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Analysis of Breakages of Longwall Powered Supports - Why Cycles Testing Does Not Guarantee Happiness

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ANALYSIS OF BREAKAGES OF LONGWALL POWERED SUPPORTS - WHY CYCLE TESTING DOES NOT GUARANTEE HAPPINESS

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ABSTRACT: In recent years, SUEK has suffered serious breakages of four sets of powered supports, including caving shields and the attachment of the powered supports to the AFC. All of these supports had undergone prototype testing prior to manufacture, but the design errors were not manifested under conventional test conditions. Breakages occurred underground where it is not possible to instrument the equipment, and where reliable data is hard to obtain by visual means. This paper describes the "forensic engineering" that led to the identification of the root cause of the damage, and the ways in which this was rectified. Two new sets of supports have also undergone design changes to prevent the same risk of damage. The solutions are simple, but developing this knowledge has cost a lot.

INTRODUCTION

Siberian Coal Energy Company (SUEK) currently operates eleven longwalls, with nine in Kuzbass in Siberia and two at Urgal in the far east of Russia, with a mix of equipment. In recent years older shearers and AFCs have been replaced with Eichoff and Joy shearers and AFCs have been upgraded mainly with DBT PF4 in seams of 1.6 to 2.8 m, and PF6 in thick seam mines extracting 3.6 to 5 m). The coal cutting and conveying equipment is all modern, imported machinery, including one state of the art Eickhoff SL900 shearer working in a 3.6 m seam, and a second machine currently on order for a 5 m seam. SUEK owns 2,455 longwall supports in two categories – 1.6 to 2.6 m, and 3.5 to 5 m sets. The company operates six to seven thin seam longwalls and four or five thick seam. One mine extracts both thin seams and thick seams, hence the variation in numbers from year to year. Of these supports, 170 are awaiting refurbishment, and one new set is being installed, but all others are currently in use.

Since 2007, SUEK has been modernising and extending longwalls and approximately 1,500 individual supports have been purchased in the period 2007-2017. There is currently only one set of Russian made supports remaining in the fleet and this will soon be replaced with a set of imported, thin seam supports. All other supports are imported models from Joy, DBT, Tagor, the old Glinik and Famur/Glinik of Poland.[2]

SUEK's program of modernisation and optimisation is continuing and during the next five years it is likely that SUEK will purchase additional supports to extend another two faces from 300 to 400 m, and replace two old sets of thin seam supports and one set of thick seam supports.

SUEK has been a major purchaser of powered supports throughout the last ten years, with substantial numbers of supports purchased from several manufacturers, and this will continue as old sets are replaced with high capacity, modern sets, and as new mines are brought into production. The company will continue to increase production, especially from longwall mines that produce high quality coal for export.

During this process, SUEK has suffered several instances of major breakages, each involving large numbers of supports. In each case SUEK personnel investigated the problems and identified the root cause, then worked with the suppliers to rectify the faults. The knowledge gained from these investigations has recently enabled potentially serious design defects to be eliminated in two batches of supports during the design review process – a full face set of

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The content of this paper reflects the opinions of the author. These are not necessarily the view of Siberian Energy Coal Company (SUEK).
[2] "Old" names of equipment suppliers are used throughout, to reflect the name of the OEM at the time of purchase and for ease of recognition.

supports for a highly productive mine and a set of 58 thick seam supports for extension of a longwall from 300 m to 400 m.

Design defects rarely occur in supports from traditional suppliers such as Joy and DBT, as these companies have accumulated vast knowledge over many years, partly by maintaining extensive contact with users, and by deploying mining engineers to monitor operational aspects and enhance designs. Companies that are considering purchase of supports from new suppliers from Poland and China cannot safely assume that the same philosophy of producing equipment suitable for mining, rather than producing mining equipment, applies to the same extent. Joy and DBT (and their predecessor companies) have operated in a fiercely competitive, customer-led market for 50 years. Polish and Chinese suppliers do not yet have the same proven track record as they have largely operated in a different environment, which has not provided the same level of market feed-back and robust criticism of any minor defect.

SUEK is still buying supports from JOY and DBT, but has also ordered five full sets and two partial sets from three different Polish suppliers during the last ten years. When purchasing such large numbers of supports it is not possible to ignore new suppliers and to maintain a closed shop approach. This process has resulted in some difficulties, but it has enabled SUEK to modernise a high proportion of the company’s longwalls, and to produce substantially more coal - despite some losses because of equipment breakage. Most importantly, SUEK has worked with the supplier of the recent face sets to find the root cause of each problem, rectify it, and then to eliminate similar problems from further sets at the design stage. The supplier has responded very positively both to rectification of damage and to implementation of design changes. On three occasions, large test rigs have been built to SUEK’s design to physically prove amended designs, and these have provided real insight and accelerated the development of designs.

A basic understanding of the cause of failures is all that is required to enable other users to check designs, identify potential for failure, and to force a supplier to modify designs if necessary. Understanding the risks will also enable purchasers to specify suitable computer modelling of designs and/or physical testing of prototypes within their contract in order to enforce the necessary checking by the supplier. Finally, if a breakage does occur, then this knowledge could speed up resolution and resumption of normal operation of a longwall.

HISTORY OF BREAKAGES OF SHIELDS

During the last ten years, a number of sets of powered supports have failed in operation in SUEK’s Kuzbass mines, including the following breakages:

1. 2008 November 7th mine: Polish 2.4-5.0 m supports with Russian AFC. Lugs ripped off approximately 100 AFC pans before the problem was rectified by fitting different clevises.
2. 2008 Krasnoyarskaya mine: A new set of 1.5-3.2 m supports from the same Polish supplier was delivered shortly after the set in November 7th mine failed. Based on analysis of failure of the earlier set these supports were modified before going underground, and successfully prevented breakage of the AFC.
3. 2009 Krasnoyarskaya mine: After six months underground, the same Polish supports were found to have extensive cracking on the upper part of the under-side of the caving shields. Repaired by over-plating the cracked areas with 20 mm of high strength steel under warranty during the first face transfer.
4. 2010 Krasnoyarskaya mine: The reinforced caving shields on the same set were found to have broken again. Extensive repairs were required to remove damaged areas and rebuild the caving shields during the face transfer.
5. 2016 Polisaevskaya mine: A modern set of 1.2 to 2.5 m supports was purchased from a Polish suppler for a fully automated longwall with a working height of 1.6 m. The same company supplied the supports and the AFC. Within four weeks and 40 metres of retreat, approximately 20 lugs had snapped off the cast AFC line pans. The failures continued and by the time the panel had mined 1 Mt, every line pan was broken. The only exception was inspection pans, which took longer to suffer damage. SUEK established that the failures were due to a design fault on the powered supports, rather

than any defect on the AFC, and proposed modifications which were made by the supplier under warranty. The suppler replaced all line pans and since then the equipment has mined 2.6 Mt without any further failure.

6. 2017 Kirova mine: SUEK ordered a 300 m set of high specification supports to extract a 2.6 m seam. Kirova is an important mine extracting 7 Mt/yr mine of semi-soft coking and premium thermal coal. This set of supports was sourced from the same Polish supplier as the 2015 Polisaevskaya supports. Analysis of the design showed that similar design defects to the Polisaevskaya set were present, and the AFC lugs and relay bars would be subjected to excessive stress and could break. Modifications were required by SUEK, and the prototype testing was expanded to include testing of the snaking of the pans, using a rig SUEK designed for testing of the 2015 modifications. The modifications were optimised using this test rig, the set was manufactured and the supports are being installed in December 2017.
7. 2017 Yalevskovo mine: SUEK ordered 58 thick seam supports to extend the longwall in Yalevskovo Seam 52 from 300 to 400 metres. These were also from the same supplier. Design flaws were detected before the contract was signed and SUEK insisted on extensive design change to the base of the supports. This was done and the supports were approved for manufacture and testing of the prototype.

During the same period, SUEK purchased 114 supports from DBT, 422 from Joy and 420 from the original Glinik Company, before it became part of Famur Group in 2012. No significant failures have occurred on any of these supports. Every set that failed had been tested on a rig for 30,000 or more cycles, in full accordance with the European Standard EN 1804. Prior to this, all designs had been checked by finite element or similar modelling by the supplier.

It is significant that most of the failures were of parts of the supports that are not tested by EN 1804, such as relay bars, base steering rams, and the AFC advance mechanism. The only failure associated with roof loading was the breakage of caving shields at Krasnoyarskaya mine. This was extensive and required all supports to be extensively repaired twice, so it was of considerable concern that it was not identified during cycle testing.

Reaction to major failures of equipment

When anything big, strong and expensive breaks an equal and opposite reaction generally occurs:

1. The supplier blames the user for doing illogical and impossible things to his fine equipment.
2. The user proves he is not responsible for abuse, but tells the supplier he will sue for the full value of lost output – regardless of the contract. Relations are fraught and time is lost.
3. The supplier blames the materials – despite the quality assurance (QA) system and certification, which he had previously boasted about. He wastes weeks looking at metallurgical analyses, microscopic inclusions and the like, but finds nothing significant.
4. The last possibility that is considered is that the breakage simply means that the applied stress exceeded the strength of the material - because the stress acting on the failed component was far higher than the designers anticipated.

Considerable time and output can be saved by first considering the possibility of excessive stress - as this is logically the most likely cause of failure. Longwall equipment is so robust that even serious abuse should not be able to break it - and abuse is hard to hide. Modern QA systems are extremely robust, so the chance of a whole set of caving shields or a complete set of AFC pans being made from the wrong material or with the wrong technology, is slim to non-existent. Welding processes are also formally defined and thoroughly checked, so weak welds are not common. In most cases weeks of lost or reduced output could have been saved if the most likely cause had been considered first, instead of last. In the case of the failed caving shields the FEA showed that the area where major cracks developed should have had stress levels of only 60 MPa, but the supplier still postulated that welding defects or deficient materials was the cause of the failure. If the cause is found to be stress that exceeds the levels anticipated by the designers, then the source of this stress and the mechanism that concentrates it can be quickly be identified and action taken to minimise production loss.

Stress and stress multipliers

One reason for resistance to the concept that excessive stress could be the culprit when enormously strong components are broken is that the associated mechanism has limited power. For example, when AFC lugs broke engineers, assumed that this could not be due to excessive stress because the thrust of the advance ram was only 400 kN during conveyor push and 650 kN during support advance. To break a lug in tension probably requires a tensile force of the order of 5-8000 kN, and this clearly cannot be generated by the ram that drives the relay bar. Furthermore, during advance of the support, the loading on the lug is limited to the force required to move the support, so it is probably less than 200 kN in most cases, occasionally increasing if advance of a support is impeded. Even so, each support acts alone during advance and neighbouring supports cannot assist a jammed support to move.

However, AFC pans do not behave in isolation, so it is possible to generate high forces during AFC push-over. During a 15 pan snake, 15 rams are pushing. If one pan cannot advance and rotate to form the snake (because it has hit a step in the floor, for example), then the surrounding pans feel this reaction and all 15 rams act to act to assist the blocked pan to force it to advance. This means that the force acting on the lug of the blocked pan may be 15 x 400 kN, rather than the 400 kN that is directly connected to it, and as this force is applied a considerable distance away from the lug it generates torque instead of linear stress. Therefore the stress may be far higher than originally foreseen.

Furthermore, the direction of stress may be reversed. Take the hypothetical case of one pan that cannot move through the snake because it is obstructed, or because the advance ram is bypassing and cannot produce force. Immediately the thrust of all the other activated rams will act on the pans adjacent to the one that is hanging back and will drag the blocked pan forward. In this case the AFC lug on the blocked pan will experience very high levels of force, but its direction will be reversed and the stresses in this lug will be tensile rather than the normal compressive stress. There will also be massive bending forces or shear forces acting on the lug as the neighbouring pans force the blocked pan to rotate in order to form the curve in the snake because pans can move forward only if they rotate.

It is also possible to multiply other forces so even a small force can produce high stress. The two most common ways of doing this are levers and wedges. A wedge with a face angle of 1 degree will multiply a force by approximately 50 times, so shallow angled contacts between components can multiple force greatly and generate extremely high levels of stress. Levers also are force multipliers. When an AFC pan is dragged forward by three or four pans on either side, these are acting as levers and they generate very high torque, which acts on the point of blockage. Another consideration is the direction of the force. It is expected forces will be compressive or tensile because the advance rams act at 90^0 to the AFC and are linear mechanisms. When the conveyor is pushed it “should” create compressive forces in the AFC lugs, and when the support is pulled in everything “should” be in tension and self-aligning. However, it is possible that during conveyor push, extremely high forces can be generated which act at 90^0 to the axis of the relay bars. This can occur only if the lug on one AFC pan becomes blocked and cannot rotate to form the snake – because the relay bar is incapable of following the trajectory of advance and rotation of the AFC lug. If this does occur then extremely high levels of lateral stress generated by multiple rams and long levers can act at 90^0 to an AFC lug, and break it in bending or shear.

Cost of failures

All failures have a financial cost, even if it is only the cost of removing and replacing damaged parts. However, when longwalls are averaging in excess of 1000 t per operating hour, every stoppage costs thousands of tonnes and substantial revenue in the financial year. In some instances, the longwall has to stop immediately, while in others, the rate of production is reduced. In every case of breakage, the time required to transfer the longwall equipment to the next panel is protracted by the need to transport and repair equipment.

A conservative estimate of the loss of production time and tonnes of ROM arising from the failures of SUEK longwall equipment in the period 2007 to 2017 is shown in Table 1. Losses exceed 3 Mt of coal. The greatest losses were associated with the new thin seam set in Polisaevskaya mine in 2015 and 2016.

Table 1: Direct loss of ROM due to equipment breakages

Mine	Cause	Year	Monthly output (Mt)	Lost time (Months)	Lost output (Mt ROM)
November 7th	Reduced tempo, plus repairs and fitting double articulated clevises. During face transfer cut off all lugs and replaced with double lugs in order to weld onto metal that was not fatigued.	2007	0.35	2	0.7
Krasnoyarskaya	Delayed start to modify attachment of AFC and relay bar to increase articulation at attachment pin	2007	0.28	0.7	0.2
Krasnoyarska	Removal of all supports from the mine to repair caving shields. Twice.	2009/10	0.28	3	0.84
Polisaevskaya	Lost output due to AFC downtime and loss of tempo	2015	0.3	3	0.9
Polisaevskaya	Transport AFC out and new one in to mine, plus repairs to relay bars	2016	0.3	1.5	0.45
Polisaevskaya	Repair of impact damage to several bases. Inspection of all advance mechanisms for damage.	2016	0.3	0.33	0.1
Total		**5**		**10.53**	**3.19**
Average ROM loss in each affected Year (Mt)		**0.66**			

NATURE OF FAILURES

Types of failure

There have been three main types of damage to longwall equipment in SUEK mines in the period 2008 17:

1. The heavy lugs that attach the relay bar of the powered supports to the AFC broke. The nature of the breakage has been slightly different, depending on the AFC design. There was also associated damage to the outer end of the telescopic relay bars because of excessive lateral force. The root cause was inadequate provision for lateral movement of the relay bar during AFC advance. Contributing factors were; excessive width of the relay bar, inadequate base steering as a result of incorrect positioning of the base steering rams, and errors relating to the design of the “steering wedges” on the relay bars and the front inner section of the bases.
2. Heavy brackets inside the base of supports that attach the AFC advance mechanism to the base bridge were ripped off on a small number of supports, and impact damage occurred on a substantial number of AFC advance cylinders. This was due to the design and positioning of the mechanism to hold down the relay bars.
3. A full set of caving shields developed multiple, large cracks in plates and welds as a result of interference between the top, outer edges of the upper lemniscate link with the vertical ribs of the caving shield. The two components were forced together at a very shallow angle as the supports yielded and converged. The root cause of the breakage was failure to include a 10-12 mm spacer on the hinge pin on both sides of the lemniscate link to maintain clearance between the sides of the caving shield and the sides of the lemniscate linkage during convergence of the supports.

Breakage of AFC Lugs by PRS

SUEK has experienced failures of AFC attachment lugs on two AFCs since 2007, with a total of more than 200 lugs broken. Typical results are shown in Figure 1, for a welded AFC, and Figure 2 for a cast AFC. In both cases the system included an articulated clevis, as shown in Figure 3. The vertical pin of the clevis allowed approximately 8^{o} of articulation in both directions – which exceeds the maximum rotation of the AFC pan in the middle of the snake. The other point to note is the very limited clearance between the attachment and the AFC lug – presumably because the designers believed that the swivel on the clevis could accommodate all necessary articulation. In both 2008 and 2015, the AFC lugs started to break within days of commencement of operation and 50 or more pans were damaged in the first few months. In both cases inspection of the adjacent, unbroken lugs did not reveal any signs of defects, excessive loadings or bending or deformation. The lugs then broke suddenly and with no prior permanent bending or cracking. This indicated that the cause was a loading condition that only occurred intermittently and whenever it occurred it broke the lug. This opinion was reinforced when breakages were found with half the broken surface showing slight rust, and the other half with a clean, fresh break, indicating two discrete failure events, at least several hours apart and not more than one or two days apart.

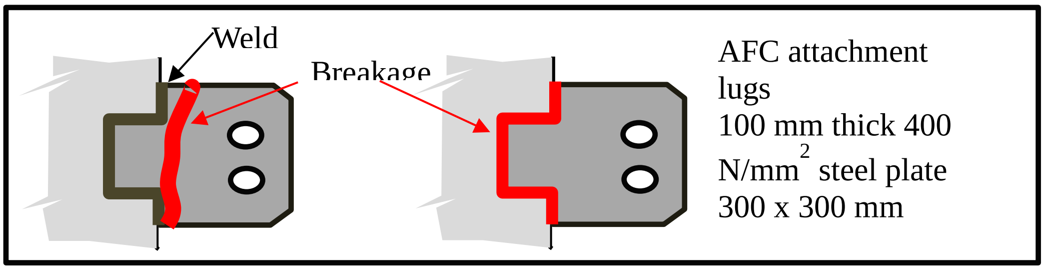


Figure 1: Breakage of welded AFC attachment lugs – 2008

Figure 2: Breakage of cast AFC lugs 2015 (every line pan was broken in this manner)

Figure 3: Clevis and attachment to AFC

The first major failure was extensive breakage of the lugs on a new, Russian-made AFC, which was attached to a new set of Polish roof supports. Because two manufacturers were involved, each blamed the other. However, a short period of observation underground proved that the damage occurred during push-over of the AFC and that the fault lay with the design of the powered supports. The clevis was redesigned to allow more articulation at the connection with the lugs, in order to prevent lock-up of the mechanism. The root cause was excessive width of the relay bars which meant the relay bar collided with the base as the AFC was pushed over. Unfortunately, the same problem occurred with a new longwall purchased from a different Polish supplier in 2015, and the same defective design was subsequently proposed for another full set of medium seam supports and for a 100 m extension of a thick seam set.

Two AFCs have been destroyed, and another was modified before going underground to prevent similar failure, plus the design of one full set and one partial set of supports had to be substantially modified at a late stage in design. Therefore, it is worth understanding this problem and the solution.

SUEK has had no breakages with structures on Joy or DBT supports operating in the same conditions, with the same operators during this period. Their designs have eliminated the root cause of these defects. SUEK also has one full face set and one partial set of 68 supports, from the original Glink Company to a well-proven design. These supports were supplied in 2010 and 2011, and no damage has occurred. The root cause of the design fault in two makes of Polish supports was failure to allow adequately for lateral movement of the AFC pans during snaking.

As a pan is pushed forward, the pan joint on the goaf side opens up and the pan rotates. This causes the attachment lug to move along the face and the relay bar must be able to follow this lug. If it hits the internal sides of the base tunnel, it can impede the rotation of the AFC pan, even if there is articulation available at the pin connecting the relay bar and the lug, or even if there is a swivelling clevis between the end of the relay bar and the lug attachment. This is shown in Figure 4.

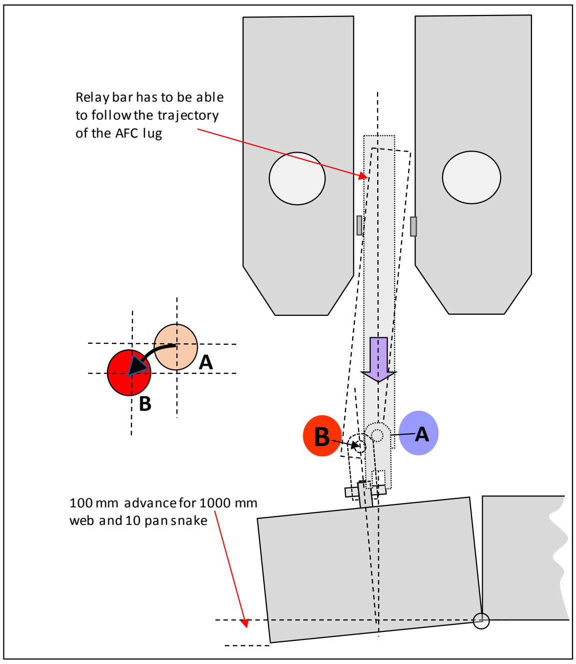


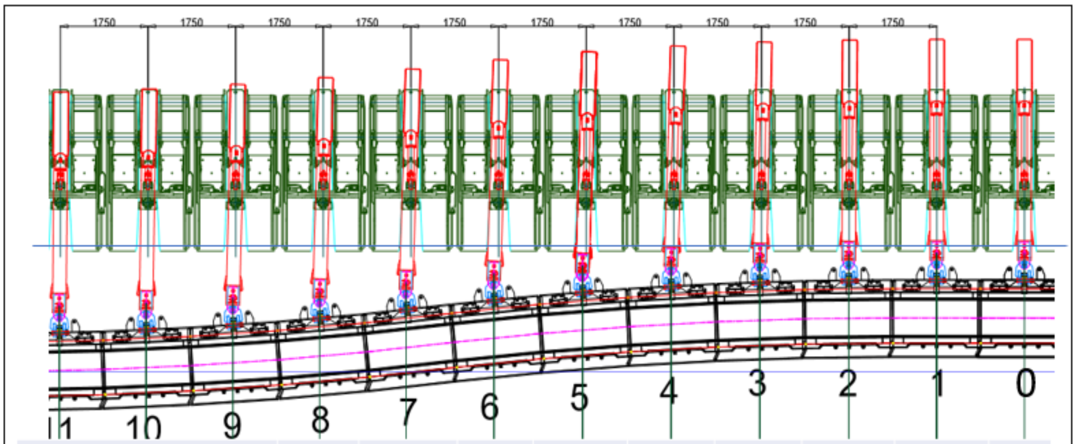
Figure 4: Lateral movement of AFC and relay bar

Once the relay bar cannot move laterally, the system is almost locked. If there is clearance between the sides of the attachment and the AFC lug, then the lug can slide along the pin, but once the lug comes into contact with the side plates of the relay bar attachment, the system is fully locked, and severe stresses will be generated if the AFC pan continues to rotate.

The cumulative lateral movement of the AFC lug/relay bar connection point is substantial. It varies depending on the length of pans, the width of pans (including depth of the lugs, to the attachment position) and the detailed design of the face side pivot points. Modern AFCs have a stepped joint at the face side, and this may mean that the trajectory of the pan is different; depending on the direction the snake is formed.

In the convex part of the curve the relay bars move in one direction, and in the concave section of the snake they move back again, until they return to their original position, in line with the centre of the support.

The first half of the snake, for a SUEK longwall with a set of Polish supports and AFC from the same company is shown in **Error! Reference source not found.**. The push-over on this face is 1 m, although all other SUEK faces operate with 0.8 m webs. The design of this support had to be modified as this drawing and subsequent testing of the prototype



Pan	8	7	6	5	4	3	2	1	0
Lug No. to Lug No.	7 to 8	6 to 7	5 to 6	4 to 5	3 to 4	2 to 3	1 to 2	0 to 1	-
Centre to centre distance mm	1750	1752	1770	1771	1773	1772	1759	1750	1750
Lateral movement of this lug mm	0	2	20	21	23	22	9	0	-
Cumulative Movement of Lug mm	97	97	95	75	54	31	9	0	0

Figure 5: 15 pan snake of 1 m web - showing lateral movement of the AFC attachment points in the convex part of the snake

This clearly showed that the AFC would be broken - unless the relay bars or clevises broke first. The AFC attachments needed to move a total of 97 mm along the face but the front end of the relay bars could not follow this. Note that the wedges are not in contact with the internal sides of the support base on support No.1 in this drawing, but they are in contact on supports 4, 5, 6 and 7. If they were shown in contact before the start of the push-over, then the relay bar would be trapped, and high forces would be developed.

The lateral movement during snaking of the AFC is considerable. In this case the lateral movement of the front end of the relay bar is 95 mm. The lateral movement decreases along the length of the relay bar from 95 mm to zero at the pivot point. The design must ensure that the relay bar can follow this amount of lateral movement of the AFC pan without locking up at the attachment point, and without any horizontal contact between the relay bar and the base of the support, other than at the attachment and at the designed pivot point, inside the base of the support.

The only way to guarantee this is to have considerable space between the sides of the relay bar and the inside of the base, and to install effective contact makers and breakers to ensure that space is created when the support is pulled in, so that it is always available during AFC push.

There are two ways of achieving this. The best way is to use blocks inside the narrow portion of the base tunnel, close to the front bridge, with similar blocks on the relay bar. When the support is fully advanced, the tapers on the blocks of the relay bar force the base of the support to move horizontally. This creates a gap of the order of 50-60 mm between the main part of the relay bar and the base, when the contact makers are engaged.

As soon as the AFC push commences and the relay bar has moved forward approximately 50 to 75 mm, contact is broken. If “banana” slots are used on the AFC attachment lugs then contact is broken during the lost-motion phase, before any force is applied to the AFC and before advance and rotation of the pans commences. The second way is to use wedges, but these create less clearance and must be positioned well forward so contact with the base is broken at an early stage in the AFC push. This means that the internal faces of the base must be carefully designed to prevent contact. Deep wedges are required to ensure there is adequate room for the relay bar to follow the AFC, but they must be short in order to break contact before the AFC starts to rotate. It appears that contact with blocks inside the narrow section of the base is a considerably more effective mechanism, as it provides maximum free rotation of the relay bar. When combined with suitable internal angles of the base, it can guarantee that contact does not occur throughout the full push-over.

Until recently, Polish suppliers have used articulated clevises at the front of the relay bar. They appeared to believe this allowed the relay bar to follow the AFC, and provided drawings that showed the range of rotation of AFC pans throughout the snake, but without showing lateral movement – which cannot be accommodated by a clevis. When the Polisaevskaya AFC was broken, the designers’ proposed replacing the clevises with even more articulation. Unfortunately, once the relay bar comes into contact with the base of the support the relay bar cannot move sideways to follow the AFC pan, so even if the clevis still has 10^0 of articulation remaining, it cannot be utilised, and elevated stresses will be produced.

During this process SUEK proposed a design for a test rig that could physically prove whether collision will occur at any point in the conveyor push-over. This ensures that an AFC pan follows precisely the same trajectory as it would on the face when it is connected to 15 or more pans, and a full snake was formed. This is shown in Figure 6.

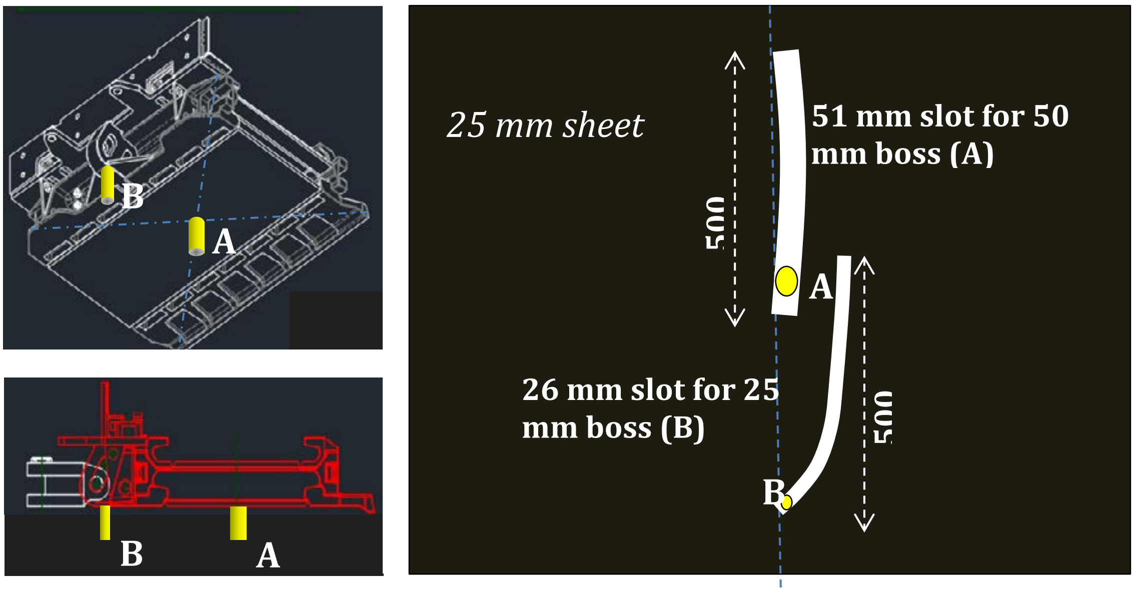


Figure 6: Conceptual design of rig to test pan snake

A modified AFC pan is placed onto a sheet of steel with curved slots that exactly replicate the trajectory of the centre of the pan and of the AFC attachment lug. The modified pan is connected to a powered support and pushed over the base sheet a distance of 500 mm, to replicate the first half of the 1000 mm push-over. In the second 500 mm of advance the AFC lugs return towards their start position, so there is no point in modelling this phase, as it cannot create contact. It is essential that the guide slots accurately represent the movement of the pans, using information obtained from the supplier of the AFC, which will be different for pans of different widths, lengths and different face side pivot designs. The rig used in the factory tests is shown in Figure 7. This also allows the base of the support to be rotated relative to the AFC to allow for the lead of the bottom gate of face, and for misalignment of supports. This rig enabled clearances and lack of contact to be checked throughout the full 500 mm of advance in the convex section of the snake. In the tests of the modifications for the Polisaevskaya supports, a swivelling clevis was retained. However, when a similar rig was used to test another, later set of supports in 2017 no swivelling clevis was used and additional clearance had been provided between the AFC lug and the vertical sides of the attachment to the relay bar, similar to the approach that has been proven by Joy and DBT.

Figure 7: Photographs of test rig replicating the snake of AFC in the supplier's premises

Use of this rig revealed that the wedges on the relay bar had to be positioned close to the tips of the support base, so they could break contact as soon as the push-over commenced, and also demonstrated the inherent advantage of contact being made inside the base tunnel, instead of on the angled tips.

Base steering

In the case of the Polisaevskaya supports, the base steering rams also appear to have been a factor contributing to breakage of the equipment. This face was inclined, although only at 7-13^0. The base steering rams did not appear to adequately correct the alignment of the supports relative to the AFC. The face operated with a lead of approximately 25 m at the bottom gate (Conveyor Road in Russian parlance), or approximately 5^0 lead, to prevent the AFC creeping down the face. This lead was effective as the head drive was maintained well clear of the bottom side of the Conveyor Road, so there was no creep. However, the orientation of the supports did not appear to be fully corrected during pull in. If the rear of the support is rotated downwards and not fully corrected, then the angle of the internal edges of the support will be less than the designer intended. This means that the angle between the relay bar and the inside of the base is decreased, and this increases the chances of the relay bar contacting the base during AFC push-over.

As SUEK successfully operates many inclined faces, and has operated on gradients of up to 26^0 it appeared that there was some difference in the steering arrangements on these supports. The Polisaevskaya supports have the base steering ram immediately behind the bridge and in front of the legs, and almost in line with the pivot point on the relay bar, which is 300 mm behind the bridge linking the two base pontoons. The steering of the supports is sluggish. Another SUEK mine has a face comprising 111 Tagor 15/22 supports along with 68 supports that were supplied by the original Glinik Company. The Tagor supports have the base steering rams behind the legs and the Gliniks have them in front of the legs.

Inspection and discussion on the face revealed that the steering of the two types of supports was noticeably different. The Tagor supports started to correct as soon as the pull-in commenced, but the steering of the Glinik supports was slow to start, followed by a big swing at the end. The Glinik supports have the base steering ram in front of the legs, in the same position as the supports at Polisaevskaya mine. Both of these sets are hard to steer. All Joy, DBT and Tagor supports owned by SUEK have the base steering rams mounted behind the legs, and they steer progressively and predictably.

SUEK has recently purchased a new set of supports for Kirova mine and ordered about 60 supports to extend a face in Yelevskovo mine (Seam 52) from the same supplier as the Polisaevskaya set. Both designs have the base steering rams behind the legs, so it appears that the supplier has recognised that the location of the base steering rams does influence the ease of steering of supports.

Impact damage

The Polisaevskaya supports also suffered damage from internal collision between the AFC advance mechanism and the inside of the base. Damage included ripping out the bracket that attaches the AFC advance ram to the base bridge, severe deformation of the piston head on some advance rams, and deep indentations on the collars of the cylinders. The location and nature of the holding down lugs is shown in Figure 8 and the damage is shown in Figure 9.

Figure 8: Internal lugs for holding down the relay bar

Figure 9: Impact damage to AFC advance rams

The supplier responded quickly and made a full set of heavier mountings and imported them to Russia. Unfortunately, the approach was a repeat of previous experiences – breakages must be due to inadequate strength – redesign it and make it stronger. There were two downsides to this proposal:

1. The new mountings were certainly heavier and stronger but installation required the old mountings to be cut out, and the new ones to be welded on. This could not be done underground. Transporting the whole set to the surface for this modification would cost SUEK four to six weeks of production due to the severe limitations of underground monorail diesel transport of heavy equipment and the need to transport the shields to off-

site workshops for modifications. On site repair was not an option as the temperature was minus 15-25^{0}C.

2. The designers had not identified the cause of the breakage, so they were designing blind. They had not carried out a survey to find facts, so even if the requirement really was strength, it is impossible to design and achieve an acceptable factor of safety unless the stresses are known.

SUEK carried out a survey of a number of broken supports that had been brought to the surface, and this established that the breakage of the mountings was due to the collar of the cylinder of the AFC advance ram impacting with the lugs inside the base that hold the relay bar down.

The advance ram is mounted with the piston at the front end of the support base, and the cylinder is attached to the rear end of the relay bar. The holding down lugs is located about 0.3 m behind the bridge. The evidence established that, as the ram closed during AFC push-over and the cylinder moved towards the front of the support, it occasionally collided with these lugs. If this happens then the ram will be blocked. This will mean that the neighbouring supports will try to pull the AFC pan (and the cylinder) forward. A total force of 4000 kN from ten advance rams acting to overcome this blockage could account for the observed damage - ripping metal off the cylinder, ripping metal off the holding lugs and serious deformation of the forged head of a piston.

Item 1 of Figure 9 shows obvious damage to the collar of the outer cylinder. This has been hitting the holding-down lug, shown as item 3, and gouging metal off it. Item 2 is the forged head of the piston on the advance ram and this serious deformation has occurred after only 2.5 Mt. The proposed ram mounting is shown in item 4. This requires extensive welding that could only be done on the surface.

The root cause was the design of the mechanism for holding the relay bar down. The broken supports were face end and transition supports, which had larger diameter advance rams, which greatly increased the likelihood and severity of contact. Inspection of the line supports revealed that approximately 50% had visible damage to the collar of the cylinders of the advance ram and to the lugs, but this was minor – with about 10-15 mm of metal ripped off.

SUEK had developed a mechanism to hold the piston head of the advance ram in place even if the original mounting failed, so it was decided to repair the face end and transition supports by fitting new mounting brackets, trimming the holding lugs down to increase clearance and replacing the seriously damaged advance rams under warranty, but to do a face to face transfer of the line supports. It was hoped that the bits knocked off the advance rams and the lugs would have created adequate clearance to prevent further damage. This avoided the significant loss of output associated with transport of all supports to the surface, and it has been successful. No further failures have occurred.

Supports modified prior to manufacture

The new supports for Kirova mine were found to have a similar arrangement for holding down the relay bar, consisting of lugs trapping the upper edges of the relay bars, located about 0.3 m behind the base bridge.

These are intended to prevent the rear end of the relay bar lifting when the base-lift mechanism is activated. This lifts the front of the support by pushing against the relay bar, but this steepens the angle between the advance ram and the relay bar. This increases the vertical component of the resultant force, and this acts at the rear attachment of the advance ram to the relay bar, lifting it vertically as it moves backwards relative to the base of the support, as shown in Figure 10. This vertical force must be counteracted by some form of retainer inside the base of the support, or lift at the front of the base will be reduced, and the rear of the relay bar could be trapped inside the support.

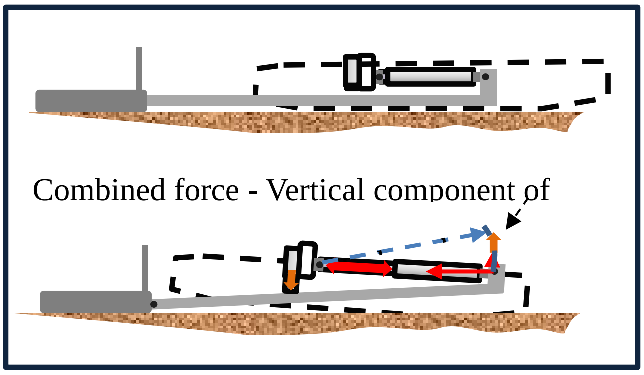


Figure 10: Resultant forces during support advance with base lift

The Kirova supports could not be changed to a rear hold-down arrangement as used by Joy and DBT because the bases are too short to allow an internal bearer plate to be used. A complete redesign, FEA and cycle testing of a new base was not feasible in the available time. Based on the limited damage to line supports on the Polisaevskaya set due to interference between the advance rams and the holding down lugs, it was decided to accept the design, along with warranty for damage. The hold down arrangement has been checked and clearances have been maximised as far as possible.

Another partial set from the same supplier for use in 4.5 m extraction was also checked by SUEK. In this case there was adequate height and length available to change these supports to rear hold-downs for the relay bars. The design of the base was changed completely as a result of SUEK's concerns, with an effective contact make/break mechanism inside the base tunnel, and a similar system to DBT for holding down the rear end of the relay bar, using a "doghouse" with an internal bearer plate that is in contact with a boss at the rear of the relay bar and ram, as shown in Figure 11.

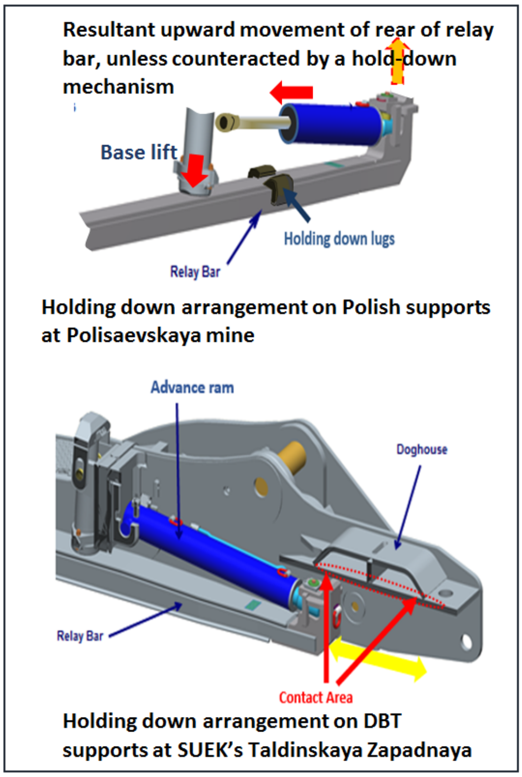


Figure 11: Comparison of different holding-down mechanisms

The function of the holding-down mechanism is to counteract the combined effect of the base lift ram and the retraction of the advance ram, to pull in the support. These forces form a couple that will lift the rear of the relay bar, thus reducing the area of contact between the relay bar and the floor, which serves to lift the base of the shield as it advances. If this is located at the rear of the relay bar then the base rotates about this contact point and the contact between the relay bar as the front is lifted by the base lift ram, raising the whole base and allowing dirt to pass underneath. The system using lugs a short distance from the base lift ram does not appear to be as effective as the doghouse and bearing block used by DBT and unless the advance ram is mounted with the cylinder at the front so that it is stationary, there is also a risk of collision between the lugs and the advance ram.

Joy uses hold-down lugs on one of SUEK's sets, but these are located far back on the relay bar to maximise lifting of the base. The top of the relay bar is wider in the contact area for the lugs to trap it without any possibility of collision. They also reverse the advance ram, so the cylinder is static and the (smaller diameter) piston moves. This eliminates the possibility of collision and probably also facilitates the flow of dirt out the rear of the support.

Broken caving shields 2007 and 2009

Four months after a face set of Tagor supports was commissioned cracking was observed on the lower surface of the caving shields on four or five supports. A full, detailed survey was carried out and this showed that the majority of the caving shields had long, wide cracks at the corners of the access cut-outs. Initially most were in the corners of the access pockets, but with time these became more extensive and then cracks developed along the outer edges of the underplates. The steel underplates in the area where cracks occurred were supposed to be low stress areas, with only 6 MPa in plate that should withstand 500 MPa. The supplier's FEA is shown in Figure 12.

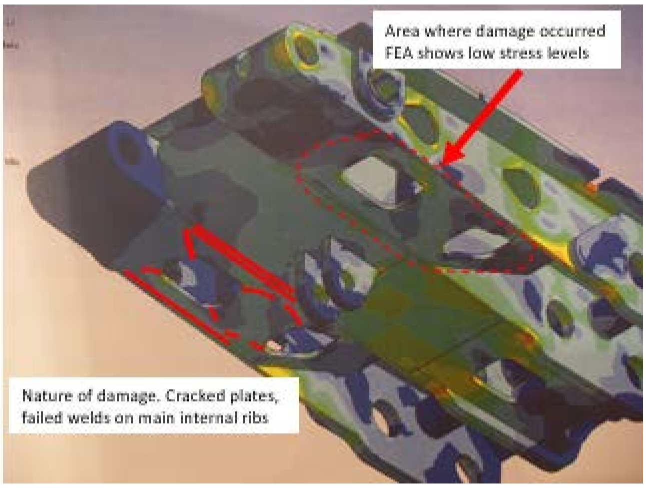


Figure 12: FEA plot of caving shield, showing failures in low stressed plates and welds

Clearly the cracks were occurring at areas of excessive stress concentrations, but it was necessary to establish the source of the stress and to determine how it was being concentrated. The supports were in use at this time so each hypothesis had to be checked out underground. The roof in this seam was irregular and difficult to hold and the telescopic canopies were ineffectual, so the face was difficult, with supports angled, and with areas along the face where the supports converged by 1 m or more. There was also a tendency for the canopies to be set at an angle with the tips up and the rear of the canopy lower, which flattened the inclination of the caving shields.

Observation of the shields eventually showed that there was high-pressure contact between the top edge of the upper lemniscate and the inside edge of the caving shield. This was normally seen as deep scoring of the metal inside the caving shield, but on several occasions fresh interference was seen and photographed. This consisted of deep scoring of the metal, and large areas of “bluing” due to very high temperatures. This damage rusted over after a day or so, so it clearly had occurred shortly before the survey.

A comparison of this area of the Tagor supports with supports at other SUEK mines quickly revealed that Joy and DBT supports had 10-12 mm spacer discs between the lemniscate link and the internal sides of the caving shield at the hinge pin. This clearly was designed to keep the sides of the lemniscate and the caving shield apart to prevent collision and creation of a stress multiplier. On some other supports the lemniscates were shaped like dog bones – wide at the hinge points, and narrower in the midsection. Both designs effectively prevent contact when the support is converging.

The supports on the face at Krasnoyarskaya Mine did not have either of these features, and were a close fit inside the recesses of the caving shield. These supports yielded and converged at a load of 900 t. If the upper lemniscate linkage and the internal or external side of the recess in the caving shield came into contact at a shallow angle during convergence then this would act like a very shallow angled wedge and modify the vertical forces so as to generate to extremely high lateral forces which exceeded the strength of the fabrications. This would induce tensile forces in the underplates of the caving shields, cracking plates and breaking welds, as observed on most of the caving shields. This was clear evidence of the source of the stresses that damaged the supports.

The only solution was to cut off all underplates and replace them with thicker, higher grade steel, with redesigned cut-outs to reduce stress concentration, and to change operating procedures to maintain a high angle on the caving shields in order to limit contact. The supports have worked continuously without further breakages.

The lack of clearance between the links and the caving shield is clearly visible in the photograph at the bottom of Figure 13. This small design error resulted in breakage of every caving shield on line, transition and roadhead supports. A 25 mm narrower link with a 12 mm spacer on each side would have prevented this damage.

Figure 13: Examples of breakage of caving shields, 2008

EN 1804 TEST

SUEK has suffered from a series of breakages, and the associated loss of output. Every set of supports had undergone cycle testing, and EN 1804 was followed explicitly in every case. The problem is the limitation of the test procedure:

- The test is static
- It tests only the components that are loaded by the roof.

It does make the support converge when it yields and it does not test the other important functions of a powered support – push-over of the conveyor, pulling in the support, steering the support during advance, and interaction of the support and the AFC pans.

Static test

The cycle testing is static, in that the top of the test rig is set to an agreed height (the normal working height) and the base of the rig is fixed. The support sits in this space and undergoes loading, yielding, unloading, and reloading thousands of times. Blocks of steel are installed under the base and on top of the canopy to induce stress concentrations, bending and twisting.

This is significantly different from the process of cycling of supports underground in a mine. In practice, when a support yields, it lowers off. If a support is overloaded then the support may converge until the legs are completely closed, but more commonly a support yields several times before it is reset, and this yielding may lower the support 50 mm or 500 mm. This is a critically important difference.

There is no suggestion that EN 1804 should be scrapped and replaced by testing in a rig that loads externally and compresses the support throughout its full range. It is not necessary, and it would not work. However, engineers involved in procurement of longwall equipment need to understand that EN 1804 is merely a test of structural integrity under set conditions of loading, and nothing more. It tests the structural design and the quality of manufacture, but not the functions of the support underground.

The problems that can occur in real life are due to the fact that as a support is converged certain components may come into contact. If the support continues to converge, then massive stress concentrations will occur. The designer obviously has not foreseen these so they are not detected by FEA, and they cannot be detected by a static rig test.

They might be seen in a compression rig, but only if the test engineers and the end users understood the potential for collision and interference to occur and created the necessary conditions of convergence combined with misalignment. However, if the potential for interference and unplanned contact is recognised then it makes more sense to engineer it out, before one piece of steel is cut, rather than test for interference using an expensive compression test stand and an expensive prototype support.

In the case of SUEK's Tagor supports the design could have been changed relatively easily – by narrowing the whole upper link, or by stepping it in by 20 mm on each side, immediately past the ends that fit on the pivot pins. Either of these very minor modifications could have prevented damage to the caving shields.

Tests only the components that are loaded by the roof

SUEK has learnt the hard way that it is essential to test more than the structural integrity of the canopy, base and caving shield and the longevity of the legs and stabiliser ram.

It is inconceivable that major parts of the structure will break into pieces. If a support has undergone computer stress analysis then failure during testing is normally limited to small or moderate cracks in areas where stress raisers have been overlooked in modelling, or inadvertently introduced during manufacturing. Modifications as a result of cyclic testing of the prototype most commonly consist of changing some tight radii, altering a welding procedure or introducing additional stiffeners and the like. If a 100 mm thick plate of 550 or 600 grade steel snapped during cycle testing there would be a contractual crisis.

But in underground conditions SUEK has suffered precisely this - sudden and complete breakage of large numbers of 100 mm plates and castings associated with powered supports and serious damage to 170 relay bars on one face alone. In total, SUEK has had more than 300 failures of AFC connector lugs – a component that is massive and which is designed to have very high factors of safety. The cause is not incorrect operation, but incorrect design, which cannot be identified during normal testing.

Additional testing clearly is required to prove the secondary functions of powered supports including:

- Base steering, to ensure that the alignment of the support can be corrected during support advance and that correction is executed throughout the full advance.
- Serious mis-alignment of supports can result in contact during AFC advance.
- Checks on the travel of the advance ram within the base tunnel and analysis of the mechanism that occurs during base lift, to ensure there is no risk of collision – for line, transition and face end supports as the cylinder diameter is likely to be different).
- Check axial and horizontal travel of the relay bar during push over of the full web, using the actual trajectory of the AFC pan at the position of the banana slot or pin hole. Check that the attachment pin does not lock up, that any articulation point (if a clevis is fitted) does not lock up, and check that the relay bar has adequate clearance inside the base throughout the full pushover. High quality computer modelling can do this, but physical testing with a test rig has proved highly beneficial in the case of non-traditional suppliers, and has greatly accelerated refinement of the base and ancillary components of the supports.
- Check that the contact-makers act as effective contact breakers and release the relay bar from the base of the support during the “lost motion” phase of the AFC push-over.

These tests and inspections are in addition to the normal inspections of hoses, ease of change-out of advance rams and base pushers.

Some of these can be checked by proper 3D computer modelling, by proven companies such as DBT and Joy (Cat and Komatsu). However, the precise trajectory of a pan during snaking depends on the design of the pan, the length of the pan and the effective width of the pan – which is the distance from the pivot point on the face side to the point of attachment to the relay bar on the goaf side. The support designer is responsible for this modelling, but the AFC supplier should be contractually obliged to provide precise details of the pan trajectory, at the centre of the pan, and at the lug. This will enable accurate modelling, and it can also be used to make a physical test rig.

The effectiveness of the base steering can be readily checked, especially if more than one prototype is made. SUEK has required construction of at least one face end, transition and line support for final construction check and detailing of hose routes, light fittings, guards, controls, before full scale manufacturing commences. This makes it easy to check the correction of the base during support advance, and to ensure that the contact makers/breakers are correctly positioned.

The area swept by the advance ram during retraction (AFC push) and extension (support advance) can be checked visually at this stage to ensure that the ram assembly and the base cannot come into contact, at any possible position and orientation of the relay bar.

The ability to shed mud and rock out of the back of the support should also be checked at this time. This is especially the case when the ram is mounted on the bridge at the front of the base and the cylinder moves in and out of the base, as the collar of the cylinder may compress material against the support during conveyor push.

The combination of EN 1804 with effectual design checks and 3D modelling can eliminate defects in design, but only if the customer’s engineers truly understand the mode of operation and functional requirements of all ancillary items. Failure of these items can stop a longwall as surely as breakage of canopies or failure of hydraulic legs and rams. SUEK has learnt not to assume that every supplier has the complete understanding of what can happen to his equipment in the underground environment.

CONCLUSIONS

It is essential to fully consider the functional requirements, design and action of the base and every ancillary device on powered supports, such as relay bars, clevises, base lifting rams and relay bar trapping, and the mechanics of base steering devices, powered side shields, AFC creep arrestors, AFC vertical steering rams, banana slots, face sprags and face end base retention devices, if any of these are fitted. It is best to develop this understanding even when purchasing from a well-proven supplier, but it is essential to fully understand all primary and ancillary functions of powered supports if you are buying from new suppliers, such as Polish or Chinese companies, in order to avoid costly failures.

Suppliers should rectify any failures under warranty, but the mining company cannot be compensated for consequential losses. It is better to question the “obvious” than to accept designs and then find they are not fit for purpose. Remember caveat emptor – “Let the buyer beware”.