquisition procedure, or both, but this in itself provides no evidence that the Castlehill/Solsgirth dam was significantly under its design strength.

There are two different records of the amount of bagged grout used to pump the Castlehill/Solsgirth dam; the statutory reports of command supervisors/inspection officials, and AMCO shift reports completed by its shift supervisors. The 106 tonnes dry weight recorded as used is slightly in excess of the calculated amount required indicating that the water/solids ratio achieved was close to the 0.4 design ratio with little if any over-watering.

Had there been any significant weakness in the bulk strength of either dam, it is likely that it would be revealed as deformation at the face of the dam during the HP interface grouting stage.

**RELATIVE LIKELIHOOD OF FLOODING OPTIONS**

For the reasons set out above, of the five sets of options considered the likelihood of the flood originating from the surface is remote. There was no known surface or near surface reservoir with a potential large enough to provide the 80,000m$^3$ necessary to generate such a flood. Furthermore, were such a reservoir to exist, in the absence of some unknown catastrophic failure for which there is no evidence whatsoever, it is
extremely unlikely that the potential flow rates would be any more than a small fraction of those that were actually calculated. Boreholes between the surface and the workings are not large enough to transmit the required flow rate to cause flooding at the rate seen.

Although there is a relatively high ratio of water-bearing sandstones (aquifers) in the Upper Limestone Formation, and particularly the Passage Formation, with a degree of inter-connectivity between them, there appears to be little chance of an aquifer being the water source. There is no history of any particular point achieving a flow rate of more than a few hundred gallons per minute, even relatively close to the surface (as in the Longannet Mine). Flow rates greater than these are unlikely to occur spontaneously in the absence of some other significant initiating event, such as seismic activity. Even if there were a conduit large enough to transmit the flow rates required, and again there is no evidence whatsoever to suggest there is, it is extremely unlikely that pore water would percolate through the rock to the conduit at anything more than a fraction of the required flow rate.

While the sudden release of water from waterlogged shafts (vertical accesses) and mines (sloping accesses) could achieve such flow rates it is doubtful whether any of them alone could contain the necessary quantity to produce a flood of this scale. Furthermore, to the south of the dams the only potential source was water from the Bogside Mines, but the Bogside Mines/Bogside pumps area of the mine remained accessible for over a week following the flood and there was no evidence of any water flow from this source. It can therefore be ruled out as a potential cause.

For waterlogged old C16/C19 area workings to the east of the Cable Belt Mine to contain 17 million gallons of water would have required single thickness, fly ash block ventilation stoppings to withstand huge hydraulic pressures for which they were never designed, and that three of them did for years is impossible to conceive. The likelihood is that these stoppings were deliberately breached to allow water to flow freely to the N6 pumps.

Silting up of the water flow path at a low point in S2 might have stopped water flowing from these workings to the old Castlehill west workings via that route, but the water level could not rise above the Castlehill/Solsgirth dam before it started to flow out via other old roadways. These roadways would also have had to silt up to allow the water level to rise further. Then would have overflowed at stopping No.92, which remained accessible and inspected up to the time of the flood with no record of any significant water make.

It therefore appears that there was no potential for 17 million gallons to accumulate above the level of the Castlehill/Solsgirth dam. There remains an extremely remote possibility that the water did originate from this area due to a combination of circumstances unknown and difficult to conceive, but it is almost beyond doubt that water continued to flow freely from this area to the old Castlehill west workings after the erection of the ventilation stoppings.

Sabotage can be ruled out as a cause of a fast flood, as even in idealised flow circumstances the initial flow rate would have been less than a sixth of what actually appeared to enter the mine in the first 20 minutes. In reality, taking into account friction loss in the pipe and through the valve, head loss and the vena contractor effect, the rate of inflow through a 300mm diameter pipe would have been considerably less.
There is also no evidence to support a slow flood theory of sabotage by opening the valve several hours earlier, leading to a much slower build-up of water. There was no progressive increase in the surface fan operating pressure as a result of steadily increasing resistance, the alarm sequence generated by this scenario is likely to have been different to that which was recorded, and the inflow rates calculated when the flood was discovered appear to exceed the theoretical maximum that could have passed through the pipe at that time.

That leaves some failure in the vicinity of one of the dam sites as the remaining possibility. At the maximum 435m design head the Castlehill/Solsgirth dam had a designed safety factor of 6.33:1 and the Castlebridge dam had a designed safety factor of almost 12:1. That either the former should fail at 48m head (one-ninth of the design head and an apparent residual safety factor of 57:1) and the latter at 55m head (one-eighth design head and an apparent residual safety factor of about 100:1) is almost inconceivable.

While on the face of it there were solid strata around both dam sites the site investigations carried out at both sites were quite limited. These investigations did not give rise to any suspicion that there was anything atypical about either site. There were some small strata breaks at the Castlebridge dam site but these were treated by curtain grouting. Furthermore the combined length of the old and new Castlebridge dams was over 20m and it is extremely unlikely that even a major strata failure would have bridged over the dam.

Although the strata at the Castlehill/Solsgirth site were apparently solid, there had been some degradation in the roadway leading to mainly minor falls, mainly on the left hand side, possibly as close as 20m to the dam, although there was no suggestion that the strata at the site itself appeared anything other than solid. It is a fact that as the head built up behind the dam water seeped and then ran out of the roof on the left hand side. Further curtain grouting failed to control it. This could suggest that there was a small conduit around the dam, which might be the result of some inherent plane of weakness in the strata running through or close to the dam site.

That this might give rise to some progressive strata failure is still extremely difficult to conceive. There would need to have been a substantial failure of the Cable Belt Mine roadway close to the dam. One of the main problems with this scenario is that the dam itself is an extremely stiff structure keyed into the surrounding strata by interface grouting to 87bar (8.7Mpa), a figure close to the vertical stress at this depth. It is reasonable therefore to expect it to have stiffened the surrounding strata providing a barrier to the extension of any developing fracture or cavity.

The hydraulic head would have had some effect but is impossible to do more than speculate what this might have been. For example, we know that water under pressure must have entered small open fractures to the north of the dam. At 48m head this could exert about 48 tonnes/m² on the fracture walls and it is just conceivable that given a fissure-type fracture with a large surface area the water pressure could generate sufficient force to detach one block and then another and so on to create a conduit.

There would have to be a cavity in the first place to allow the rock to move. Whether or not a simple lagging failure would be enough to create a sufficiently large cavity for progressive failure to occur, or whether the failure of one or more steel supports is an
essential precursor is not known. However, the arches weren’t strutted together and could have rotated under load.

One possible interpretation of the alarm sequence is that the inundation started through the roof close to the dam, and that either falling lagging or supports, or the sheer weight of water, caused the ventilation ducting to drop, or obstructed it, generating the air velocity alarm. There is however an element of doubt that all the alarms recorded by the MINOS system were genuine given that water might have affected the low voltage data transmission system.

Inundation as a result of some failure in the vicinity of the Castlebridge dam causing elevated flows via the old Castlehill west side workings is a possibility but seems less likely bearing in mind both the strength of the Castlebridge dam, the combined length of the new and old dams, and the alarm sequence at Castlehill.

CONCLUSION

Evidence of fact on the actual failure is extremely limited. What there is points to a rapid inrush of around 3.6 million gallons of water within the first 20 minutes and 17 million gallons within the first 2.5 hours. The comments on possible failure scenarios are therefore little more than informed guesswork and need to be treated with caution. All of them appear to be extremely unlikely or inconceivable, and none reasonably foreseeable.

Of the possibilities some failure of the strata in the vicinity of the Castlehill/Solsgirth dam seems the least inconceivable and best fits in with what little we know. That does not mean to say that this is what occurred, merely that it seems to be slightly more likely than the other scenarios considered.

Breaching the Piperpool pumping borehole north of the dams, either by drilling from the surface through the valve at the bottom, or blasting it off with explosives, would allow water from north of the dams to rise in the borehole to its current level. Comparing this level and its subsequent rate of rise with the water level and rate of rise in the Castlehill and Longannet Mines would determine whether the water bodies to the south and north of the dams were in fact connected. However, even if they were connected it would only indicate that there had been some failure, not how or why it occurred.

The only way to determine beyond doubt the cause of the incident would be to pump out the mine (including if necessary the Castlebridge/Solsgirth side of the dam). The cost of this would be substantial, and with little to gain in health and safety benefits, difficult to justify.

RECOMMENDATIONS

The recommendations are coloured by the fact that the precise mechanisms surrounding the cause of the flooding are unknown and will remain so. The recommendations therefore proceed on the assumption that there should be a general
tightening of procedures to reduce even further the already small risk of catastrophic failure of a dam or its surrounding strata. The recommendations are split between the mine, other mines and the Code of Practice.

The Longannet Complex
There are no recommendations relating to the Longannet Complex itself.

Other mines
The Mines Inspectorate has already stimulated a review of other mines to identify where, if at all, similar circumstances prevail. Mine owners will take any necessary actions indicated by this review.

There is a need for all mines with significant inflows of water to mine workings to monitor carefully the amounts being pumped from each area in order to determine inflow rates and subsequently to assess the likelihood of flooding in the event of some failure of part of the water management system and the risks to mineworkers arising out of such a failure.

The Code of Practice
There is a need for guidance on the following issues to supplement the Code of Practice insofar as it relates to dams in working mines:

(a) On the assessment of the geology, hydrogeology and engineering properties of the strata within a minimum defined distance of a prospective dam site, including the use of geophysical techniques where appropriate;
(b) On the acquisition of samples and other information to support the above assessment;
(c) In relation to the characteristics of fill material, including strength, permeability and durability;
(d) In relation to the design and specification of curtain and interface grouting;
(e) In relation to quality control in construction, including competent, independent oversight, and the acquisition, storage and testing of samples of the fill material by an independent third party;
(f) In relation to the treatment of the strata in the host roadway on either side of a dam site;
(g) In relation to the ongoing monitoring of the stability of the host roadway in which a dam is situated, particularly where it is anticipated that water level behind a dam will build up quickly at any time following dam construction, and the carrying out of any necessary roadway maintenance.

It is a matter for further debate within the industry whether some or all of these need doing for every dam or just those dams or strata the failure of which could endanger lives. The Mines Inspectorate has already started to lead a discussion within the industry on the most appropriate way forward.
**APPENDIX 1**

**LIST OF FUNCTIONS OF THE PEOPLE WHO PROVIDED INFORMATION DURING THE COURSE OF THE INVESTIGATION**

<table>
<thead>
<tr>
<th>Position</th>
<th>Company/Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chief Draughtsman</td>
<td>AMCO</td>
</tr>
<tr>
<td>Civil Engineer, consultant</td>
<td>WS Atkins</td>
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<tr>
<td>Divisional Director</td>
<td>AMCO</td>
</tr>
<tr>
<td>Former chargehand electrician, Longannet Complex</td>
<td></td>
</tr>
<tr>
<td>Former command supervisors, Longannet Complex (x8)</td>
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</tr>
<tr>
<td>Former deputy manager, Longannet Complex</td>
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</tr>
<tr>
<td>Former mineworkers, Longannet Complex (x2)</td>
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<tr>
<td>Former senior technician, WEEKS Laboratories Ltd</td>
<td></td>
</tr>
<tr>
<td>Former workman’s inspector, Longannet Complex</td>
<td></td>
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<tr>
<td>Geologist, consultant</td>
<td>IMC</td>
</tr>
<tr>
<td>Mechanical engineer</td>
<td>AMCO</td>
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<tr>
<td>Mine manager, Longannet Complex</td>
<td></td>
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<tr>
<td>Mine owner’s representative</td>
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<tr>
<td>Mine surveyor, Longannet Complex</td>
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</tr>
<tr>
<td>Mineworkers, AMCO (Dam construction) (x4)</td>
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<tr>
<td>Mining engineering consultant, IMC</td>
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<tr>
<td>President, NACODS Scotland</td>
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<tr>
<td>President/General Secretary, NUM Scotland</td>
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<tr>
<td>Senior Contracts Manager, AMCO</td>
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<tr>
<td>Undermanager, Longannet Complex</td>
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APPENDIX 2

LIST OF HSE PEOPLE WHO ASSISTED IN THE INVESTIGATION

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
</tr>
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<tbody>
<tr>
<td>Mr S Cartney</td>
<td>HM Specialist Inspector (Civil Engineering), HSE</td>
</tr>
<tr>
<td>Mr J R Leeming</td>
<td>HM Inspector of Mines, HSE</td>
</tr>
<tr>
<td>Mr M Williams</td>
<td>HM Inspector of Mechanical Engineering in Mines, HSE</td>
</tr>
<tr>
<td>Mr S P Wing</td>
<td>HM Principal District Inspector of Mines, HSE</td>
</tr>
</tbody>
</table>
APPENDIX 3

PLANS

Plan 1
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