

Design methodology for the Levelok conveyance arresting system used in the mining industry

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I have been employed by WJ Engineering since 2015 and was promoted to the hydraulic department design and managing engineer position in 2016. Working alongside Mr. B.J. Werkman, numerous Levelok systems have been audited, installed, and commissioned by WJ Engineering. In addition, the MK7, MK7s, and MK7 Elec Levelok Systems were designed and will be the main focus of this study. The development of these systems is a continuous process to adhere to the quality policy of WJ Engineering (PTY) LTD. I am grateful for the assistance provided by WJ Engineering (PTY) LTD during my studies. I appreciate the accessibility given to me for the use of their facilities and software programs. Special thanks to the engineering management and especially to the WJ Hydraulic department for their support.

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ABSTRACT

Proceeds from gold and diamond mining operations make a significant contribution to the South African economy, and therefore deep-level mining has become widely practiced throughout the country. Six of the ten deepest mines in the world are located on the South African treasure route, where the extraordinary depths of vertical hoisting present a range of challenges, with rope stretch being one of the more common challenges.

The Levelok conveyance arresting system is a solution that secures the positioning of a conveyance next to a shaft station to counter the problems associated with hoisting rope stretch. The concept behind the Levelok system has numerous potential advantages, but unfortunately, the system historically did not yet fully deliver on the promises of these advantages

The objective of the study was to address the shortcomings of the system, by studying and evaluating the Levelok Systems in the current industry as well as developing a design and evaluation methodology. The findings can be used to predict if the Levelok hydraulic power pack would be suitable for the customer requirements before it is approved for delivery.

To achieve these main objectives, the research presented in this dissertation highlights some of the complexities associated with the Levelok systems. The most complex apparatus of these systems is the decompression cycle assembly. Different arrangements of this apparatus and how the flow of hydraulic fluid through the narrow annulus between its spindle and seat affects the control output were explained and studied.

Using the knowledge obtained, a new decompression cycle arrangement was designed. This new invention has been patented in WJ Engineering's name with patent reference number PA165722/ZA and was the result of the application of the design methodology that was followed for the MK7, MK7s & MK7 Elec Levelok cage systems. The methodology for the design of a pneumatic actuated system and 24V DC operated system has been outlined in this dissertation.

The different designed systems of the MK7 range were tested and analysed with a constructed Levelok Power pack Decompression Cycle Conveyance Displacement Mathematical Prediction Model. All results were found to satisfy all system requirements and delivered a constant output for different tests completed using the test benches at WJ Engineering (PTY) LTD and on-site tests in vertical mine shafts. With the confirmed, tested concentric annulus size of 0.07 - 0.08 mm in the MK7 decompression cycle arrangement, the decompression cycle pressure curve of the Levelok system was rectified. Thus, the control output of the Levelok system, of obtaining the required stable "slide" of the arrested conveyance after clamp release, was improved. The result of this dissertation addressed all system shortcomings and all objectives of the study.

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NOMENCLATURE

ϕ_p :	Piston diameter.
μ :	Hydraulic fluid viscosity.
μ_s :	Static friction coefficient.
μ_k :	Kinetic friction coefficient.
a :	Acceleration.
A :	Metallic area of rope.
E :	Apparent modulus of elasticity of rope.
f :	Friction force of shoe on a guide.
F_2 :	Clamping force.
F_C :	Clamping force.
$F_{dynamic\ friction}$:	Dynamic friction Force.
F_R :	Forces acting on conveyance displacement.
F_s :	Spring force.
g :	Gravitational acceleration.
l :	Annulus length.
L :	Length of rope under load.
ΔL :	Elongation (Rope Stretch).
m :	Mass.
m_c :	Conveyance own mass.
m_p :	Payload mass.
n_c :	Number of clamps.
Δp :	Pressure drop.
P_1 :	Precharge of hydraulic bladder accumulators.
P_2 :	Main pressure needed from hydraulic bladder accumulators.
P_3 :	System pressure needed from hydraulic bladder accumulators.
P_m :	Measured pressure values.
Q :	Volume flow.
R :	Orifice inner diameter of the seat.
S_c :	Winding rope spring constant.
$Slip\ press$:	Slip pressure point value
t :	Time.
t_f :	Final time with a single time step increment.
t_i :	Initial time.
V_1 :	Required hydraulic bladder accumulator volume.

V_2 :	Volume of hydraulic fluid after hydraulic bladder accumulators' discharge.
V_3 :	Volume of hydraulic fluid full capacity in hydraulic bladder accumulators.
V_f :	Final velocity.
V_i :	Initial velocity.
W :	Size of the annulus.
ΔX_1 :	Moment lever arm from bearing to shoe on the guide.
ΔX_2 :	Moment lever arm from bearing to the hydraulic cylinder.
X_f :	Final displacement.
X_i :	Initial displacement.
CAD:	Computer Aided Design.
CFD:	Computational Fluid Dynamics.
FEA:	Finite Element Analysis.
FloEFD:	Engineering Fluid Dynamics. A CFD tool supplied by Mentor Graphics.
IFM:	Electronic supplying company.
LED:	Light Emitting Diode.
MK1:	Mark 1 Levelok cage system originally designed by Peter Horne.
MK4:	Mark 4 Levelok cage system operated with pneumatics.
MK5:	Mark 5 Levelok cage system operated with pneumatics and electronic interlocks.
MK6:	Mark 6 Levelok cage system same as MK5 system with a different airline.
MK7:	Mark 7 Levelok cage system fitted with the new decompression cycle arrangement and operated with pneumatics.
MK7 ELEC:	Mark 7 Electrical Levelok cage system. This system makes use of a 24V DC electronic control system and is fitted with a 4 kW 24V DC motor used to supply hydraulic pressure.
MK7s:	Mark 7 Levelok cage system fitted with the new decompression cycle arrangement and operated with pneumatics and electronic interlocks.
NDT:	Non-Destructive Test.
OEM:	Original Equipment Manufacturer. In the case of this dissertation WJ Engineering (PTY) LTD.
PLC:	Programmable Logic Controller.
QA:	Quality Assurance.

DECLARATION OF DEFINITIONS

Airline:	A pneumatic controlled assembly of a Levelok power pack, normally fitted with a pneumatic timer, 3/2 valve, regulator, water trap, and pressure relief valve.
Audit:	This refers to a Levelok system audit. The process where tests are completed on an operational system in a mine shaft, for evaluation purposes and checks.
Bank-level:	The surface level of a vertical mine shaft. This is where all mining personnel, and equipment are loaded, to be transported to the different sub-levels in the vertical mine shaft.
Conveyance:	A transportation device used in the mining industry to transport men, material, or ore up and down mine shafts stopping at different shaft station levels.
Clamp lock valve:	The component assembly fitted to a Levelok clamp to assist during an emergency. In the case of a hydraulic pipe failure, the clamp lock valve traps the hydraulic fluid in the Levelok clamp's cylinder, so it will not release during operation.
Decompression curves:	Visualization of the hydraulic decay in a Levelok system when the decompression cycle is actuated.
Decompression cycle:	The controlling unit of a Levelok hydraulic power pack. The decompression cycle arrangement controls the decay of hydraulic pressure in a Levelok system when released.
Flask:	A steel structure similar to that of a skip conveyance, installed at the loading station of a vertical shaft. This "bucket" forms part of the loading sequence line and is used to measure the weight of ore before it is disgorged into a skip conveyance.
Guide gauge:	The distance, measured in mm, between two guides (Face to face) in a vertical mine shaft.
Interlock:	A electrical limit that is put in place to activate or deactivate electrical signals, usually used for safety purposes in mining operations.

Kingpost:	Normally a hefty beam section carrying the main load on a shaft station.
Levelok:	The Levelok conveyance arresting system is a solution that is used in deep-level mining to secure the positioning of a conveyance next to a shaft station, to address the challenges caused by rope stretch during the loading and unloading of conveyances.
Main clamping pressure:	The maximum design pressure of a system when a Levelok system is clamped and a signal is sent to the winder driver to indicate safe clamping pressure of the system.
Manifold:	The steel block component of a hydraulic power pack where all the control valves are mounted. This block consists of multiple portal vanes connecting all the hydraulic valves and is normally machined with a milling machine.
Mine X:	The pseudonym used to hide the names of the respected mines.
Minitest:	The component fitted to a Levelok hydraulic power pack or clamp, to be used as a hydraulic pressure testing point.
Narrow annulus:	The gap between the spindle and seat.
Onsetter:	The person in charge of the necessary electronic signals that are sent to the winder driver for communication purposes for when a conveyance must be hoisted or halted.
On-site tests:	Tests done at Mine X at different Shaft stations.
Payload:	The additional weight that is loaded into a conveyance for transport. This can be men, equipment, or ore.
Rope end mass:	This is the total mass of the conveyance connected to the hoisting winding rope. The mass includes the payload, mass of external & internal equipment, guide rollers, and all rope attachments.
Rope stretch:	When a hoisting steel wire rope is subjected to tensile loading it will elongate elastically. This stretch in the rope will become unnoticeable after releasing the load. For deep single drop mines, rope stretch on the steel wire rope of some conveyances can be anything between 1 – 3m [17].

Shaft characteristics:	The specific requirements such as shaft depth, type of steel wire rope, etc. to trial the Levelok system against.
Shaft station:	Location in a shaft where conveyances stopover for the loading and unloading of men, material, or ore.
Sliding:	The term used for the displacement of a conveyance when a Levelok system is released.
Slip pressure:	The minimum pressure value in the hydraulic line of a Levelok arresting system, where the Levelok clamps can hold the conveyance steady. Any pressure value lower than this value will cause the conveyance to start moving out of the clamps' grip.
Spindle & seat:	The two main components of the decompression cycle arrangement.
System pressure:	The maximum pressure of a system when a Levelok system is clamped.
“The fast approach”:	When the hydraulic fluid reservoir of a Levelok power pack is pressurized the fluid inside it is transported through a check valve to the actuating part of the hydraulic cylinders in the Levelok clamps, and the clamps clamp against the guides. Due to the use of the pneumatic pressure supply, a quicker stroke actuating response is achieved than one will get from the hydraulic pump.
Winder driver:	The person in charge of the controls of the winder hoist.
Re-deck the cage:	Phrase used for the procedure where the onsetter signals the winder driver to hoist the conveyance up or down in the shaft so another deck floor of the conveyance can be level to the working station floor, ready for loading (e.g. A 2-deck cage conveyance will be re-decked once, and a 3-deck cage conveyance will be re-decked twice during loading.).

CHAPTER 1

INTRODUCTION

1.1 Prolegomenon

The Levelok system was originally designed and developed by the late Peter Horne and has been used in the mining industry for more than 40 years [1] [2]. Horne Hydraulics South Africa faced bankruptcy in 2016 after which WJ Engineering (PTY) LTD procured the Levelok trading name. WJ Engineering is a leading conveyance manufacturer in the mining industry and most of the conveyances designed and fabricated by WJ Engineering are incorporated with a type of Levelok system [3].

The Levelok system is a conveyance arresting system that is employed to counter the problems associated with rope stretch during the loading and unloading of ore, men, and material. The basic system comprises of hydraulic operated clamps (Figure 1) and a hydraulic power pack (Figure 2). Figure 3 illustrates the positions of these two main components of the Levelok man, material cage system as mounted on top of the cage conveyance's roof.



Figure 1: 4.5 Ton Levelok man, material cage clamp [4].



Figure 2: Levelok man, material cage power pack [4].

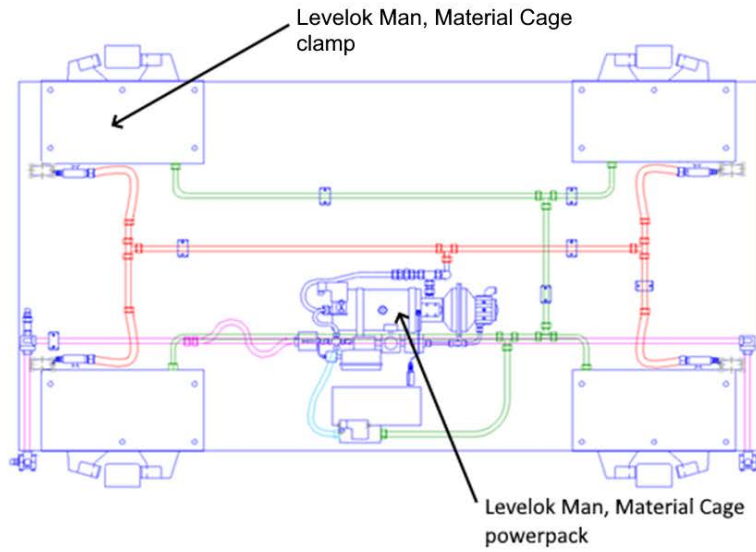


Figure 3: Illustration of the roof of a man, material cage, to demonstrate where the Levelok man, material cage system components are mounted [4] [5] (Note: The conveyance in the illustration is placed on its side. During the installation of the conveyance in the shaft, a “tip-and-tail” maneuver is used to orientate the conveyance vertically.).

There are two main variants of Levelok systems, namely the Levelok man, material cage system, and the Levelok skip system. The main differences between the two types of systems are:

- The Levelok man, material cage system is situated on the cage itself, as illustrated in Figure 3, because there are numerous levels in a vertical mine shaft where loading and unloading of men or material will occur.
- The Levelok skip system is not transported with the conveyance but is instead installed on to steel sections at the loading station, as this is the only location where loading of ore occurs. A schematic of the Levelok skip system is illustrated in Figure 4:

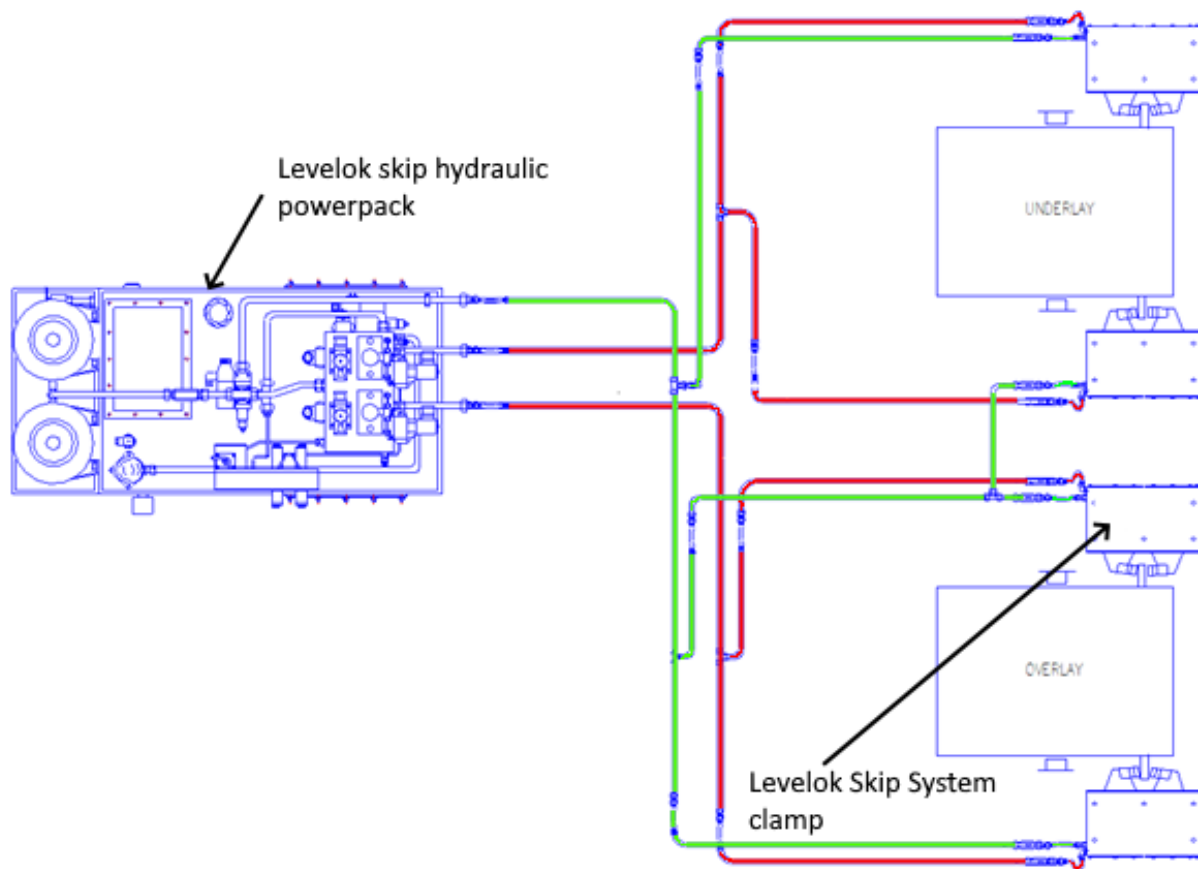


Figure 4: Illustration of a Levelok skip system at the loading station of a respective shaft [10].

Both of these types of systems have different layout combinations and control philosophies to suit the specific shaft characteristics and promise numerous potential advantages, including:

- No spillage of material during skip loading.
- Rope life on conveyances is increased.
- Time-saving - the re-decking of men and material can be implemented faster.
- Safe transfer of men and material while loading or unloading the cage.

Unfortunately, the systems have not yet fully delivered on these promised advantages.

1.2 Problem statement

The research problem relates to the study of the design of the Levelok system, a hydraulic-based system used as a method of conveyance arresting in various mines around the world.

The bulk of the research is therefore focused on the Levelok system itself. As mentioned, ideally the concept behind the Levelok system has numerous potential advantages, but unfortunately, due to various reasons which will be briefly mentioned below, the system does not yet fully deliver on the promises of these advantages in practical situations.

According to Lamprecht (2015) [8], the Levelok system primarily has three major drawbacks. The first of the drawbacks that Mr. Lamprecht pointed out was that the system is time-consuming to operate and, also, does not align the conveyance in the shaft. The third, and most important drawback that Mr. Lamprecht identified, is the fact that the Levelok system does not release correctly, causing the load of the conveyance to be rapidly transferred to the winder rope, causing the conveyance to oscillate up and down in the shaft.

Similar cases have been reported by different mining operations, such as with the Levelok systems being used at Goldfield's gold mine, South deep Twin shafts. These conveyances, with a maximum payload, typically experience a 2.9 m rope stretch [17]. The oscillation phenomenon of the conveyances has been reported to occur on both their 2-deck and 3-deck cages. Both the Shaft Engineer [18] and Engineering manager [19] have claimed that the MK5 Levelok cage systems do not damp the oscillations of their conveyance consistently after release, adding that the oscillation frequency also differs each time.

After numerous visits to different mines that make use of the Levelok skip system, the author also experienced visually that the system releases imperfectly and the load is not transferred gradually onto the winder rope. The dynamic forces exerted onto the winder rope caused by an oscillating conveyance, can be a big contributor to a shortened rope life [3]. This rapid movement of the conveyance after release causes ore to overshoot the mouth of the skip conveyance, causing damage to the conveyance's bridal assembly and hoisting equipment.

This rapid load transfer is most likely the cause of a decompression cycle that is not functioning according to its design [3].

Coetzee (2016) [20] has been working with both types of Levelok systems for a few years and he has not only observed the same phenomenon on the systems but found that the decompression arrangement of the Levelok cage system is unreliable due to O-rings failing on the spindle itself. With undesirable leakage occurring in the decompression arrangement, it can be an amplification of the already unresolved problem.

The problem of the decompression cycle not performing to the design was not addressed in Peter Horne's notes [14], instead, the Horne Hydraulics procedure was an iterative process. With the commissioning of a Levelok system, different spindle and seat sets with different calculated annulus sizes were taken with them to site and the best set was chosen by an iterative testing procedure. This procedure was confirmed by Mr. H. Stephenson as well [1].

Yet after they have identified the best spindle and seat set and conducted successful tests, the system did not generate the desired output consistently.

The problem statement can, therefore, be summarized. That the fundamental problem identified, is that the Levelok conveyance arresting system does not release the arrested conveyance desirably during operation. This is attributed to an incomplete understanding of the decompression cycle, and an incomplete documentation calculation methodology for the quality testing against specific consumer requirements, taking shaft and winder rope characteristics into account.

1.3 Research purpose

The purpose of this study is, therefore, to not only investigate and understand the decompression cycle, the control philosophy of the Levelok system, and for finding the suitable annulus size between the spindle and seat to produce the desired output, but also to develop a methodology of quality testing against specific consumer requirements taking shaft and winder rope characteristics into account.

1.4 Objectives

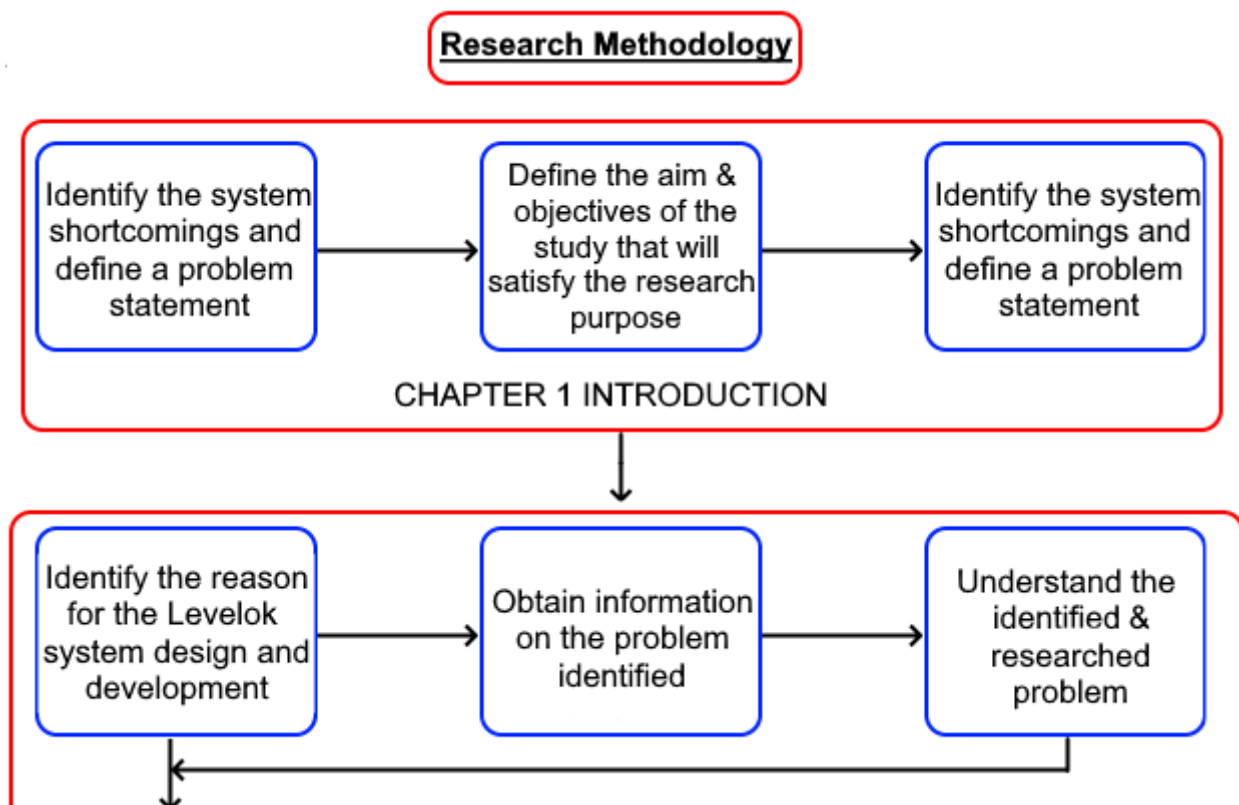
The main objective of the study is to develop a design and evaluation methodology with which to predict if the Levelok power pack is suitable according to the customers' requirements before it is approved for delivery. Thus, assuring that the Levelok system will reliably function according to its concept and design consistency, with rope stretch being taken up gradually and with all aspects adhering to the WJ Engineering company quality policy, even before the system is installed and commissioned.

The objectives of the study can, therefore, be summarized as:

- Study the Levelok system and understand how the different components thereof interact with each other.
- Study and understand the different Levelok hydraulic power packs and how it evolved over the years.
- Study and understand the function and operation of the decompression cycle.
- Understand how the decompression cycle affects the control output.
- Study the control philosophies of the different systems and how it affects the control output.
- Understanding the different requirements to achieve the desired output of the system.
- Develop an evaluation methodology by use of the specific shaft and system characteristics. Thus, develop a mathematical model that can be used to predict how the Levelok power pack will perform before it is installed and commissioned.
- Conduct numerous tests on different systems with the use of the prediction mathematical model.
- Analyse the MK4 & MK5 decompression arrangement, and the output thereof. Identify the shortcomings and develop a decompression arrangement that addresses these shortcomings and gives a constant reliable output.
- Develop a documented design methodology for the MK7 range of Levelok systems.
- Conduct numerous tests on different MK7 Levelok systems with the use of the prediction mathematical model for verification and validation.
- Construct a conclusion on the findings of this study.

1.5 Task Clarification

To achieve the objectives of this dissertation summarized in Section 1.4, a task clarification framework was constructed. The goal of the framework was to assist with the research study to assure all aspects were covered. This framework is structured into two main groups, namely Research Methodology and Testing & design methodology. These two frameworks are visualized in Figures 5 & 6, and also provide an overview of the content of the chapters that follow this introduction.



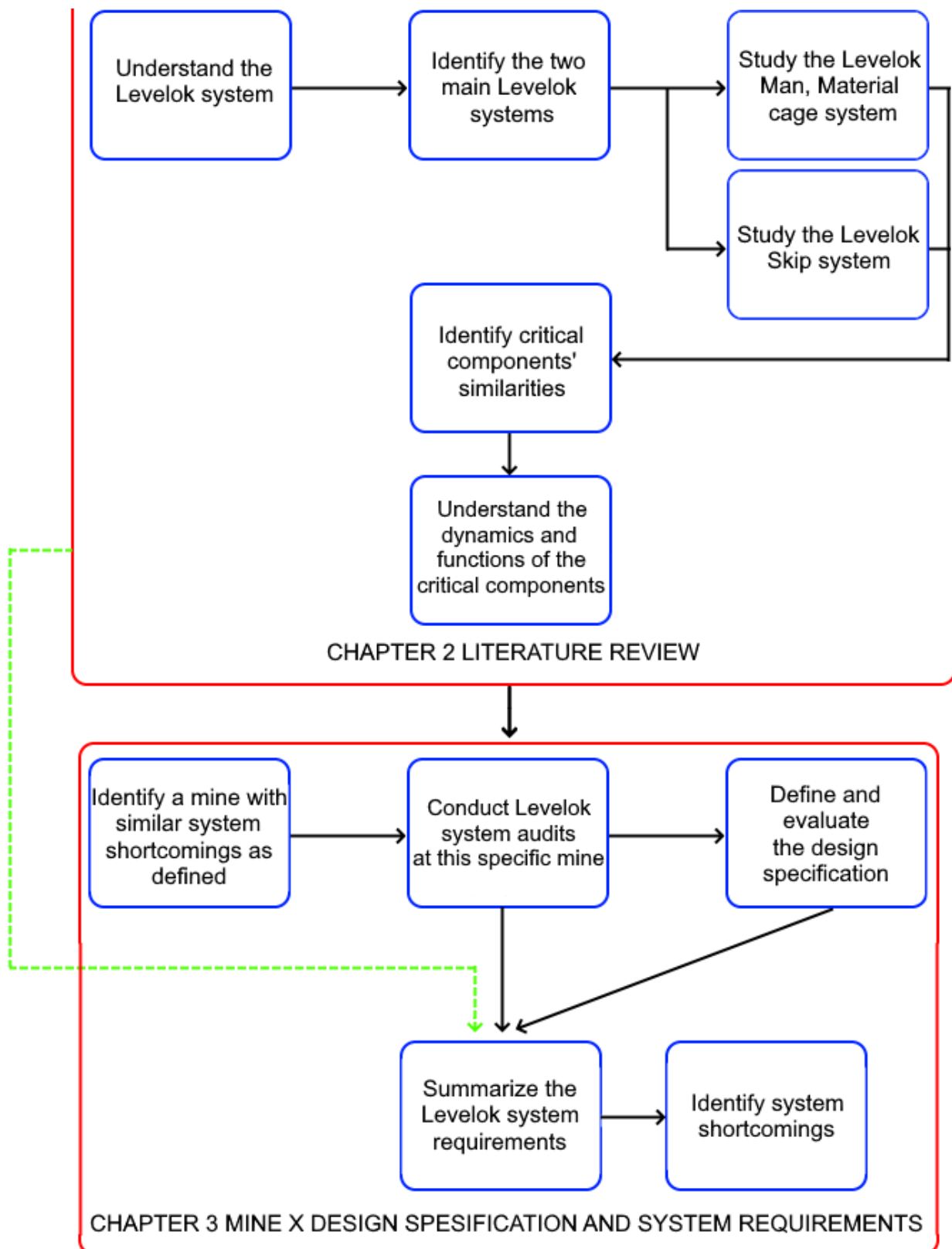
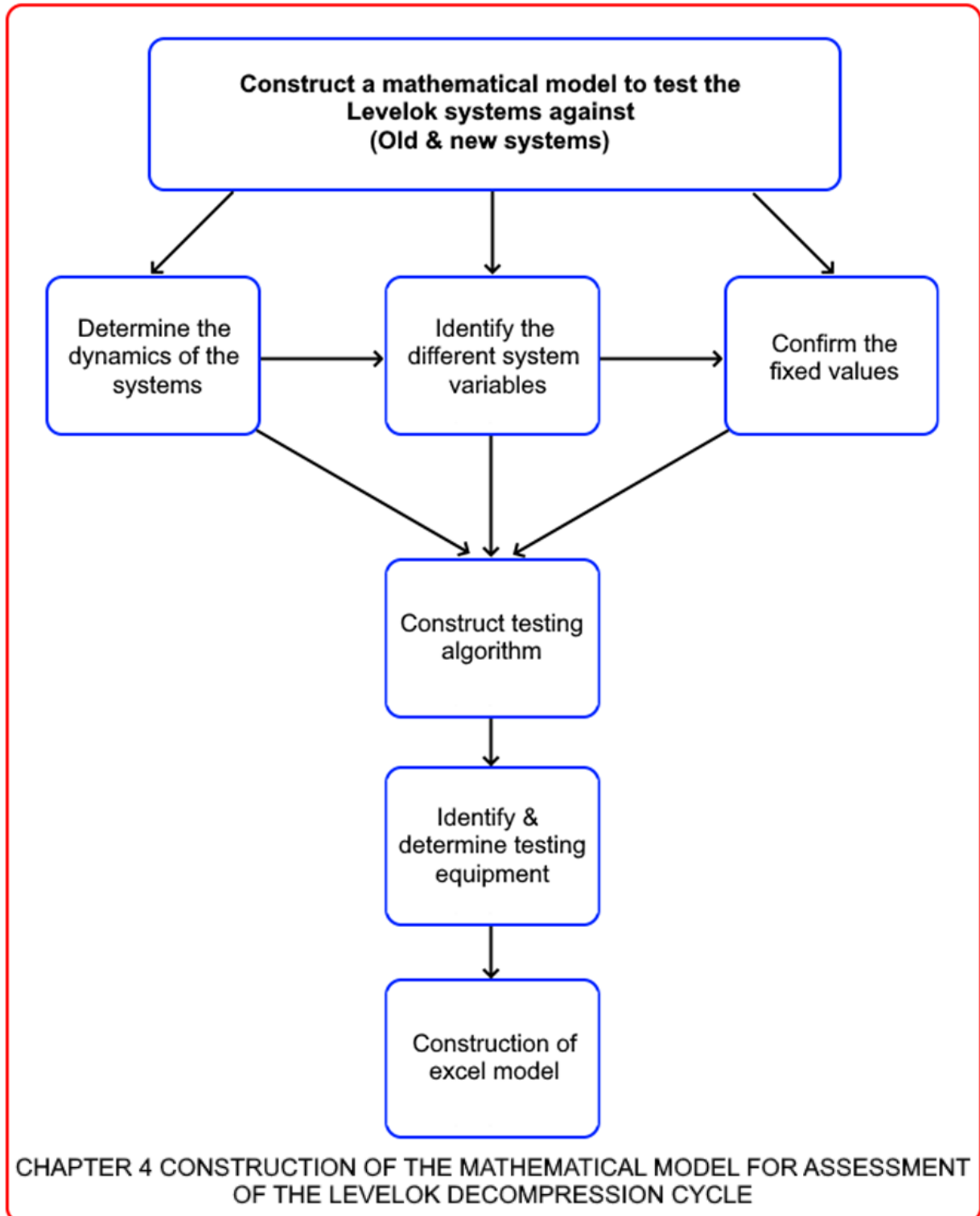


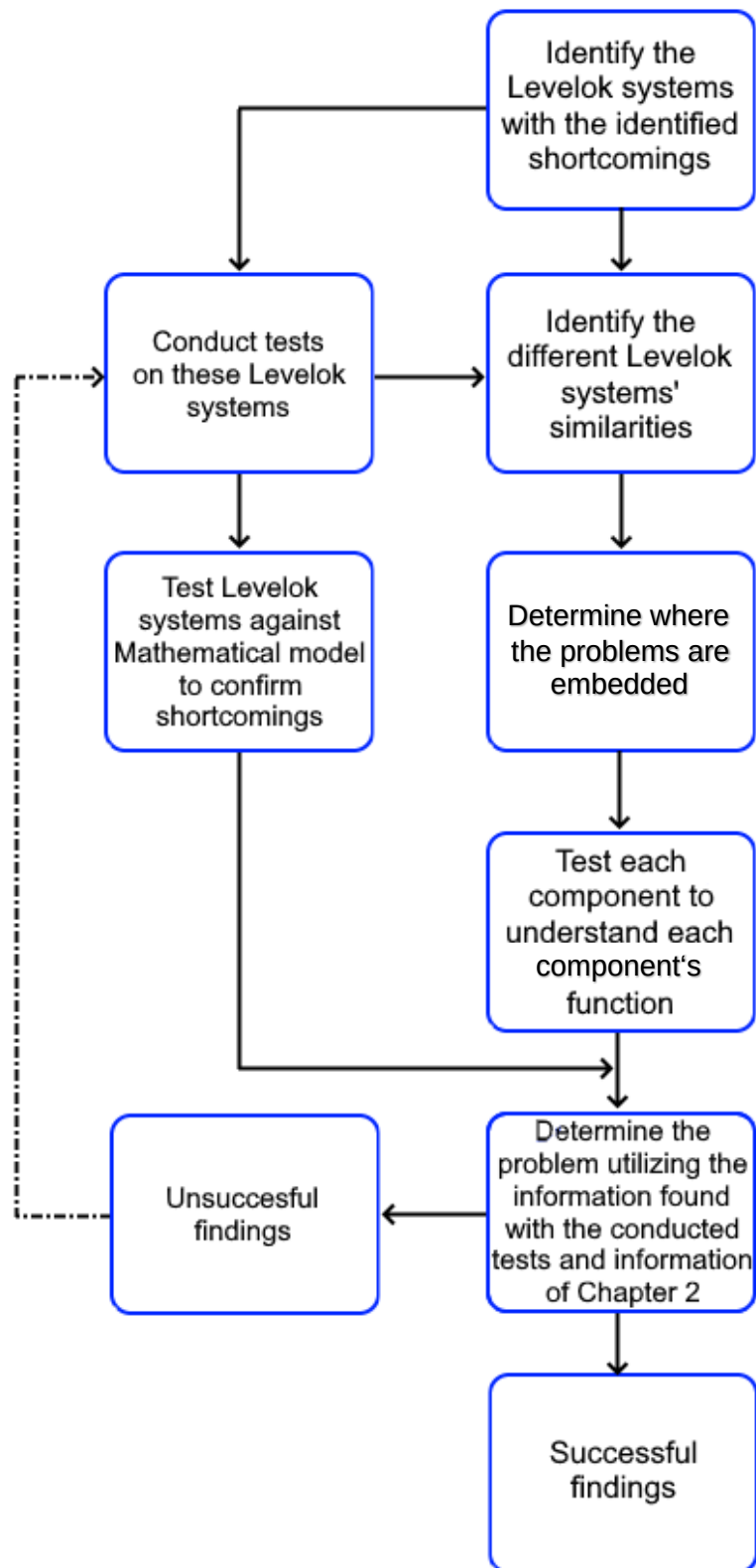
Figure 5: The task clarification framework for the Research methodology.

Research Methodology



Testing and design methodology





CHAPTER 5 TESTS ON MK4 - MK5 LEVELOK SYSTEMS AND FINDINGS

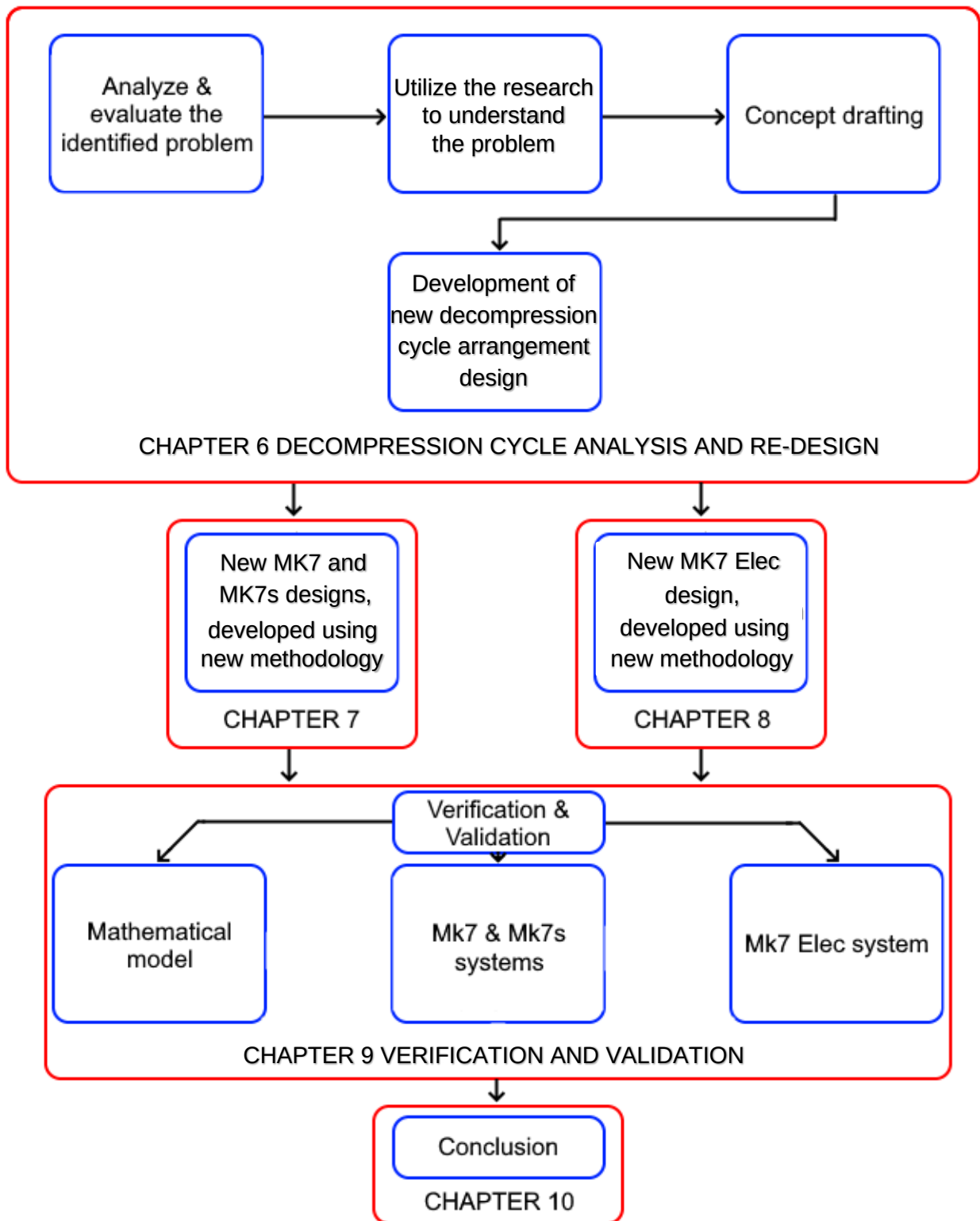


Figure 6: The task clarification framework for the Testing and design methodology.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Mining in South Africa has become an environment of high risk due to the depletion of minerals closer to the surface forcing deep level mining to become a more common operation [26]. Mining at greater depths with existing infrastructure has presented some technical challenges. One of the challenges that had to be addressed is that of conveyance hoisting wire rope stretch. The problem of rope stretch has become greater due to the transporting of men, equipment, and mineral loads of ever-increasing mass up and down the deeper vertical mine shafts. The need for a simple and reliable solution has become increasingly important.

Without the use of an effective system of overcoming rope stretch during loading and unloading, serious complications are guaranteed to arise [27]. Some of these complications include:

- The possibility of a fatal accident. At deep levels, the rope stretch of the hoisting wire rope can cause a conveyance to move up and down in the shaft quite rapidly and this can cause personnel to find themselves in a dangerous situation when getting in and out of the conveyance.
- The loss of shaft time in having to re-deck the cage while loading or unloading men or material. When a conveyance is docked at a station level and a big load is added to or removed from the conveyance can cause the conveyance to move down or up the shaft respectively due to rope stretch.
- The damage caused to the conveyance and equipment resulting from shock loads caused by the displacement of the conveyance due to rope stretch. Shock loads can include a fall of a heavy rock into a skip conveyance or a heavy locomotive that is loaded into a cage, causing the conveyance to move unexpectedly, which can cause a scenario where equipment can be damaged and personnel injured.
- The possibility of the derailment of a locomotive or other wheeled unit during offloading and the time wasted in getting it back on the rails.
- Rock spillage while loading a skip. Too much rock spillage at the loading station can cause the shaft to be filled with rock from the shaft bottom and can cause the shaft to be stopped for rock removal.
- Decrease in rope life due to the high dynamic loads resulting from sudden application of loads to the rope.

2.2 Conveyance hoisting & Rope stretch

Deep-level vertical shaft mining makes use of a conveyance hoisting procedure with the main purpose of transporting men, material, or rock. Conveyances are hoisted using a winder hoisting machine situated in the winder house. The hoisting wire rope is connected to the winder machine drum and spooled around it. From the winder house, the hoisting wire rope expands around a sheave wheel down the shaft connected to the conveyance at the end of it. This briefly described schematic is illustrated in Figure 7 [28].

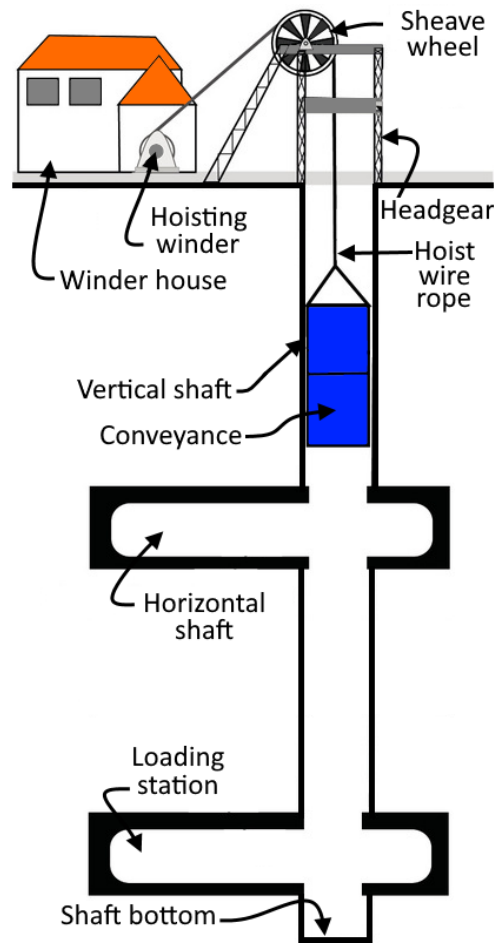


Figure 7: Basic schematic of the conveyance hoisting layout in a vertical mine shaft [28].

The position of a conveyance in the vertical shaft is dependent upon the amount of hoisting wire rope that is reeled in or out by the hoisting winder. The hoisting winder machine is normally controlled by a winder driver or PLC [1]. The winder driver receives bell signals from lock bell systems at different levels controlled by onsetters. The onsetter sends diverse signals to the winder driver, each one specifying a different level position a certain conveyance needs to be stationed.

From these signals, the winder driver can release the brakes on the winder hoisting machine and reposition the conveyance to its new location in the shaft. The winder driver makes use of a depth indicator [8] to regulate the position of the conveyance in the shaft but is still dependent on receiving signals from the onsetter to stop at the desired position on a level. Thus, the onsetter and winder driver need to work efficiently together as it influences the final positioning of the conveyance.

When the conveyance is positioned at a level, its position can change due to the spring effect of the hoisting wire rope when the winder driver suddenly applies the brakes on the hoisting winder machine, causing the conveyance to come to an abrupt stop. The factor that can change the conveyance's position is that of rope stretch due to the elasticity characteristics of the hoisting rope (e.g. as described in the Haggie steel wire ropes for mining technical manual [29]). When a load is added to a conveyance, rope stretch is caused by numerous parameters of the hoisting rope, but the main characteristic is the type of rope construction and the quality of its core. Table 1, supplied by Haggie [29], lists the various type of Haggie steel wire rope constructions supplied to the mines, together with the formulas to calculate the metallic area of the wire rope, in terms of nominal rope diameter and its corresponding practical values for modulus of elasticity:

Table 1: Approximate metallic areas, in terms of nominal rope diameter (d) and practical values for modulus of elasticity for ropes of various constructions [29].

Construction	Metallic Area	Modulus of elasticity (GPa)
6x7(6x1)/F	$0.405d^2$	110
6x19(9/9/1)/F, 6x25(12/6F+6/1)/F	$0.405d^2$	100
6x19(9/9/1)/IWRC	$0.475d^2$	110
8x19(9/9/1)/F	$0.355d^2$	86
6x36(14/7+7/7/1)/F	$0.410d^2$	96
6x14 Triangular strand rope	$0.465d^2$	103
6x26 to 6x29 Triangular strand rope	$0.450d^2$	103
6x30 to 6x33 Triangular strand rope	$0.457d^2$	110
Non-spin winding ropes	$0.500d^2$	110
34 LR UHP	$0.493d^2$	115
18x7 Non-spin UHP	$0.500d^2$	115
Half Locked Cfluid Rope	$0.640d^2$	138

The Haggie steel wire ropes for mining technical manual also presents Equation 1, to calculate this elastic stretch [29]:

$$\Delta L = \frac{F \times L}{A \times E} \quad (1)$$

Where $\Delta L = \text{Elongation (Rope Stretch) [m]}$

$F = \text{Tension in rope [N]}$

$L = \text{Length of rope under load [m]}$

$A = \text{Metallic area of rope [m}^2\text{]}$

$E = \text{Apparent modulus of elasticity of rope [Pa]}$

From this equation, it is clear that the rope stretch can change due to the change in one or a combination of the four parameters presented. The tension in the rope depends on the rope end mass (conveyance's own weight + payload). The conveyance's own mass is a constant load on the wire steel rope, but the change in the payload is the variable that can influence the rope stretch at different levels in the shaft. The length of the rope under load is thus also a variable to consider as loading and unloading of conveyance can occur at different shaft level stations. The only two variables that stay constant for a specific construction of steel wire rope are the metallic area and the apparent modulus of elasticity of the rope.

Furthermore, there is a list of studies that have been done over the years on the behavior of winder hoisting ropes. Examples of these studies include, "On the torsional behavior of triangular-strand hoisting rope", by Rebel, Borello, and Chandler (1996), where the helical construction of a triangular-strand rope and the forces that work on it when the rope is suspended vertically are discussed [21]. This paper provides a graph, shown in Figure 8, demonstrating the measured parameters of a winder over a full winding cycle. A similar illustration is found in, "Hoist & Haul", by Brokenshire and Andersen (2010) [2], and the same conclusion can be drawn. Due to rope stretch causing the conveyances to oscillate in the shaft, more extreme forces are exerted onto the hoisting wire rope and thus can be a direct cause for excessive damage and fatigue on the hoisting rope [3].

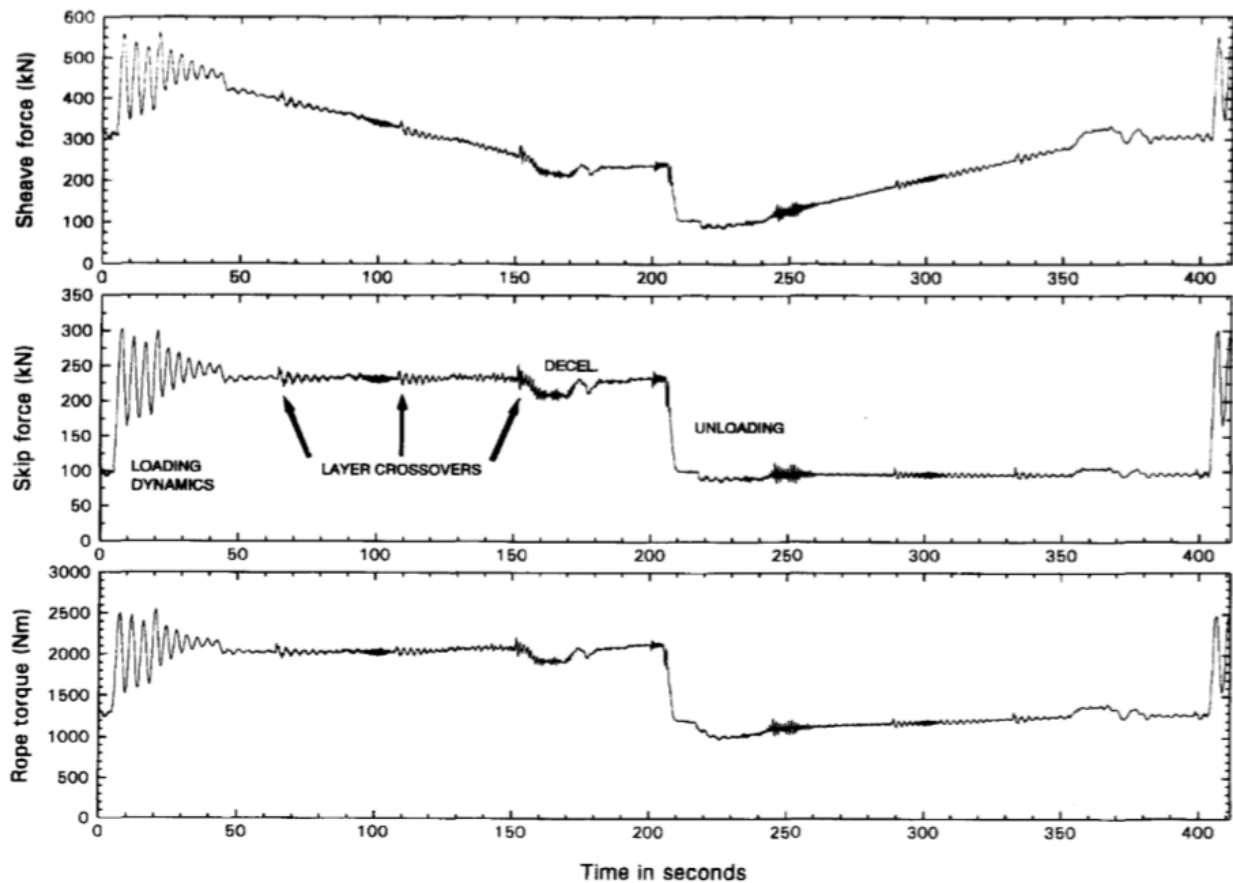


Figure 8: Results retrieved from “On the torsional behavior of triangular- strand hoisting rope”, by Rebel, Borello, and Chandler (1996) [21]. The measured force and torque values of a double-drum rock winder during a winding cycle.

In Figure 8, the skip position, velocity, acceleration, and dynamic forces are plotted against time for a 2200m length of wind with a rope end mass of 9820 kg and a payload of 11 750 kg. The forces and torques working on the conveyance's hoisting wire rope were measured with calibrated strain gauges situated on the conveyance drawbar, and the sheave wheel's outer diameter ring.

From the illustration, it is clear that during loading of the conveyance the forces on the skip oscillate between 160 kN and 350 kN for this specific shaft system. These dynamic forces are applied directly to the hoisting wire rope and thus are a direct cause for excessive damage and fatigue on the hoisting rope. Referring to the second Newton law, in theory, these dynamic forces can be dramatically decreased if there is a method of holding the conveyance secured during the loading procedure, thus decreasing the acceleration of the rope end load. Furthermore, if this method makes use of the structural infrastructure at the loading station, the dynamic forces applied to the hoisting rope can be damped, due to the forces being transferred from the rope to the loading station steelwork.

Horne [14] also did similar strain gauge tests on hoisting systems to calculate the different forces that impact on the system, with and without Levelok systems, and compared it with the data accumulated in his preserved notes [14]. Figure 9 illustrates the results obtained from one of these on-site tests.

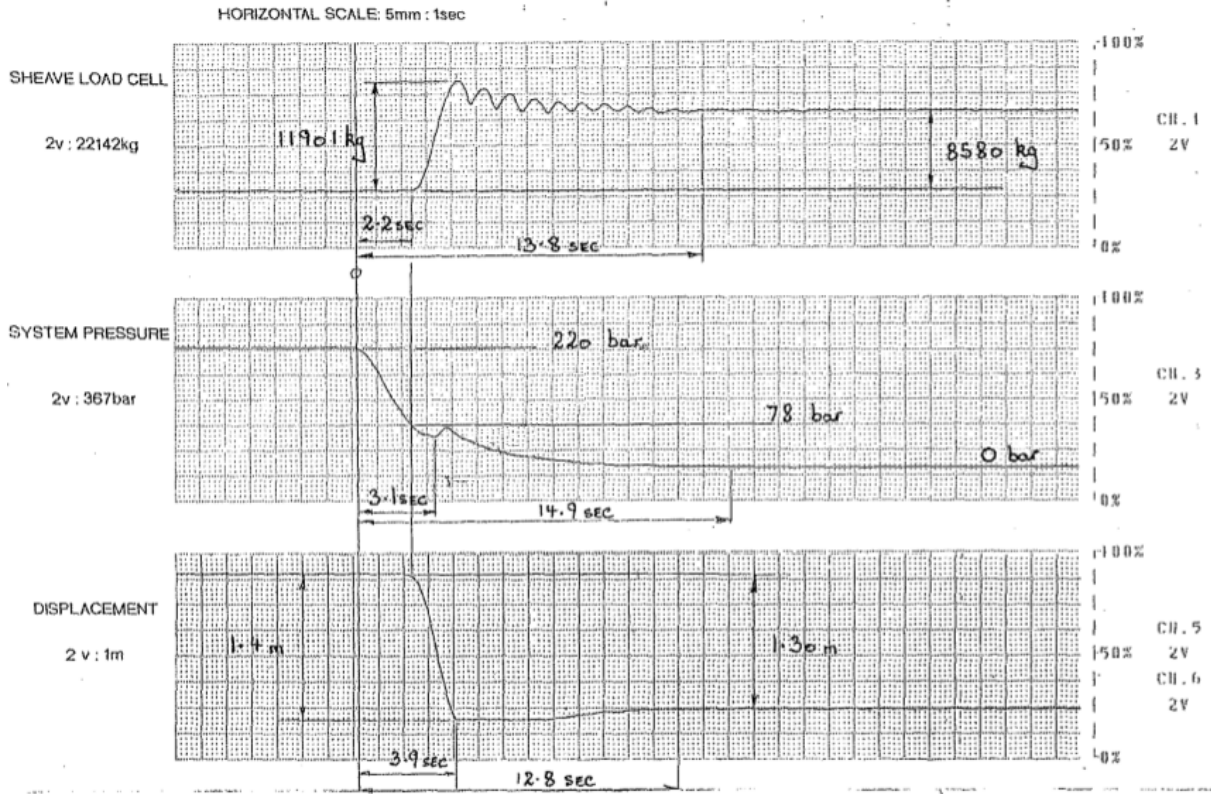


Figure 9: Results from Horne [14] obtained from on-site tests conducted on a conveyance, fitted with a Levelok system, during the loading procedure loading.

The conveyance displacement, dynamic forces on the sheave wheel, and the Levelok system pressure are plotted against time for a 2000m length of wind with a rope end mass of 9 615 kg and a payload of 8580 kg. The illustration in Figure 9 represents the situation when the Levelok system on the conveyance is released after the conveyance is loaded. The rope stretch is taken up gradually, thus dampening the dynamic forces on the hoisting rope and the sheave wheel.

When comparing the results of Figures 8 & 9, keeping in mind that the data was captured with a different type of dataloggers and methods, it can be visually noticed that due to the Levelok system the dynamic forces during the loading procedure are dampened. The conveyance is arrested with the clamping system during the flask empties its load into it, thus the loading impact forces are transferred to the loading station steelwork and not the hoisting wire rope. When loading of the conveyance is completed, the Levelok system releases the conveyance gradually, transferring the payload weight force gradually to the hoisting wire rope. With the added Levelok function to the loading sequence procedure, it is calculated that the maximum forces exerted on the hoisting wire rope is 70% smaller, and the duration of the force oscillations measured on the sheave wheel is reduced by approximately 26 seconds.

2.3 The Levelok system

The mining industry in South Africa has been one of the main driving forces behind innovation over the years. The Levelok system is only one of many innovative solutions engineers working in this industry have developed. All these innovative ideas have one thing in common - all of them originated from a specific problem that was identified.

The Levelok system has been in development for more than 40 years. It provides a simple, safe, and quick method of holding a conveyance in the shaft during loading or unloading, thus overcoming the problem of rope stretch in deep-level mining.

The Levelok system can be defined as simple, safe, and quick, when considering the factors listed in Table 2 [1] [3]:

Table 2: The factors defining the Levelok system to be simple, safe, and quick response system [1][3][27].

Factor	Simple	Safe	Quick
The system comprises hydraulic clamps, operated by a hydraulic power pack, which hold the conveyance steady during the transfer of load and then release their grip at a controlled rate to allow the rope stretch to be taken up smoothly.	X	X	
No structural modifications are required for the conveyance or level station. The Levelok system can be fitted to existing cages with minimum shaft downtime.	X	X	X
To power, the system, a supply of pneumatic air pressure or a low voltage power supply is required, depending on the type of system installed.	X	X	X
With the Levelok man, material cage system none of the components project into the shaft, and the clamp arms do not protrude beyond the guide channels. (As illustrated in Figure 3 [4][5])	X	X	
The hydraulic clamps of every Levelok system can support twice the load of the maximum designed mass.		X	
Accidents can be more readily avoided as personnel can get into or disembark the conveyance more safely.	X	X	X
A stationary skip during loading means no spillage.	X	X	X
A controlled release of the hydraulic clamps after loading or unloading reduces dynamic rope loads and thus fatigue.	X	X	
An electrical interlock system prevents any operator from causing an unsafe situation for himself, other personnel, or any equipment.	X	X	
Within 10 seconds of the onsetter connecting the pneumatic air supply to the man, material cage, the hydraulic clamps are fully applied.	X	X	X
Within 3 seconds of the skip arriving at the loading station, the hydraulic clamps will lock it in position.	X	X	X
No time is wasted in having to redeck the cage during the loading of heavy wheeled units.	X	X	X

Within 10 seconds of the onsetter unplugging the pneumatic supply hose or the release button is pressed, the cage will have moved to its new position in the shaft and can be rung away.	X	X	X
Multy deck man material cages can be loaded simultaneously, thus saving shaft time when hoisting shifts.	X	X	X

As mentioned in Section 1.1 there are two main types of Levelok systems, namely the Levelok man, material cage system, and the Levelok skip system, with the main differences being where the Levelok equipment is installed for operation.

Both of these types of systems have different layout combinations and control philosophies to suit the specific shaft characteristics.

2.3.1 Levelok Man - Material Cage System

The Levelok man, material cage system has been in operation in mines all over the world as a conveyance arresting system for many years [2]. The most common configuration comprises four Levelok clamps (Figure 1), which are powered by a single hydraulic power pack (Figure 2), together with components and piping which are mounted on top of the cage, as illustrated in Figure 10.

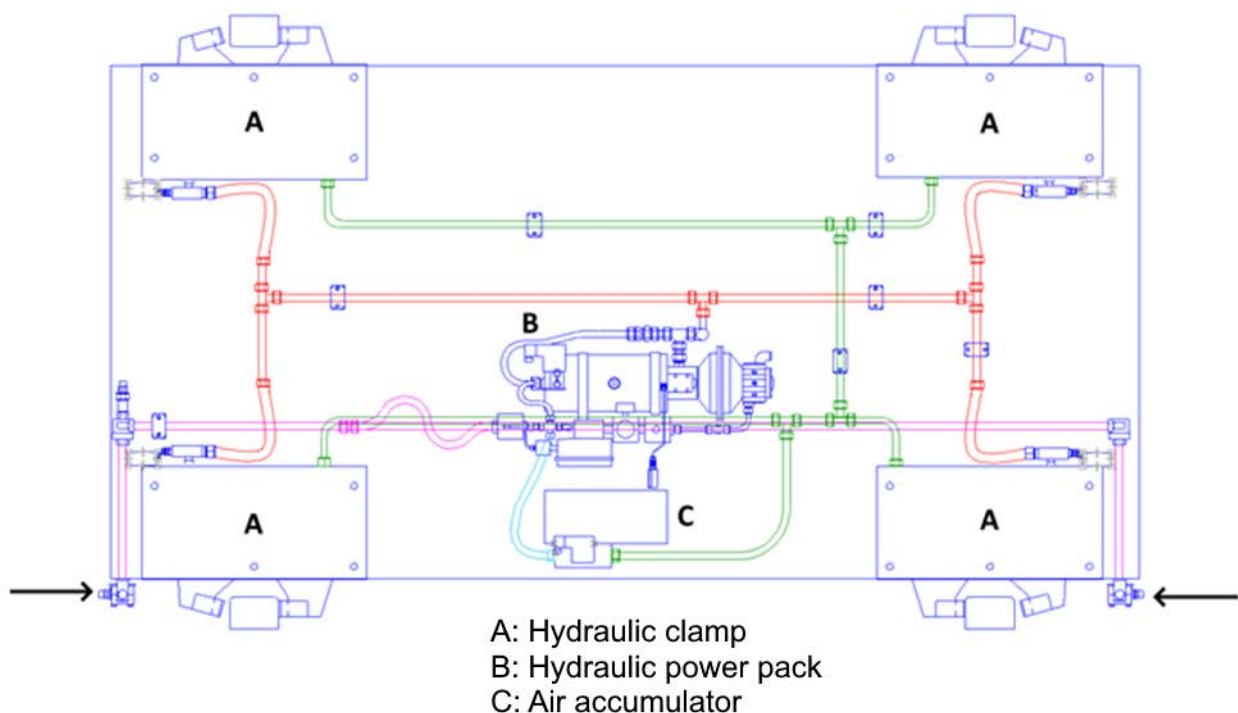


Figure 10: Levelok man, material cage system, 4 clamp layout [5].

The four hydraulic clamps (A) are connected in parallel to the hydraulic power pack (B). The complete system is actuated from a pneumatic air supply on the station which is connected to the cage by a fly-hose and a quick-release coupling. The pneumatic supply is used in the hydraulic system as well as actuating different pneumatic components on the Levelok power pack. The clamps are retracted with stainless steel springs and assisted with a pneumatic accumulator (C), which is integrated to work with the power pack.

The purple and green piping shown in Figure 10 represents the pneumatic airlines. The pneumatic supply to the power pack from the fly-hose is represented by purple and the green represents the pneumatic supply from the pneumatic accumulator to the “clamps open” actuating side of the hydraulic cylinders in the Levelok clamps. The pneumatic accumulator (together with the retraction springs installed inside the Levelok clamps) is the component that ensures that the clamps are fully retracted from the guides when the system is released of hydraulic pressure. This modification was added from the MK5 Levelok system to assist the retraction springs for smoother movement when the clamps are released. The minimum supply pressure required from the mine to operate a Levelok system is 4 Bar [1][14]. The red piping represents the high-pressure hydraulic line supplied by the Levelok hydraulic power pack.

The step-by-step clamping and unclamping procedures of the MK4, MK5 & MK6 Levelok man, material cage systems are explained in Annexure A. This is similar to the procedure guidelines found in the WJ Engineering quality specifications [6] [7], mining specifications [8], and numerous Levelok operational manuals supplied to Levelok operational mines [9].

From these procedures together with the system diagram from Figure 10 and its corresponding hydraulic diagram illustrated in Figure 11 (Component list in Table 3), we can better understand the working sequence of the Levelok man, material cage systems [3] [14].

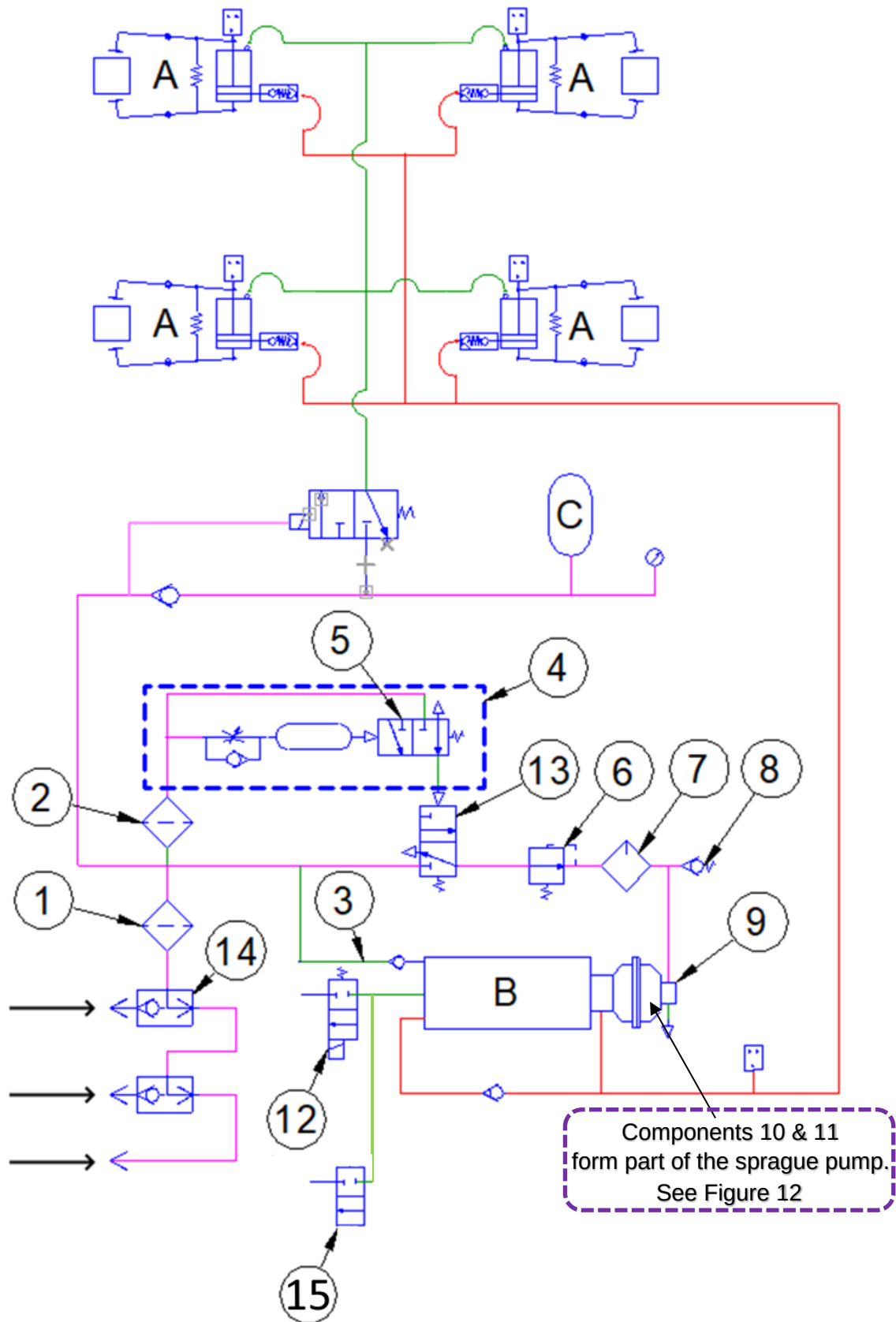


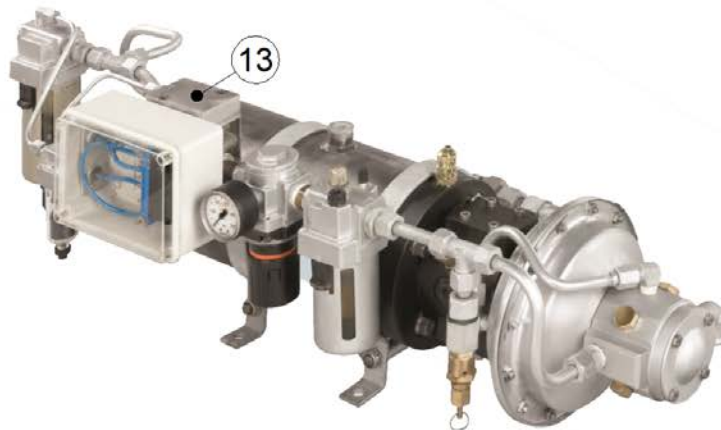
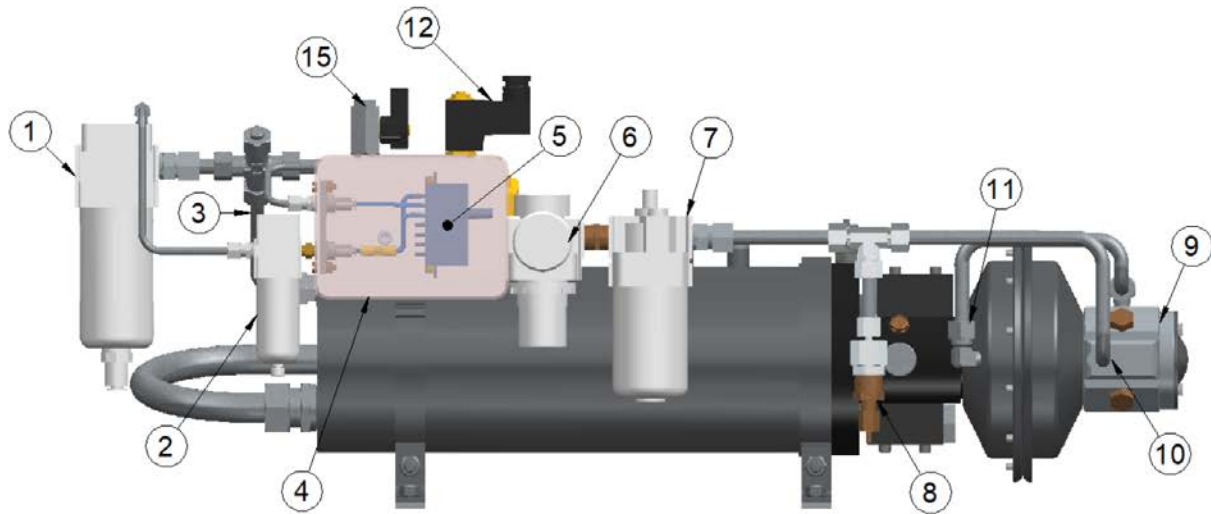
Figure 11: Corresponding hydraulic diagram [5] of the system diagram shown in Figure 10 [5].

Table 3: Component list of diagrams illustrated in Figures 10,11 & 12 [5].

<u>Component number</u>	<u>Description</u>
1	1" Water trap filter
2	1/2" Water trap filter
3	The pneumatic inlet to the fluid reservoir
4	Timer assembly box
5	Pneumatic timer
6	Pneumatic pressure regulator
7	Fluid lubricator
8	The pneumatic pressure relief valve
9	Sprague pump body
10	The pneumatic inlet to Sprague pump
11	Pneumatic supply to Sprague pump pneumatic actuated piston
12	12 V DC Solinoid release valve
13	2 to 3-way valve (Pneumatically operated)
14	Shuttle valves
15	Manual release valve
A	Hydraulic clamp
B	Hydraulic power pack
C	Pneumatic accumulator

As illustrated in Figures 10 & 11 the fly-hose can be connected to the cage via a quick coupler on either side of the conveyance entry doors (Illustrated with ←). Some cages have multiple decks, thus the pneumatic line is extended to each deck, each with its quick coupler connections. The pneumatic pressure is transported from the fly-hose through shuttle valves (14) to the hydraulic power pack's airline. The airline of the MK6 Levelok power pack is somewhat different from that of the MK4 & MK5 airlines, but the components and their functions are similar. These differences can be compared with the assemblies shown in Figure 12:

MK4 & MK5 Levelok Power pack airline



MK6 Levelok Power pack airline

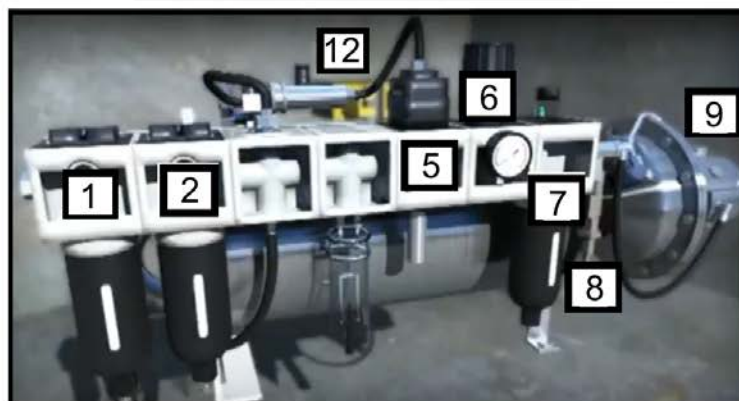


Figure 12: MK4, MK5 & MK6 Levelok power pack airline assemblies [4] [30] [31].

The first component in the airline is a water trap (1) to filter all the water out of the pneumatic pressure supply, supplied from the level station. Some mines have significant problems with water in their pneumatic supplies underground [1][18][20], thus some systems are supplied with more than one water trap. From here the pneumatic pressure is directed by a T-fitting or a cross-fitting to supply two different functions.

In the one T-connection direction the hydraulic fluid reservoir is pressurized (3). When the hydraulic fluid reservoir is pressurized the hydraulic fluid inside it is transported through a check valve to the actuating part of the hydraulic cylinders in the Levelok clamps via the red piping, illustrated in Figures 10 & 11, and the clamps clamp against the guides. This is called “The fast approach”, because of the use of the pneumatic pressure supply (Min: 4 Bar) that sustains a quicker stroke actuating response than one will get from the Sprague pump (9) alone.

The time delay for this action is anything between 4-8 sec depending on the pneumatic timer (5) setting calculated from the total volume of the fluid required to take up the volume in the hydraulic cylinders needed to clamp the system to the guides. At this point, the pressure in the red piping is equal to the pneumatic supply.

In the other direction of the T-connection, the pneumatic pressure is filtered with a smaller water trap (2) to protect the pneumatic air timer (5) situated in the air timer assembly box (4). The function of the pneumatic timer (5) is to supply a time delay before the Sprague pump (9) is actuated. This is done to allow “The fast approach” to clamp the Levelok clamps against the guides. If there would have been no pneumatic timer (5) the Sprague pump (9) would be actuated prematurely and would be forced to pump the hydraulic fluid from the fluid reservoir to the hydraulic clamps that would take a very long time. Thus, it would cause the system to take up a lot of shaft time.

After a few seconds, the state of the pneumatic timer (5) changes and the timer opens a 2 to 3-way valve (13). Pneumatic pressure is then regulated with a pneumatic pressure regulator (7). A fluid lubricator (7) is used to lubricate the compressed air to protect the Sprague pump (9). The pressure relief (8) is another protection component to assure the system is not over-pressured when the pressure regulator (7) fails. When the pneumatic pressure arrives at the Sprague pump's inlet (10) the shuttle body inside it directs the pressure to the air piston (11) of the Sprague pump (9). The pump is actuated and starts pumping the fluid into the red piping (Figures 10 & 11) causing the system to reach the “Main clamping pressure” of 200 Bar or more in approximately 15 sec.

When the “Main clamping pressure” is reached the Sprague pump (9) stops pumping because a pressure equilibrium is reached due to the setting that is set with the pressure regulator (7). The pneumatic pressure to a hydraulic pressure ratio of these power packs is 1:60 [1].

On completion of loading or unloading of the conveyance that is safely clamped, the Levelok clamp pressure is released. Actuating the release of an MK5 & MK6 system is different from that of an MK4 system. The MK4 system is released by just disconnecting the fly hose from the conveyance and park it to the park panel on the “king post”. As soon as pneumatic pressure is removed from the hydraulic fluid reservoir tank, the decompression cycle is actuated and the system starts to release.

For the release on the MK5 & MK6 systems, the procedure is similar. There is a check valve placed on the fluid reservoir pneumatic pipe inlet (3), assuring that the hydraulic fluid reservoir stays pressurized even if the fly hose is removed from the conveyance. The system can then only be released by pushing the release button on the Bell tower of the station level, which in turn sends a 12V DC supply to the solenoid release valve (12) that decompresses the hydraulic fluid reservoir. This 12V DC supply is maintained for 45 sec. If the system fails to release due to a solenoid failure, the manual release valve(15) can be used to actuate the decompression cycle.

When the system is released the decompression arrangement in the power pack is the controlling entity that allows the conveyance to smoothly move into its new position in the shaft causing the rope stretch to be taken up in a controlled manner [3].

2.3.1.1 Decompression arrangement

The decompression arrangement is the controlling entity of the Levelok hydraulic power pack, as mentioned in Section 2.3.1. This assembly is used during clamping of the system to build up pressure in the power pack, as well as to control the gradual decay of hydraulic pressure of a Levelok system when the Levelok clamps are released. The section view of a Levelok man, material cage power pack is illustrated in Figure 13. This figure displays the different components inside of a Levelok man, material cage power pack, and the corresponding component numbers & descriptions are listed in Table 4.

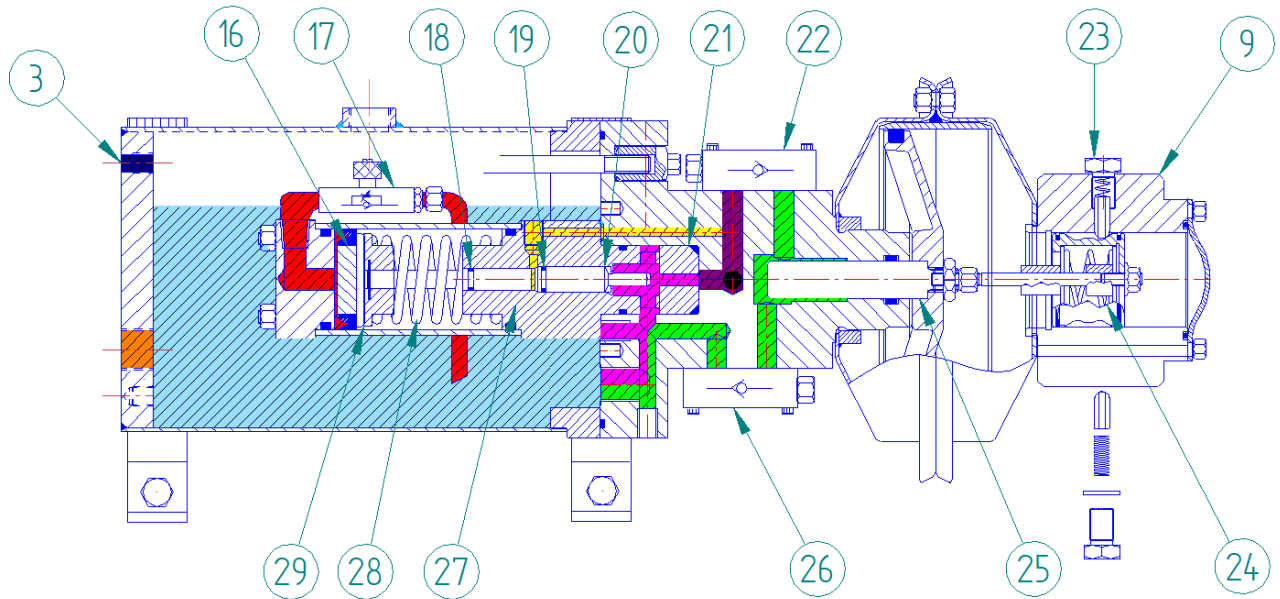


Figure 13: Section view of a Levelok man, material cage power pack for illustration of the decompression arrangement operation [12].

Table 4: Component list of Figure 13 [12].

<u>Component number</u>	<u>Description</u>
16	Piston
17	Throttle check valve
18	Spindle O-ring 1
19	Spindle O-ring 2
20	Spindle
21	Seat
22	Pressure outlet check valve
23	Detent pin assembly
24	Shuttle assembly
25	The plunger connected to the air piston of the Sprague pump
26	Inlet check valve
27	Spindle body
28	Spring
29	Spring collar

The piston (16), throttle check valve (17), spindle body (27), spring (28), and spring collar (29) form part of the decompression arrangement, with the spindle (20) & seat (21) being the two main controlling components thereof. The rest of the components located in the power pack, each have their own function to work in unison with the decompression arrangement.

The different colours illustrated in Figure 13 represent the different hydraulic fluid paths inside the Power pack. The dark blue and orange represent the inlet and outlet of the fluid reservoir respectively. The aqua blue is the hydraulic fluid level in the power pack before the Levelok system is utilized. The red and green colours illustrate the low-pressure pathways, and the dark purple and yellow are the high-pressure pathways. The black dot represents the high-pressure pathway via the red piping leading to the hydraulic cylinders situated in the Levelok clamps. When the system is released the hydraulic fluid will follow the pink illustrated path.

In Section 2.3.1, it was explained that when the pneumatic pressure supply is connected to the conveyance, the pressure eventually reaches the hydraulic power pack. The pneumatic pressure is directed with a T-connection to the fluid reservoir (3), with the function to pressurize the hydraulic fluid reservoir and the hydraulic fluid inside of it.

With this pressurization of the hydraulic fluid in the fluid reservoir, some of the fluid is pushed through the fluid reservoir outlet illustrated with the orange path in Figure 13. This is to allow for the “The fast approach” of the Levelok clamps before high-pressure clamping.

The pneumatic pressure also pushes some of the hydraulic fluid into the red pathway, through the throttle check valve (17), and into the piston (16) chamber. This low-pressure hydraulic fluid then pushes the piston (16) forward, which in turn pushes the spring collar (29) and compressing the spring (28) against the spindle body (27).

The spindle (20) is connected to the spring collar (29) with a circlip, thus the spindle (20) moves in unison with the spring collar (29) when it is pushed forward with the piston (16). The spindle (20) moves linearly inside the spindle body (27) and through the seat (21) until the spindle chamfer seals against the seat (21). The displacement of these components in the hydraulic fluid reservoir occurs in the first 4-8 seconds after the pneumatic pressure supply is connected to the system. When the spindle (20) seals against the seat (21), all components in the hydraulic fluid reservoir will stay in their stationary position until the pressure in the reservoir is released.

During the displacement of the spindle (20) the hydraulic fluid in the reservoir is also pushed into the green pathway (Figure 13), through the Inlet check valve (26), and into the plunger compartment of the Sprague pump (25). As explained in Section 2.3.1, after a few seconds (Normally 4-8 sec) the pneumatic pressure will enter the Sprague pump's inlet (10).

The pneumatic pressure causes the shuttle assembly (24) inside the Sprague pump (9) to oscillate in its chamber from left to right and right to left continuously. The detent pins (23) control the position of the shuttle assembly (24) as it oscillates. The function of the shuttle assembly (24) is to direct the pneumatic pressure to the different sides of the air piston (11) (25). This, in turn, cause the air piston (11) to also oscillate from left to right and right to left, actuating a pumping action of the plunger (25) in the plunger compartment (green pathway, Figure 13).

The pumping of the plunger (25) forces the hydraulic fluid through the pressure outlet check valve (22) due to the check valve arrangement, entering the purple pathway. During this moment in time, the spindle (20) is still sealed against the seat (21). This allows the system to build hydraulic pressure as the plunger (25) is pumping, transporting the high-pressure hydraulic fluid through the black dot pathway (Figure 13) through the red piping (Figures 10 & 11) to the hydraulic cylinders situated in the Levelok clamps (A). The Sprague pump (9) and its components will come to a standstill as the Main clamping pressure is reached.

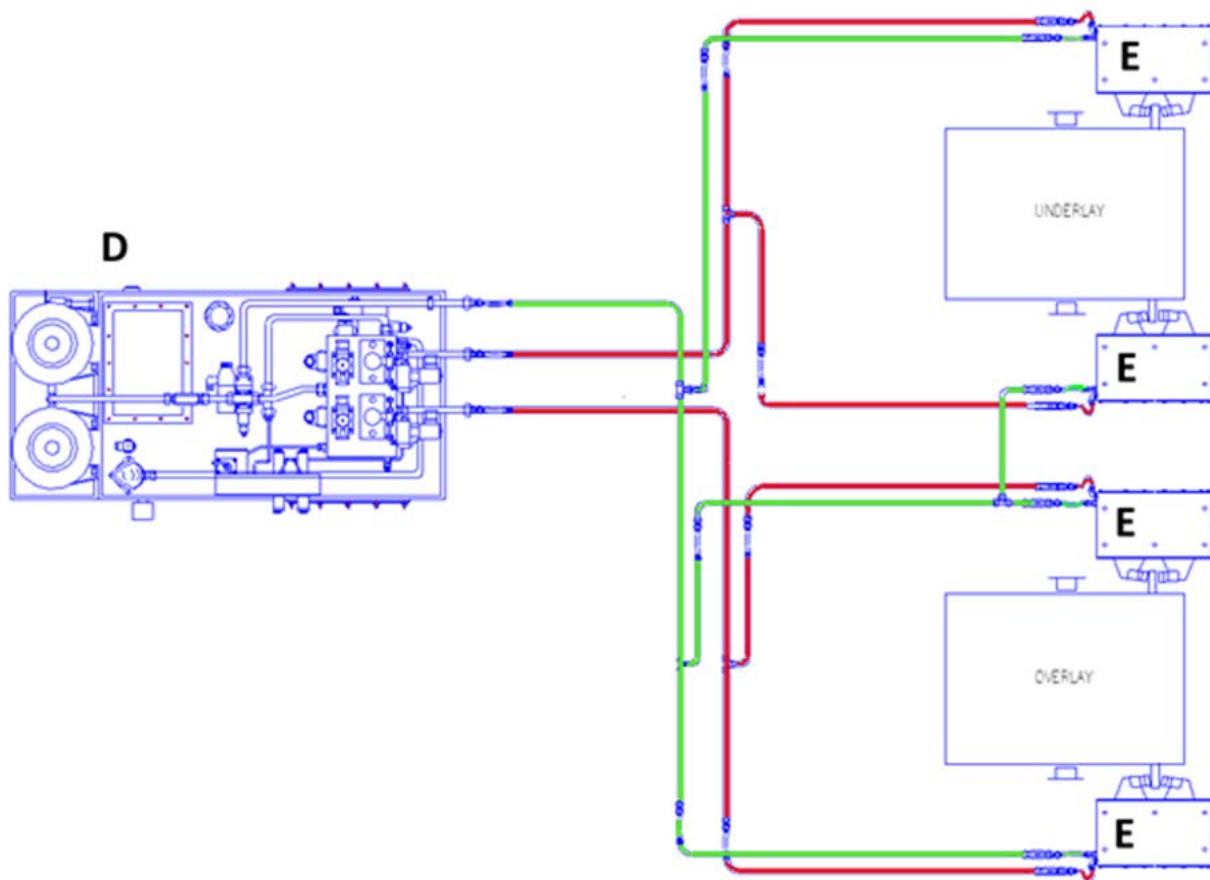
The yellow high-pressure hydraulic fluid pathway illustrated in Figure 13, has a very important functionality that forms part of the Decompression arrangement. The pressure behind the piston (16) is equal to the pneumatic pressure supply (Normally 4 – 8 Bar), which is much less than the hydraulic pressure (Max. 250 Bar) working on the spindle (20) front area. Thus, the yellow pathway was created to direct the high-pressure fluid to the back end of the spindle (20) to cancel out the unbalance of the forces working on it. The spindle O-rings 1 & 2 (18)(19) seals between the spindle (20) and the spindle body (27) to keep the high-pressure hydraulic fluid against the calculated undercut area located on the spindle.

When the systems are released the hydraulic fluid reservoir is depressurized. The spring (28) forces the hydraulic fluid out of the piston chamber (16) through the throttle check valve (17). The throttle check valve then displays its main function, which is the controlling release of the hydraulic fluid in the piston chamber (16). Thus, the throttle check valve (17) can be utilized to set the time response of the system release.

As the throttle check valve (17) slowly releases the hydraulic fluid back into the hydraulic fluid reservoir, the spindle (20) starts to move out of the seat (21). This allows the high-pressure hydraulic fluid to leak through the narrow annulus between the spindle (20) and seat (21), following the pink pathway, illustrated in Figure 13, back into the hydraulic fluid reservoir. A detailed explanation of the hydraulic fluid flow through the narrow annulus and the decompression cycle curve is explained in Section 2.3.3. After the spindle (20) has contracted in full from the seat (21) all components are situated in their initial position before the pneumatic supply was connected to the system.

2.3.2 Levelok Skip System

The Levelok skip system is another widely used conveyance arresting system [2], that was designed to support skips during the loading of ore at the loading station of vertical mine shafts. This system consists of a more complex hydraulic power pack than that of the Levelok man, material cage power pack. This hydraulic power pack is located at the loading station of the respective conveyance shaft, forming part of the operating loading sequence line, which is normally controlled by the loading station PLC. The most common configuration of such a system is illustrated in Figure 14.



D: Levelok skip hydraulic power pack
E: Levelok hydraulic clamp

Figure 14: Levelok skip system layout [10].

The objective of the system is to hold the skip steady during the loading of ore, utilizing two hydraulic clamps (E) gripping onto steel sections (T-bars) projecting from the side of each skip. From Figure 14 it is shown that the Levelok skip system utilizes one hydraulic power pack to clamp two conveyances in the shaft. The hoisting procedure for skip conveyances allows the overlay skip to empty a load on the surface while the underlay skip is loaded at the loading station and vice versa. Thus, only one skip is clamped by the Levelok skip system at a time.

The step-by-step clamping and unclamping procedure of a Levelok skip system are explained in Annexure A. This is similar to the procedure guidelines found in the WJ Engineering (PTY) LTD quality specifications [6] [7] and numerous Levelok skip system operational manuals supplied to Levelok skip system operational mines [11].

The Levelok skip hydraulic clamps are powered by a double-acting hydraulic system, hence the green low-pressure hydraulic line and red high-pressure hydraulic line as illustrated in the illustration of Figure 14 [10]. The hydraulic supply is obtained from a hydraulic skip power pack (D) which contains motor-pump units (normally 500V), control valves with electronic equipment (normally 110V operated), operating manifolds, and accumulators, better visualized in Figure 15.

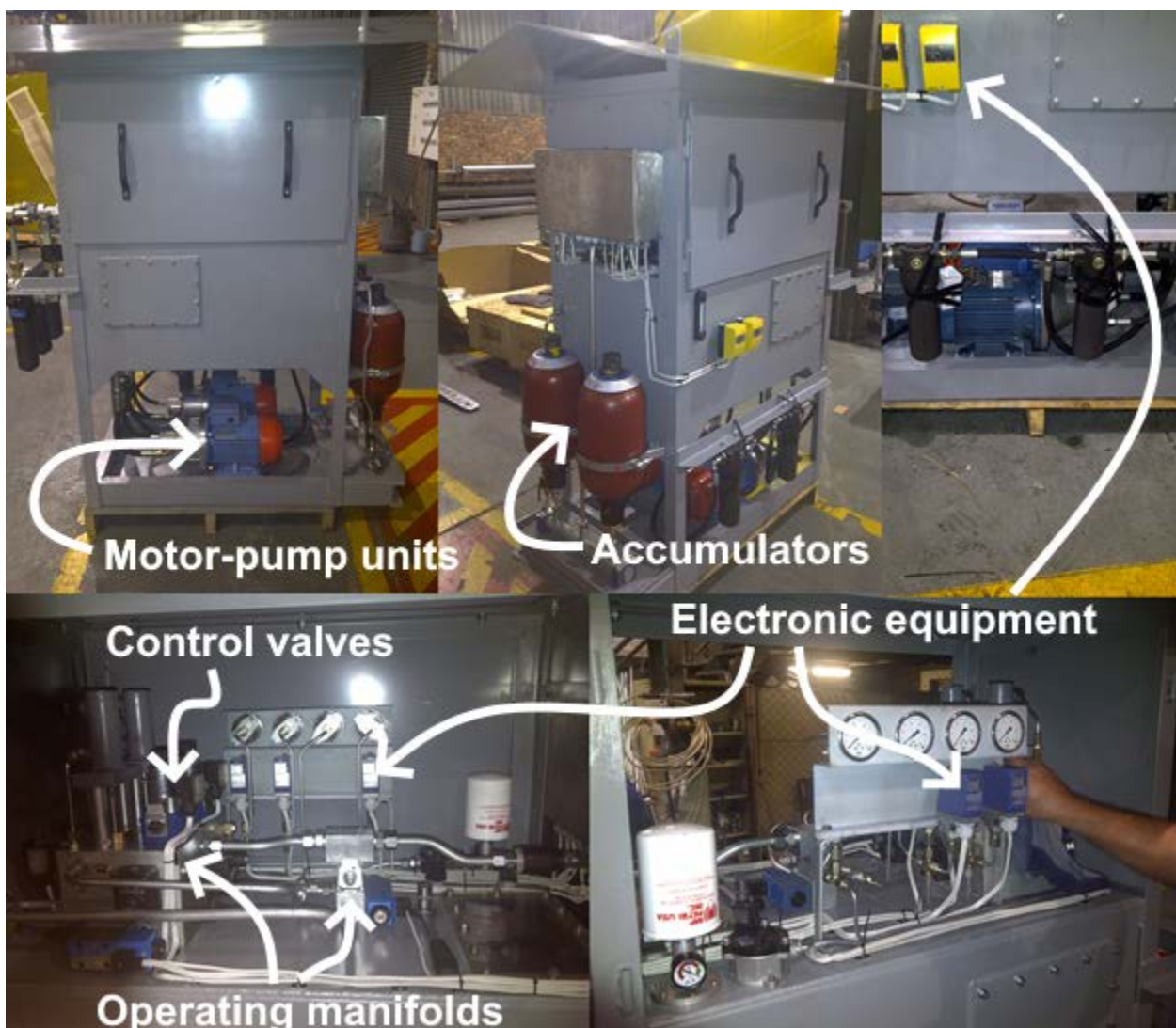


Figure 15: Levelok skip system power pack [4].

To better understand how these different components interact with each other and the functions of these interactions benefit the system, the equivalent hydraulic diagram of the Levelok skip system presented in Figure 14 can be studied and is illustrated in Figure 16 [32], together with its corresponding component list represented in Table 5 [32].

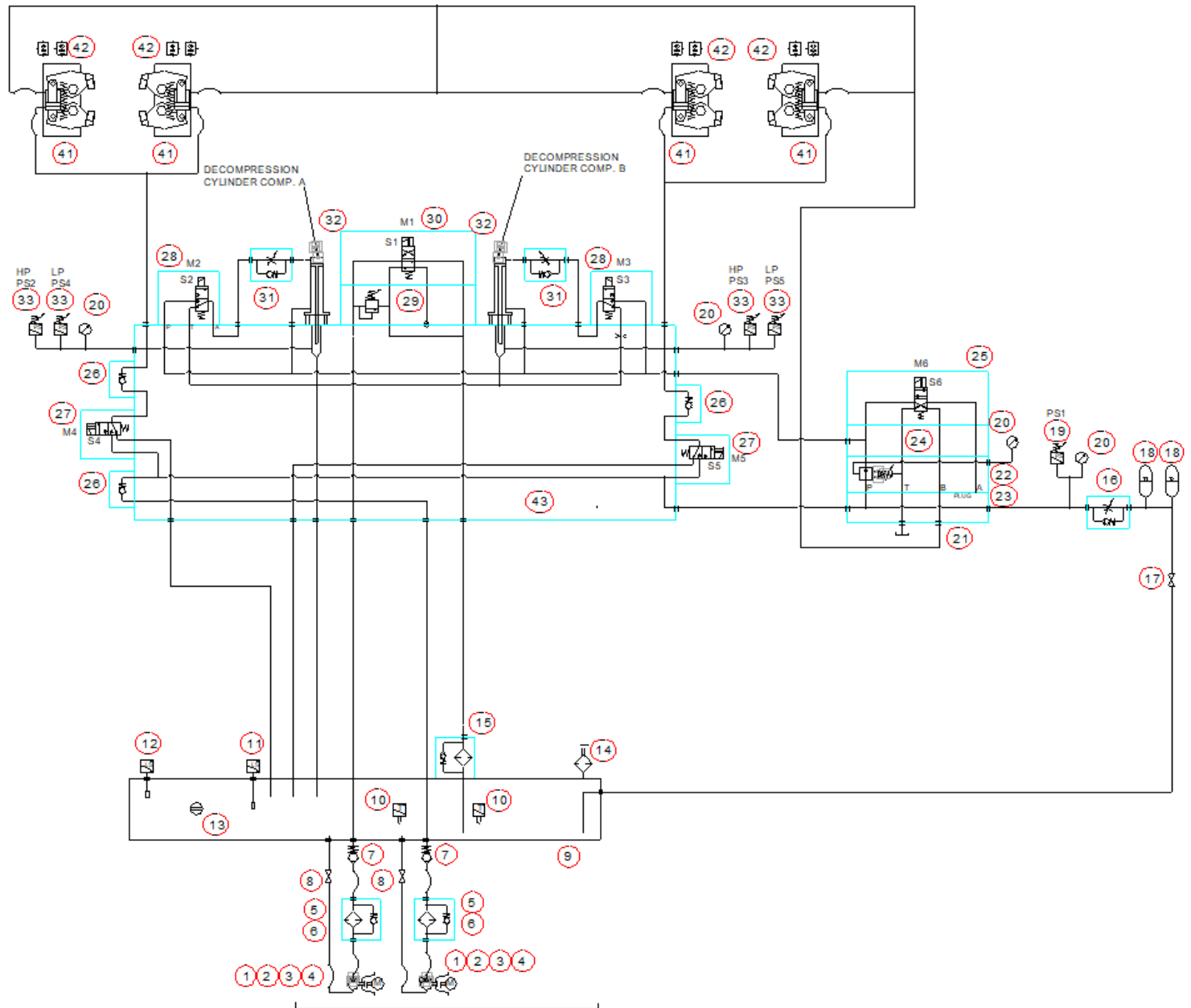


Figure 16: Equivalent hydraulic diagram of the Levelok skip system hydraulic power pack working in the system presented in Figure 14 [32].

Table 5: Component list of the hydraulic diagram illustrated in Figures 16 & 17 [32].

Component number	Description	Component number	Description
1	Gear pump	19	Differential pressure switch
2	Drive coupling	20	Pressure gauge
3	Bell housing	21	Manifold
4	Electric motor	22	Body locator
5	High-pressure filter	23	Pressure reducing valve
6	Filter element	24	Adaptor block
7	Check valve	25	Directional poppet valve NG6
8	Ball valve	26	Check valve
9	Reservoir	27	Directional poppet valve NG10
10	Thermostat	28	Directional poppet valve NG6
11	Low low fluid level switch	29	Relief valve
12	Low fluid level switch	30	Directional control valve
13	Fluid level gauge	31	Throttle check valve
14	Filler breather	32	Decompression arrangement
15	Tank top filter	33	Pressure switch
16	Barrel throttle check valve	41	Levelok clamp
17	Maintenance press. release valve	42	Magnetic/pressure switch
18	Accumulator	43	Manifold block]

The hydraulic diagram from Figure 16, represents a symmetrical dual clamping system designed for an overlay and underlay conveyance system. Thus, similar valves that have similar functions and key components (such as the decompression arrangement) are controlled with the same control philosophy. When the system in Figure 14 is changed in a manner that it will only clamp one conveyance, making it a single conveyance arresting Levelok system, the Hydraulic diagram presented in Figure 16 can be simplified to the hydraulic diagram presented in Figure 17 [33] (Table 5 [32] component list still applies). This simplified hydraulic diagram of the split of a dual system is done only to assist with a better understanding of the system. In the mining industry, this will never work, as all skip conveyances always work in pairs as they interact as counterweights for one another.

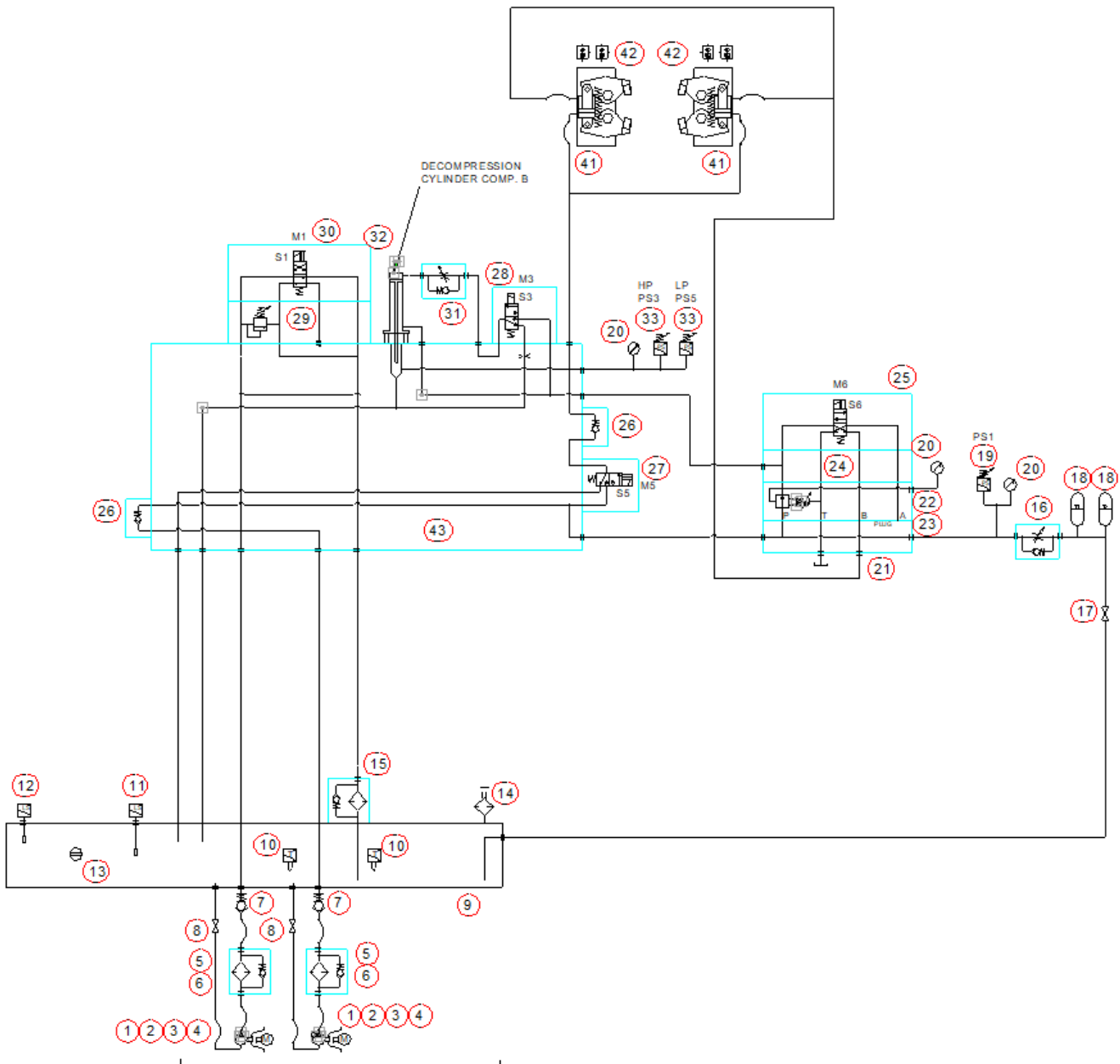


Figure 17: Simplified hydraulic diagram for a better understanding of the Levelok skip system hydraulic power pack [32].

From this simplified hydraulic diagram, hydraulic fluid is stored in a reservoir (9). The hydraulic fluid ISO 68 that is used in this system has a different viscosity than the hydraulic fluid ISO 32 that is used in the Levelok man, material cage systems. The different specifications of these hydraulic fluids are represented in Annexure B [34] [37]. How these different viscosities affect the systems and their respective decompression cycles are discussed in Sections 2.3.3 & 2.3.4.

The hydraulic Levelok skip power pack is designed to operate the hydraulic skip clamps (41) using a high-pressure application pressure of 24 MPa and a low-pressure retracting pressure of 6 MPa.

The pressurized hydraulic fluid for the operation of the clamps (41) is stored in a pair of 10-liter accumulators (18), which are kept charged by a hydraulic gear pump (1) driven by an electric motor (4). There is a second motor pump unit (1)(2)(3)(4) installed on the hydraulic power pack and is acting as a standby unit. The two pump units (1)(2)(3)(4) are each directly coupled to a 4 pole, 3 kW electric motor (4). The gear pump (1) has a specified output with a flow rate of about 6.5 l/min and a maximum operating pressure of 24 MPa.

The online pump runs continuously and a differential pressure switch PS1 (19) brings it into the circuit when the accumulator (18) needs recharging and by-passes its output through a charging valve M1 (30) and relief valve (29) back to the tank at low pressure when the accumulator is fully charged, as illustrated in the hydraulic diagram of Figure 17.

A single solenoid valve M5 (27) directs hydraulic fluid from the accumulators to the clamping system. The control of the decompression arrangement (32), is the use of low-pressure hydraulic fluid directed by the solenoid valve M3 (28). The directional poppet valve M6 (25) controls the low-pressure hydraulic fluid. This low-pressure hydraulic fluid is used in the decompression arrangement cylinder (32) and to assist the retraction of the Levelok clamps (41) when the system is released, to ensure that the arms of the clamps (41) are fully retracted. The low pressure is obtained by a pressure reducing valve (22)(23) (mounted on a manifold block (24)) set at 6 MPa.

The speed at which the clamps (41) are applied is controlled by the setting of the barrel throttle check valve (16) in the accumulator outlet line, and this valve would normally be set to apply the clamps (41) within 1 to 3 seconds.

A pressure switch PS3 (33) will sense when the clamps (41) are under full pressure, and this will signal the flask door to open to load the steady arrested skip conveyance. A second pressure switch PS5 (33) will signal when the clamping pressure drops to a low level and the skip can be hoisted away.

The pressure solenoid control valves, as well as the decompression valves, are all mounted on a common manifold block (43), and the pressure switches and the pressure gauges (20) are piped up to ports on the block.

The power pack is fitted with two hydraulic fluid level switches (11 & 12), one a warning of "low hydraulic fluid level" and a second to trip the power pack on 'low/low hydraulic fluid level". The system is also equipped with two temperature switches (10). The high-temperature switch warning will be set to 50 °C and the high/high-temperature switch trip will be set at 65 °C. These switches are wired into the motor starter circuit and to the loading station PLC panels.

To clamp the Levelok skip system the following sequence is followed by the loading station PLC. When an empty skip in the conveyance compartment is in position and the PLC “skip in position” signal is true, then the decompression solenoid valve M3 (28) and low-pressure retraction valve M6 (25) is energized and a ½ second later system pressure solenoid valve M5 (27) is energized. The clamps (41) are applied by high-pressure hydraulic fluid from the accumulators (18), and line pressure (represented by the red piping in Figure 14) will then build up to operating pressure and switch the PS3 (33) condition. This transmits a signal to the flask controls to open the flask door and the ore will then be discharged from the flask into the skip. A load cell under the flask will signal a complete emptying of the flask and this will then signal the release of the clamps (41).

This signal will initiate the unclamping of the Levelok skip system sequence in the loading station PLC. Solenoid valve M5 (27) is de-energized followed by the time delay of ½ second before solenoid valve M3 (28) is de-energized. The operating clamp pressure will decay through the decompression arrangement (32) (31). The hydraulic decompression cylinder connected to the spindle retracts the spindle from the seat that in turn decreases the clamp operating pressure and allows the gradual releasing of the clamps (41). The skip gradually slides downwards as the rope steadily takes up the payload of the skip. The solenoid valve M6 (25) will de-energize when the low-pressure PS5 (33) signal is activated to bring the clamp arms (41) off fully with low-pressure hydraulic fluid. At the same time, the loading station PLC receives the signal to hoist the skip.

When all the clamp arms (41) are fully retracted, magnetic/pressure switches (42) are operated to signal the loading station PLC that the arms are clear and the skip can approach the loading station on the return trip.

The gradual release of the operating clamping pressure in the Levelok skip system is also controlled by a decompression arrangement of the Levelok power pack. The operation of the main components that control the gradual release in system pressure is explained in Section 2.3.3

2.3.3 Levelok power pack decompression cycle

The main characteristic of the Levelok system is its ability to control the gradual pressure release in the hydraulic clamps, causing the conveyance to slide in a controlled manner into its new position in the shaft after loading or unloading [1] [3]. The decompression cycle of the hydraulic power packs, as mentioned, is the controlling component and the heart of the Levelok system. It needs to consistently work effectively and reliably for the system to operate successfully.

The general arrangements and control philosophies of the decompression cycles for the Levelok man, material cage system, and the Levelok skip system are somewhat different, but the main concept and components are comparable [12] [13]. To illustrate these similarities Figure 18 displays the decompression arrangements of a Levelok man, material cage power pack, and a 3kW Levelok skip power pack.

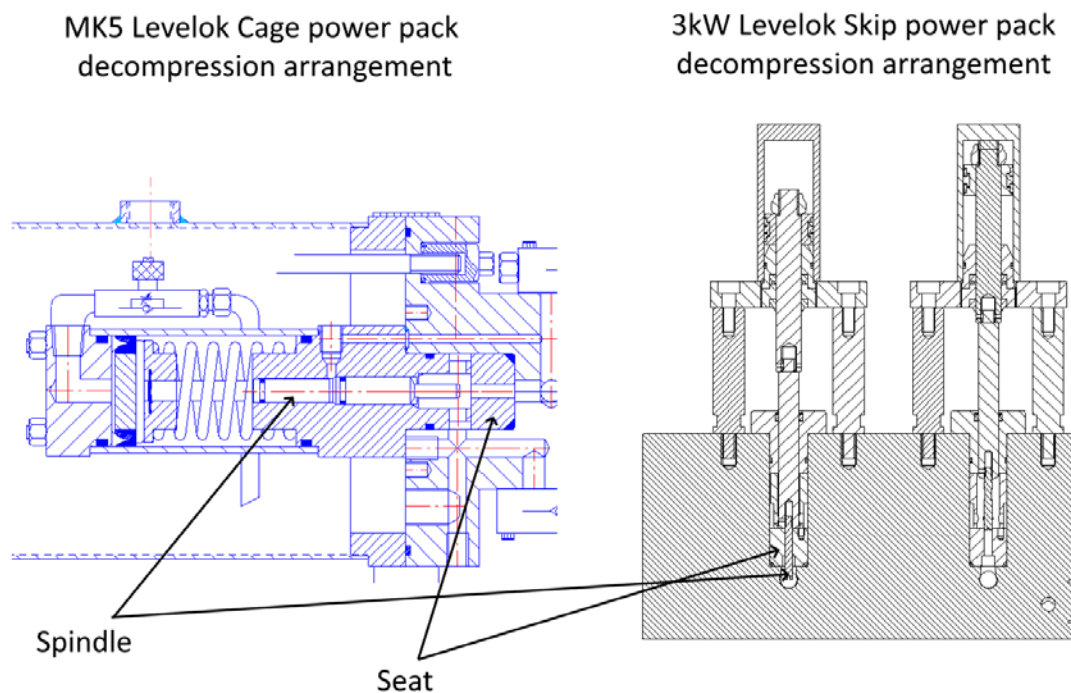


Figure 18: MK5 Levelok cage power pack and 3kW Levelok skip power pack decompression arrangements [12] [13].

This illustration shows the two main components, which are the spindle and seat. The required pressure drop characteristic in the system is provided from the leakage of hydraulic fluid through the narrow annulus between these two components. Figure 19 illustrates the pressure decompression cycle curve over time as the spindle moves through the seat.

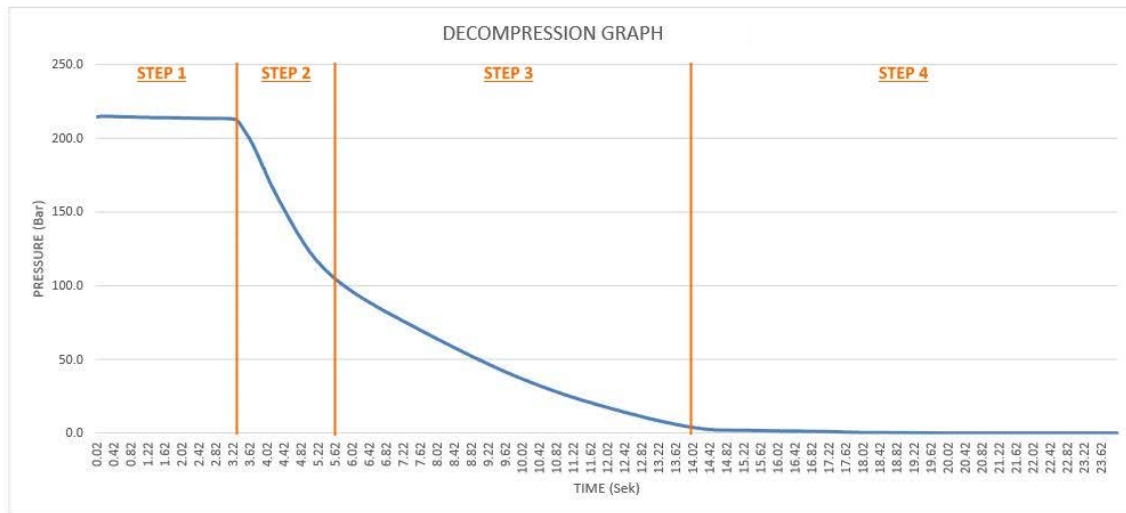
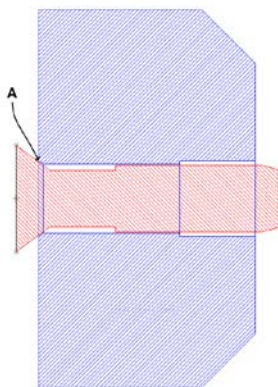


Figure 19: Example of the decompression graph over time of a Levelok power pack [15].

The decompression cycle curve illustrated in Figure 19 is divided into four simplified steps. These sections are used to better understand the dynamics between the spindle and seat and the flow of the hydraulic fluid through the narrow annulus between them. The four steps accompanied by the four corresponding illustrations in Figures 20 to 23 explain the main concept of the different characteristics of the spindle and seat mechanism that causes the pressure decay to occur [3].

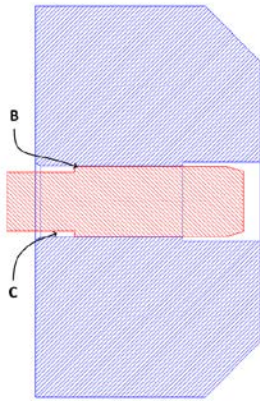
Step 1



At this position in time, the spindle is pushed forward into the seat by means of pneumatic pressure or hydraulic fluid, acting from behind the spindle. At point **A** in Figure 20, the spindle is constrained against the seat and thus seals off any fluid leakage. This enables the power pack to build and maintain hydraulic pressure [3].

Figure 20: Step 1 of the spindle and seat position [3].

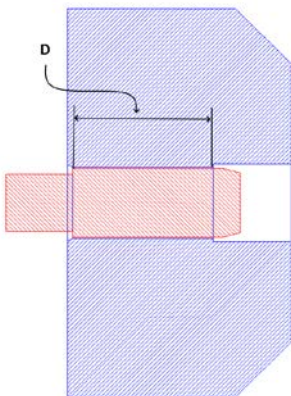
Step 2



Once the unclamping procedure is initiated, the decompression arrangement allows the spindle to unseat from the seat and to slowly retract. The high-pressure hydraulic fluid from the clamps is then allowed to leak through the narrow annulus between the spindle and seat, as illustrated at point **B** in Figure 21. At point **C** there is an undercut, shortening the narrow annulus distance, which allows faster leakage of the high-pressure fluid for a short time period [3].

Figure 21: Step 2 of the spindle and seat position [3].

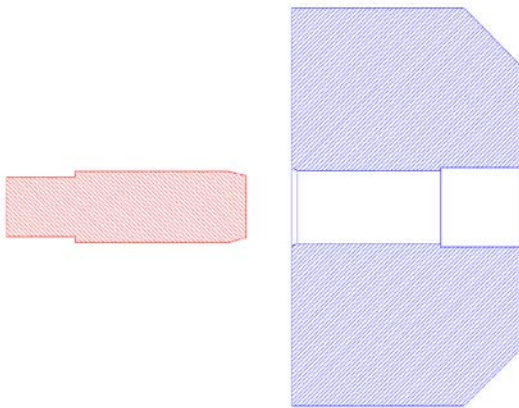
Step 3



When the narrow annulus distance is at a maximum, as illustrated by point **D** in Figure 22, the friction between the fluid leaking through the narrow annulus and the decompression arrangement components also attains a maximum, thereby reducing the leakage of the high-pressure fluid. As the narrow annulus distance becomes shorter again, the rate of leakage increases [3].

Figure 22: Step 3 of the spindle and seat position [3].

Step 4



When the spindle is fully retracted as shown in Figure 23, the resistance against the flow of fluid is drastically reduced, thereby relieving the system of all of the hydraulic pressure, and the decompression cycle has ended [3].

Figure 23: Step 4 of the spindle and seat position [3].

The decompression cycle curves represented in Figure 19 can be studied further by focusing on the dynamics of the conveyance being arrested. During the section described by Step 1, the pressure in the system is at the main designed clamping pressure. This is normally the minimum clamping pressure needed to hold the conveyance when its maximum payload weight is loaded into it, multiplied by a certain safety factor. Normally this safety factor is 3 or more.

The rate of decay in the pressure of the hydraulic fluid in the system after the releasing sequence is initiated, is much higher during Step 2 than that of the rate of pressure decay in Step 3. This is because the slip pressure of the conveyance is normally at a pressure between 60-80 Bar at full payload. The rate of decay in pressure is thus allowed to be faster between maximum pressure and slip pressure to save time during unclamping. As soon as slip pressure is reached the rate of pressure decay is minimized as this is the part in Step 3 where the conveyance gradually slides into its new position in the shaft and gradually takes up the rope stretch.

The size of the narrow annulus between the spindle and seat, which is the controlling entity of the gradual displacement of the conveyance in the shaft, is smaller for the decompression arrangements of the Levelok man, material cage power pack than that of the narrow annulus in a 3kW Levelok skip power pack. This is due to the different viscosities of the different hydraulic fluids used in the different systems [1] [3]. (The specifications of the different hydraulic fluids are represented in Annexure B [34] [37]). How the viscosity of the hydraulic fluids affects the narrow annulus sizes is discussed in Section 2.3.4

2.3.4 Flow of a fluid through a narrow annulus.

The fluid flow through a narrow annulus and the characteristics thereof, is of considerable interest in many areas of engineering, as it is used in many engineering applications [23]. Some of these applications include the annular flow production in diverged and horizontal wells [35], chemical mixing devices, bearings, and in the drilling of oil wells [36]. As discussed in Section 2.3.3. the flow of hydraulic fluid through the narrow annulus in the decompression arrangement of a Levelok hydraulic power pack can be added to this list.

Due to this considerable interest, numerous studies have been completed, to better understand the characteristics of liquid flowing through a narrow annulus. Erhunmwun and Oladeinde (2016) published an article on the “*Analysis of flow in a concentric annulus using a finite element method*” [23], analysing the velocity distribution of an incompressible fluid flowing through a cylindrical annulus pipe. The investigation on the flow through a narrow annulus by adding heat was done by Guanghui, Junli, Kenji Fukuda, and Douman (2003), in their published article in the *Journal of Nuclear Science and Technology*, “*A Theoretical Model of Annular Upward Flow in a Vertical Annulus Gap*” [24]. A similar study was done by Guangyao, Lu, and Jing, Wang in their published article, “*Experimental investigation on heat transfer characteristics of water flow in a narrow annulus*” [25].

Most of these studies mentioned were completed on incompressible fluids, such as water. The fluid used in the decompression arrangements in this study is also incompressible, as hydraulic fluids are used with different viscosities [34] [37]. The ISO68 hydraulic fluid is commonly used by different mines [1] [3]. Normally the mine specifies the viscosity of the hydraulic fluid to be used, but otherwise with the design of the decompression arrangement, the type of hydraulic fluid that needs to be used in a specific system, must be specified in the Levelok system operational and maintenance manual that is supplied to the Levelok system operational mines.

Thus, with the hydraulic fluid being incompressible, the motion of the fluid through a narrow annulus is governed by the incompressible version of the Navier-Stokes equations. To determine an accurate characterization of the fluid flow through the narrow annulus using the Navier-Stokes equations has been researched before. It is this research that has assisted in solving more complex fluid flow situations using numerical computation methods.

There are several possible methods of analysis from first principles on which the flow through a narrow annulus is based on consideration of the conditions pertaining to a small three-dimensional section of fluid sandwiched between planes of sufficient area. This area is considered relative to the section thickness, thus which any pressure gradient can be neglected and the pressure on any plane perpendicular to the direction of flow is uniform.

The fluid flow through a narrow annulus can be considered to be laminar when the gap W is very small compared to the average radius R . The fluid is treated as viscous and therefore at the contact surfaces, the velocity of the fluid flow can be considered as zero, due to the non-slip boundary condition. This statement is visualized in Figure 24 and is confirmed by Erhunmwun and Oladeinde (2016) [24].

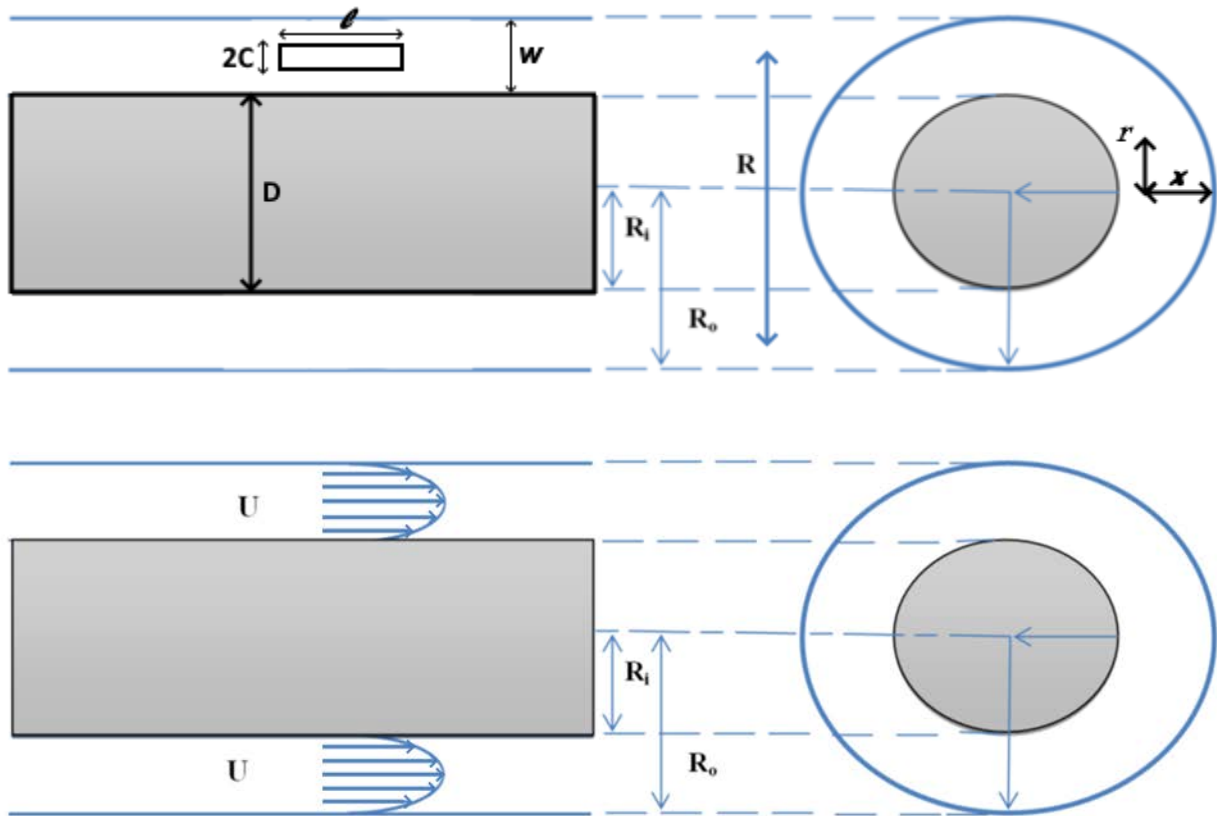


Figure 24: Laminar fluid flow through a narrow annulus [24].

The shear stress in viscous flow is proportional to the velocity gradient. Take an element of thickness $2C$ and length l along the center of the annular space as shown in Figure 24. The shear stress on the horizontal surfaces of this element can be calculated with Equation 2 [23] [24] [25]:

$$\tau = \mu \frac{du}{dc} \quad (2)$$

Where $\frac{du}{dc}$ = Velocity gradient in the radial direction from the centreline of the annulus.

μ = Viscosity.

With laminar flow, the flow lines are parallel and the pressure gradient in the radial direction is zero, as illustrated in Figure 24 and found in the results of Erhunmwun and Oladeinde (2016) [24]. The pressure difference in the axial direction has to overcome the two shear forces on the surfaces of the chosen element.

Hence 2a:

$$\therefore \Delta p \times 2\pi R \times 2C = 2\pi R \times 2l \times \tau \quad (2a)$$

Since due to symmetry the shear stresses will be equal and Equation 3 is obtained.

$$\therefore \frac{\Delta p}{l} = \frac{\tau}{C} \quad (3)$$

Since neither Δp nor l is dependent on the radial coordinates, thus hence (3a).

$$\tau = CK \quad (3a)$$

The shear stress is, therefore, a linear function of C . At the wetted surfaces the shear stress is τ_w and $C = W/2$, thus hence (3b):

$$\therefore K = \frac{2\tau_w}{W} \quad (3b)$$

Hence Equation 4:

$$\therefore \tau = \frac{2\tau_w}{W} C \quad (4)$$

By combining Equations 3 & 4, Equation 5 is obtained:

$$\therefore \Delta p = \frac{2\tau l}{W} \quad (5)$$

By combining Equations 2 & 3 gives Equation 6:

$$\frac{du}{dc} = \frac{c\Delta p}{\mu l} \quad (6)$$

By integrating Equation 6, Equation 6a is obtained:

$$\int du = \frac{\Delta p}{\mu l} \int dC$$

$$U = \frac{\Delta p}{2\mu l} C^2 + K$$

$$U = 0 \text{ where } C = W/2$$

$$\therefore -\frac{\Delta p}{2\mu l} \frac{W^2}{4} = K$$

$$\therefore U = \frac{\Delta p}{2\mu l} \left(C^2 - \frac{W^2}{4} \right) \quad (6a)$$

The maximum velocity is in the center where $C=0$, thus Equation 6b is obtained:

$$\therefore U_{max} = \therefore -\frac{\Delta p}{8\mu l} W^2 \quad (6b)$$

The volume flow rate can be obtained from the integral of the flow through a thin annular surface of thickness dC .

Hence Equation 7,

$$\begin{aligned} dQ &= U \times dC \times 2\pi R \\ \int dQ &= \int \frac{\Delta p}{2\mu l} \left(C^2 - \frac{W^2}{4} \right) dC \times 2\pi R \\ Q &= \frac{\pi R \Delta p}{\mu l} \left[\frac{C^3}{3} - \frac{W^2 C}{4} \right] \frac{W}{2} \\ Q &= \frac{\pi R \Delta p}{\mu l} \left[\frac{W^3}{24} - \frac{W^3}{8} \right] \\ \therefore Q &= -\frac{\pi R \Delta p W^3}{12\mu l} \quad (7) \end{aligned}$$

Where $Q = \text{Volume flow [m}^3/\text{s]}$
 $R = \text{Orifice inner diameter of the seat [m]}$
 $\Delta p = \text{Pressure drop [Pa]}$
 $W = \text{Size of the annulus [m]}$
 $\mu = \text{Hydraulic fluid viscosity [m}^2/\text{s]}$
 $l = \text{Annulus length [m]}$

By studying these equations of velocity and flow rate one can better understand the dynamics of the flow of an incompressible fluid through a narrow annulus. It is clear, that the viscosity of the hydraulic fluid and the geometry of the components that form the narrow annulus influence the flow characteristics, but the variable that is of utmost importance is the size of the annulus (W) restricting the flow.

From these findings, the equations derived from the first principles can be used for the analysis of the decompression arrangement in Chapter 6.

CHAPTER 3

MINE X DESIGN SPECIFICATION & SYSTEM REQUIREMENTS

3.1 Background

Over the last 40 years, the clientele of the Levelok system has grown to the extent that the system is used successfully in numerous international mine shafts. The main goal of these mining companies is to mine more efficiently, productively, and safely. With this objective, the mines are forced to explore deeper into the earth's crust, thus sinking shafts to world record depths. The increase in these depths is stretching the hoisting steel wires of the hoisting winders to the extreme and this is where the Levelok system is supposed to produce its best results. Unfortunately, this is not the case for all Levelok operational mines.

The purpose of this study is to investigate this statement, identify the system shortcomings, and address it, and improving the system so it will adhere to the WJ Engineering quality policy.

The South African treasure route consists of six out of the ten deepest mines in the world [38], one of whom is one of the deepest single drop mine shafts in the world. This particular shaft, which has been in operation for more than 70 years, was one of the former clients of the Horne Hydraulics Group, that has been using the Levelok system on its conveyances from 2001 when the 2.3km depth range was breached [1] [3]. Unfortunately, the Levelok systems installed on the conveyances at this mine have not yet been delivered to its full potential (refer to operational test measurements captured in Chapter 5). Due to NDA agreements in place, the name of the respective mining company and shaft will be referred to as Mine X in this dissertation. In this study, the Levelok systems at Mine X will be investigated, tested, re-evaluated and critical components redesigned using the newly proposed design methodology.

The MK5 Levelok man, material cage systems that are installed on the 2-deck & 3-deck cage conveyances in this shaft, have the same equipment and system layouts as the layout illustrated in Figure 10 [5] in Section 2.3.1.

The MK5 Levelok man, material cage power pack is similar to the power pack illustrated in Figure 13 in Section 2.3.1. The 4.5 Aluminium Levelok clamp general arrangement and hydraulic cylinder layout demonstrating the key design dimensions are illustrated in Figure 25 [39]. The corresponding Levelok clamp specification sheet is represented in Annexure C [40].

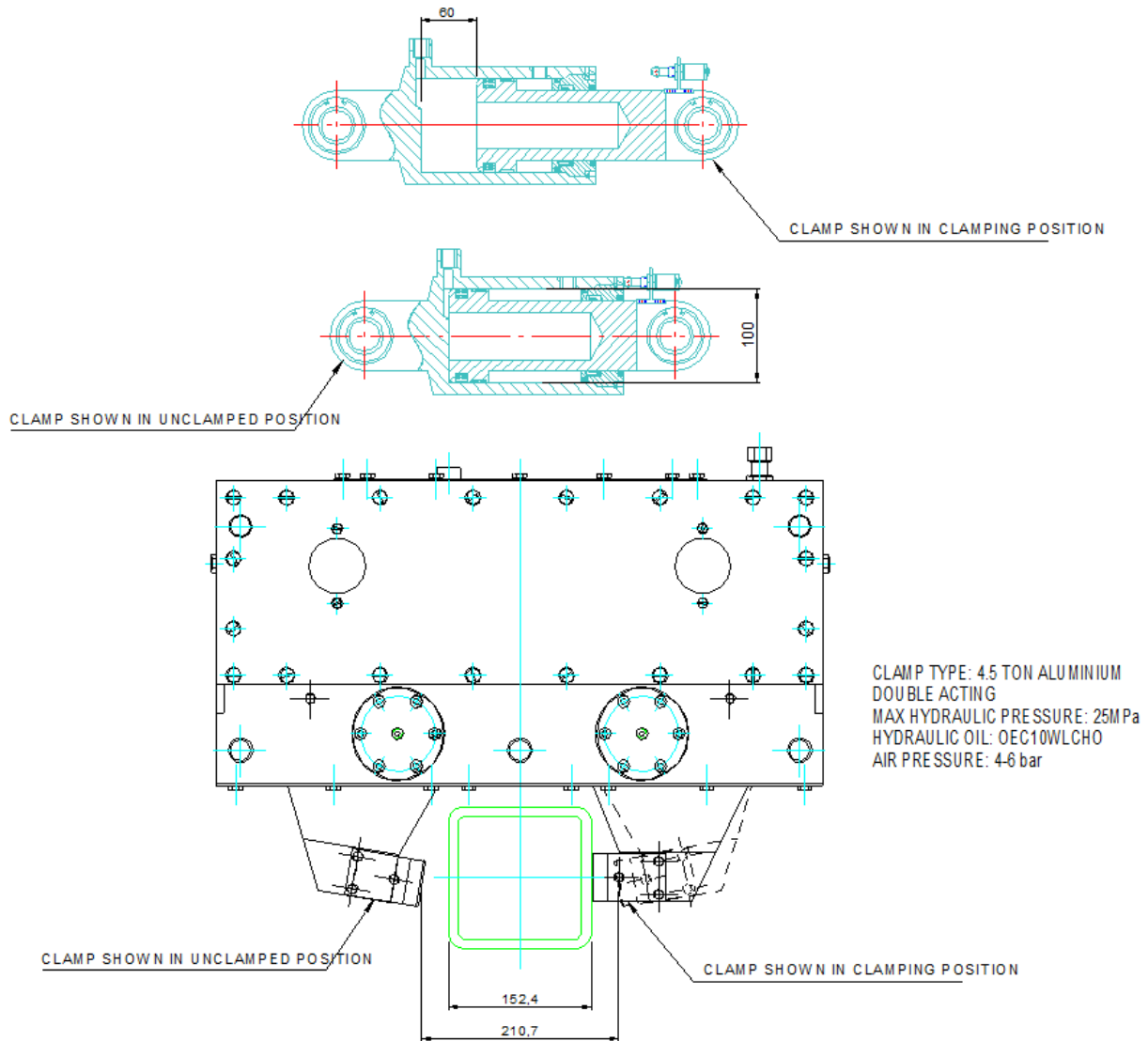


Figure 25: The 4.5 Aluminium Levelok clamp with hydraulic cylinder general arrangement demonstrating key dimensions [39].

The key points that need to be noted from the general arrangements illustrated in Figure 25 are:

- A 100 mm diameter bore cylinder is installed.
- The stroke on the cylinder assembly is 60 mm (when fully clamped to the guides).
- This is a double-acting cylinder assembly (hydraulically and pneumatically operated).
- The clamp has a maximum opening of 210.7 mm from clamp shoe to clamp shoe.

The MK5 Levelok man, material cage systems were installed to the conveyances due to the extreme rope stretch at deeper levels that were experienced during loading and unloading of the conveyances, causing an unsafe situation to mining personnel. The reason for this rope stretch is due to the 18 000 kg maximum payload being operated at the 110 level. This is the deepest level that the Levelok systems are operated at Mine X and is situated 2 986 m beneath the surface [41].

Using this information, together with the winding rope classification provided by the winding rope testing certificate [41] represented in Annexure D, the rope stretch can be calculated using Equation 1 in Section 2.2. The winding rope being used is a 42 mm diameter compound triangular strand 6x30 [41] hoisting rope supplied by Haggie. It must be noted that these conveyances each have double rope attachments, thus the payload is divided between each hoisting wire rope in the rope stretch calculations.

The metallic area is calculated to be (Table 1) $0.457(0.042)^2 = 0.000806148 \text{ m}^2$

The Modulus of elasticity is (Table 1) 110 GPa

The rope stretch is calculated with the use of Equation 1:

$$\Delta L = \frac{F \times L}{A \times E} \quad (1)$$

$$\Delta L = \left(\frac{\frac{18000}{2} \text{ kg} \times 9.81 \text{ m/s}^2 \times 2986 \text{ m}}{0.000806148 \text{ m}^2 \times 110 \times 10^9 \text{ Pa}} \right)$$

$$\Delta L = 2.973 \text{ m}$$

This calculated rope stretch value of almost 3m was confirmed during the numerous completed system audits at Mine X. During these audits it was also found that certain basic system requirements were not yet met.

From these audits there were four main findings:

- All equipment installed on the conveyances was confirmed to be the same as the description in this section. The installations are complete and are mechanically fully functional.
- After clamping, the Levelok systems held all the conveyances steady during loading and unloading.
- Not all interlocks to the system were in operation and were found to be canceled out in the electrical panels of the winder hoisting machine.
- The release of the clamping system did not adhere to the system requirements. The clamps release too fast and the conveyance accelerates rapidly up and down the shaft with a maximum amplitude of 3 m when fully loaded (so-called “yo-yo effect”).

To serve the purpose of addressing these shortcomings and improving the system, it is important to state and understand the design specifications and system requirements. By following the testing & design methodology set out in Section 1.5 in Chapter 1, this purpose can be fulfilled.

3.2 Design specification

This Levelok man, material cage holding system is designed to support a total out-of-balance mass of 18 000 kg utilizing four clamp units acting on the 152.4 mm wide guide section in the shaft. The clamp capacities are based on a static coefficient of friction of 0.27, steel on steel, and a hydraulic fluid clamping system pressure of 21 MPa. The calculated design calculation sheet for this specific system is attached under Annexure E [43].

In this design calculation sheet, all values highlighted in orange are fixed inputs and the values highlighted in grey with orange-coloured lettering are calculated using the fixed input values. The fixed input values are listed in Table 6 [43], together with the description of where the values were obtained for further use in the system design calculations. Most of the values obtained are specific to the Levelok systems installed at Mine X, as most of the components, such as the Levelok clamps and piping, are to be reused in the new system after the completion of this study and the necessary improvements were made. Only the power packs, seals, and controls were changed after the system modification and still adhere to the design specification represented in Annexure E [43]. This will be discussed further in Chapters 7 to 10.

Table 6: Fixed input values list with a description of where the values were obtained. [43]

Fixed value inputs	Value		Description
Shoe clearance from the guide	0.029	m	Obtained from drawing PH4004 Rev 2 [39]. Also illustrated in Figure 25.
Diameter of cylinder	0.1	m	Obtained from drawing PH4004 Rev 2 [39]. Also illustrated in Figure 25.
Cylinder stroke	0.06	m	Measured on drawing PH4004 Rev 2 using Solid Edge [39] [44]. Also illustrated in Figure 25.
Arm dimension X1	0.154	m	Measured on drawing PH4004 Rev 2 using Solid Edge [39] [44].
Arm dimension X2	0.18	m	Measured on drawing PH4004 Rev 2 using Solid Edge [39] [44].
Friction insert coefficient	0.27		The calculated value was obtained by friction tests done in Chapter 4.
System pressure	210	Bar	45% of Power pack pressure capacity obtained from 3.5 bar pneumatic pressure. At this system pressure, a safety factor of 4.6 is obtained, securing the conveyance even against shock loads [1] [3].
Holding mass	18	Ton	Maximum payload obtained from the general notes of the cage general arrangement drawings [45].
Safety factor	2		Safety factor for clamps. Clamps can hold twice its capacity load. This is a minimum requirement, as per WJ Engineering's best engineering practice of mining safety equipment [3] [16].
Number of clamps	4		The conveyance is guided with 4 guides that can be clamped on [1] [3].
Clamp shoes maximum opening	210.7	mm	Measured on drawing PH4004 Rev 2 using Solid Edge [39] [44].
Hydraulic fluid	32 Viscosity		Specified hydraulic fluid obtained from the Levelok man, material cage arresting system operational manual [9].
Spindle diameter	6.22	mm	Obtained from drawing PH9000 Rev 0 [46].
Spindle undercut	7	mm	Obtained from drawing PH9000 Rev 0 [46].
Seat undercut	7	mm	Obtained from drawing PH9000 Rev 0 [46].
Power pack pressure switch setting	18	MPa	Specified pressure to send a signal to winder driver display and signal to conveyance lights as specified in the Levelok man, material cage arresting system operational manual [9].
Timer setting	6	sec	The specified time for the so-called "Fast approach" on the clamps as specified in Chapter 2 Section 2.3.1 and specified in the Levelok man, material cage arresting system operational manual [9].
Clamping time	20	sec	Calculated time obtained by tests completed in Chapter 5.
Release time	32	sec	Calculated time obtained by tests completed in Chapter 5.

Power pack max pressure hold time	1	hr	Specified pressure test time obtained from the WJ-SPEC-20 Levelok power pack stripping, assemble, and testing procedure document [6].
Accumulator max pressure hold time	1	hr	Specified pressure test time obtained from the WJ-SPEC-20 Levelok power pack stripping, assemble, and testing procedure document [6].
Minimum decompression electrical hold time	45	sec	Specified pressure test time obtained from the WJ-SPEC-20 Levelok power pack stripping, assemble, and testing procedure document [6].
Clamp lock valve setting	0.7	mm	This is the rupture valve setting inside the clamp lock valve, used as a safety measure when there is a sudden drop in pressure in the system [1] [3] [7].
Clamp pressure switch setting	2	Bar	This is the setting of the programmable pressure switch installed to each clamp lock valve of each clamp. This pressure switch supplies a signal of each clamp to the winder driver display. This, in turn, indicates the status of each clamp on the conveyance, to assure each clamp is operating correctly and indicate when it is safe to hoist the conveyance when clamps are fully retracted.
Coil voltage	12 or 24	V DC	The voltage being used depends on the operating system of the Levelok system. For the Levelok MK7s system, it is 12V DC and for the Levelok MK7elec system, it is 24V DC.

Using these listed fixed values in Table 6, together with the free body forces diagram derived from the Levelok clamp general arrangement [39] and the clamp & conveyance payload forces diagram [45] illustrated in Figure 26 [50] [52], the critical system design settings and the Levelok equipment being used can be evaluated.

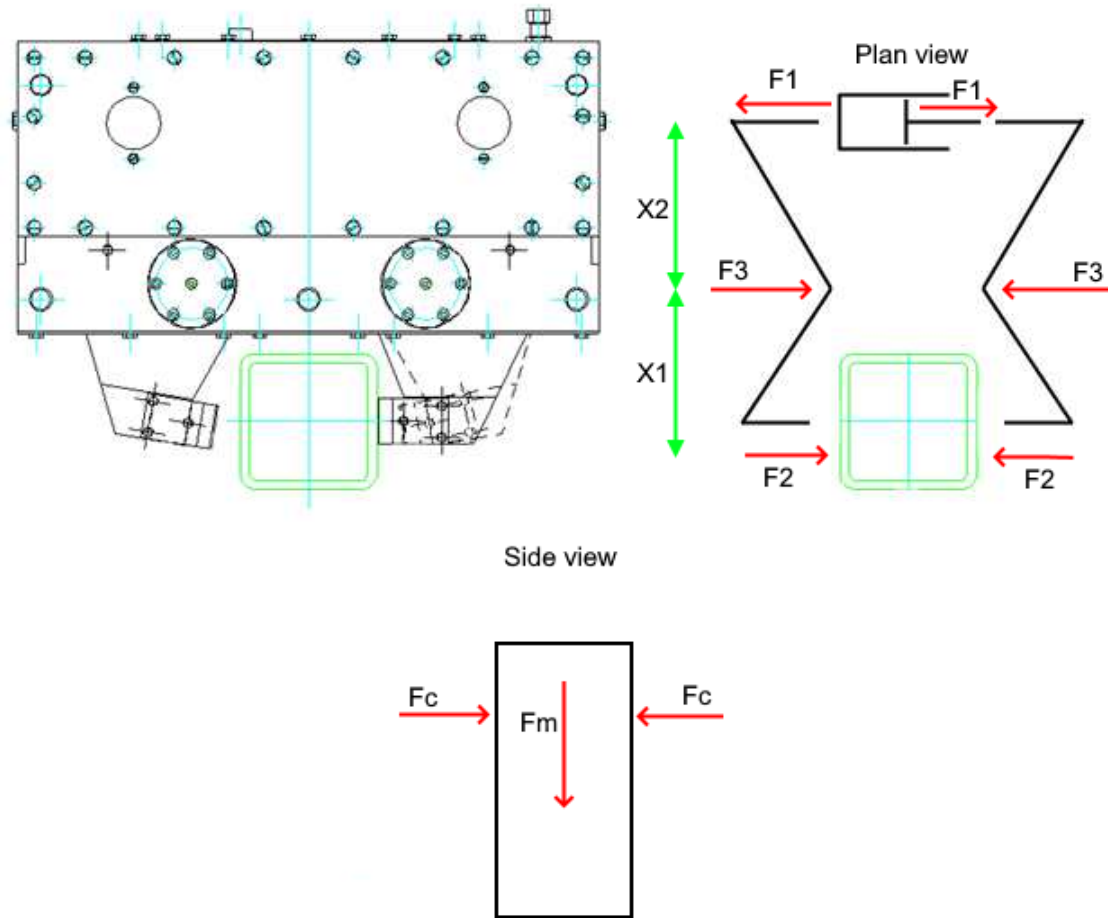


Figure 26: The free-body forces diagram derived from the Levelok clamp general arrangement and clamp & conveyance payload forces diagram [50] [52].

The most important function of any Levelok clamping system is its ability to hold the conveyance steady during the load and unloading of a payload. To ensure the Levelok system will deliver to this expectation, the system pressure can be evaluated against the pressure at the point of slip with a full payload.

The rated pressure at the point of slip, with a full payload, can be calculated by using Equation 8:

$$\text{Slip press.} = \frac{m_p \times g}{\mu_s \times \Delta X_2 / \Delta X_1 \times n_c \times \left(\frac{\phi_p}{2}\right)^2 \times \pi \times 2 \times 10^5} \quad (8)$$

Where *Slip press.* = Measured in Bar.
m_p = Payload mass [kg]
g = Gravitational acceleration [m/s²]
μ_s = Coefficient of static friction [unitless]
ΔX₁ = Moment lever arm from bearing to shoe on guide [m]
ΔX₂ = Moment lever arm from bearing to hydraulic cylinder [m]
n_c = Number of clamps [unitless]
φ_p = Piston diameter [m]

How this equation was derived will be discussed in detail in Chapter 4. With Mine X's conveyances having a maximum payload of 18 tons, the slip pressure can be calculated to be at 89 Bar. Thus, the safety factor on system pressure is calculated to be 2.3 and the safety factor against the main clamping pressure signal sent to the winder driver display is 2. These values satisfy the minimum requirements as specified in Table 6.

System pressure is accomplished after 15 sec after the pneumatic hose is connected to the system and the pneumatic timer has allowed for the "fast approach" to complete. The amount of hydraulic fluid volume needed to fill the cylinders during clamping is calculated using Equation 9:

$$\text{Clamping volume per clamp} = \pi \times \left(\frac{\phi_p}{2}\right)^2 \times C_s \times 1000 \quad (9)$$

Where *Clamping vol/clamp* = measured in liters
φ_p = Piston diameter [m]
C_s = Clamp stroke [m]

The total calculated hydraulic fluid volume needed for the “fast approach” and clamping to system pressure is 1.885l, 0.471l per clamp. The volume of the hydraulic fluid in the hydraulic piping and hoses are not added to the calculation, as the system is bled during commissioning and thus contains hydraulic fluid at all times. Thus, the Levelok power pack’s reservoir capacity of 7.37l is more than enough to sustain the system during clamping.

The force that the Levelok clamp exerts onto the shaft guide at system pressure can be calculated with basic physics force-pressure relations. However, due to the difference in arm distances from the Levelok clamp cylinder and clamping shoe to the main arm bearings, the clamping force is an amplification of the cylinder force and must be considered in the calculations. Utilizing the free-body forces diagram, drawn in Figure 26 these forces were calculated with Equations 10 & 11:

$$P_s = \frac{F_1}{A_p}$$

$$F_1 = \pi \times \left(\frac{\phi_p}{2}\right)^2 \times P_s \quad (10)$$

Where F_1 = Cylinder pressure force [kN]
 ϕ_p = Piston diameter [m]
 P_s = System pressure [Pa]

$$F_2 = F_1 \frac{\Delta X_2}{\Delta X_1} \quad (11)$$

Where F_2 = Clamping force [kN]
 F_1 = Cylinder pressure force [kN]
 ΔX_1 = Moment lever arm from bearing to shoe on guide [m]
 ΔX_2 = Moment lever arm from bearing to hydraulic cylinder [m]

The total clamping force F_c on each side of the conveyance is calculated with Equation 12:

$$F_c = F_2 \times 2 \text{ clamps} \quad (12)$$

$$F_c = 385.56 \text{ kN}$$

The holding capability F_m of the system can be calculated by multiplying the total clamping force F_c on each side of the conveyance with the static friction coefficient of 0.27, hence Equation 13:

$$F_m = F_c \times \mu_s \quad (13)$$

$$F_m = 104.1 \text{ kN}$$

Thus, it is calculated that each clamp on the installed systems has a 5.3-ton holding force capability when clamped at a 210 Bar system pressure rating. When compared to the required 4.5-ton holding force capability, it is safe to confirm that the Levelok Clamps are to the required specification.

These Levelok clamps are fitted with double-acting cylinders with all components machined from stainless steel. The specifications on the hydraulic seals used in the cylinders are discussed in more detail in Chapters 7 and 8 as the specifications differ due to specific system requirements. Two stainless steel springs are provided in each clamp to assist with retracting the cylinder when clamp pressure is released, as illustrated in Figure 27 [47].



Figure 27: Illustration of the stainless steel springs that are provided in each clamp to assist with the retracting of the hydraulic clamps [47].

Chapters 5 and 6 highlights more on the power pack tests and design respectively. All tests recorded in Chapter 5 were completed according to the system settings listed in Table 6 unless otherwise documented for specific reasons.

3.3 System requirements

With the design specification and the information obtained from Chapter 2, the system requirements can thus be summarized in Table 7 [11]. In this table, each system requirement that has been achieved and confirmed is marked with green. This is done for clear visualization of which system requirements have to be addressed. The author utilized the calculations done in Section 3.2. and the information gathered from the numerous Levelok system on-site audits to determine which of the system requirements were achieved at Mine X.

Most of the requirements are design specifications implemented by the OEM to the Levelok system, but there are certain requirements (such as requirements 7, 15 & 16) that are the responsibility of the mine. These requirements were communicated with the client to ensure that the system functions properly.

During continuous system audits the mine's responsibilities with relation to the OEM specifications are checked, as well as during the initial commissioning of the Levelok system. Table 7 [11] will be used as a standard checklist and basis to evaluate if all system requirements are met during an audit event. This list will also be used in Chapter 9 of this study for verification & validation.

From the application of Table 7 [11] during the Mine X audit processes, it was found that from the 20 system requirements there was only one system requirement that was not yet met, and that was the proper behaviour during the release phase of the Levelok system to allow the conveyance to slide slowly to its new position in the shaft and gradually taking up the rope stretch. Thus, the yo-yo effect due to payload addition or removal was not canceled.

The rectification of this specific system's shortcomings was one of the main objectives of the current study and was achieved by following the task clarification framework as set out in Section 1.5 in Chapter 1.

Table 7: Levelok system's main system requirements [11].

System requirements		
Number	Requirement	Achieved
1	The Levelok man, material cage holding system is required to support a total mass of 18 000 kg utilizing four clamp units.	X
2	Each Levelok clamp must have a minimum of 4.5 Ton clamping capacity. Four clamps clamping onto 4 different guides.	X
3	The Levelok clamps geometry must allow for clamping onto a 152.4mm top hat guide.	X
4	There must be a clear clearance between the guide and Levelok clamp opening position when the system is unclamped and is traveling in the mine shaft, to assure that no clamp will interfere in the hoisting of the conveyance.	X
5	At 180 Bar system hydraulic pressure, the signal must be supplied to the communication system of the conveyance. This signal is used for the activation of the safety lights installed to the conveyance for the Levelok system operation and is sent to the winder driver display for indication purposes and interlocking.	X
6	Maximum system hydraulic pressure to be set at 210 Bar on the Levelok power pack.	X
7	The minimum operating pneumatic pressure supplied by the mine is 4 Bar.	X
8	Each Levelok clamp is to be fitted with a pressure switch for clamping indication on the winder driver display for individual clamping functionality and interlocks. Setpoint set at 2 Bar.	X
9	Safety factor on safe clamping of the conveyance to not be less than 2 for maximum payload slip pressure against maximum clamping system pressure	X
10	Hydraulic fluid to be used in the system is 33 viscosity hydraulic fluid (Unless otherwise stated due to design) and will be discussed further in Chapters 5 & 6.	X
11	Timer setting on the pneumatic timer to be set at the minimum time needed for the "fast approach" cycle to be completed.	X
12	Maximum clamping pressure to be achieved in a maximum time of 20 sec.	X
13	The release time of a Levelok power pack is to be no longer than 1 min.	X
14	The release of the Levelok system allows the conveyance to slide slowly to its new position in the shaft, thus gradually taking up the rope stretch due to payload added or removed (thus, no yo-yo effect).	
15	System voltage to be 12 V DC or 24 V DC depending on system design, discussed further in Chapters 7 to 8.	X
16	Solenoid electrical hold time to be set longer as maximum decompression time.	X
17	Power pack max pressure hold time without a Pneumatic supply to be more than 1 hour.	X
18	Accumulator max pressure holds time without a Pneumatic supply to be more than 1 hour.	X
19	Clamp lock valve setting to be set for each clamp at 0.7mm.	X
20	Levelok system to be implemented at different station levels in the shaft.	X

CHAPTER 4

CONSTRUCTION OF THE MATHEMATICAL MODEL FOR ASSESSMENT OF THE LEVELOK DECOMPRESSION CYCLE

4.1 Background

Over the years of the design and development of the Levelok system, the Horne Hydraulics group had developed a Levelok hydraulic power pack decompression testing procedure, that has been adopted by WJ Engineering to form part of the WJ-SPEC-20 QA Levelok power pack stripping, assemble and testing procedure [6]. A similar explanation of the Levelok hydraulic power pack decompression testing procedure is represented in Annexure F [6] and was followed for the various tests conducted as part of this study.

Following this procedure and simultaneously using the necessary hydraulic pressure testing equipment, similar decompression graph results of one Levelok powerpack (with three different decompression settings, together with the same testing conditions) could be obtained as the examples displayed in Figure 28 [51] :

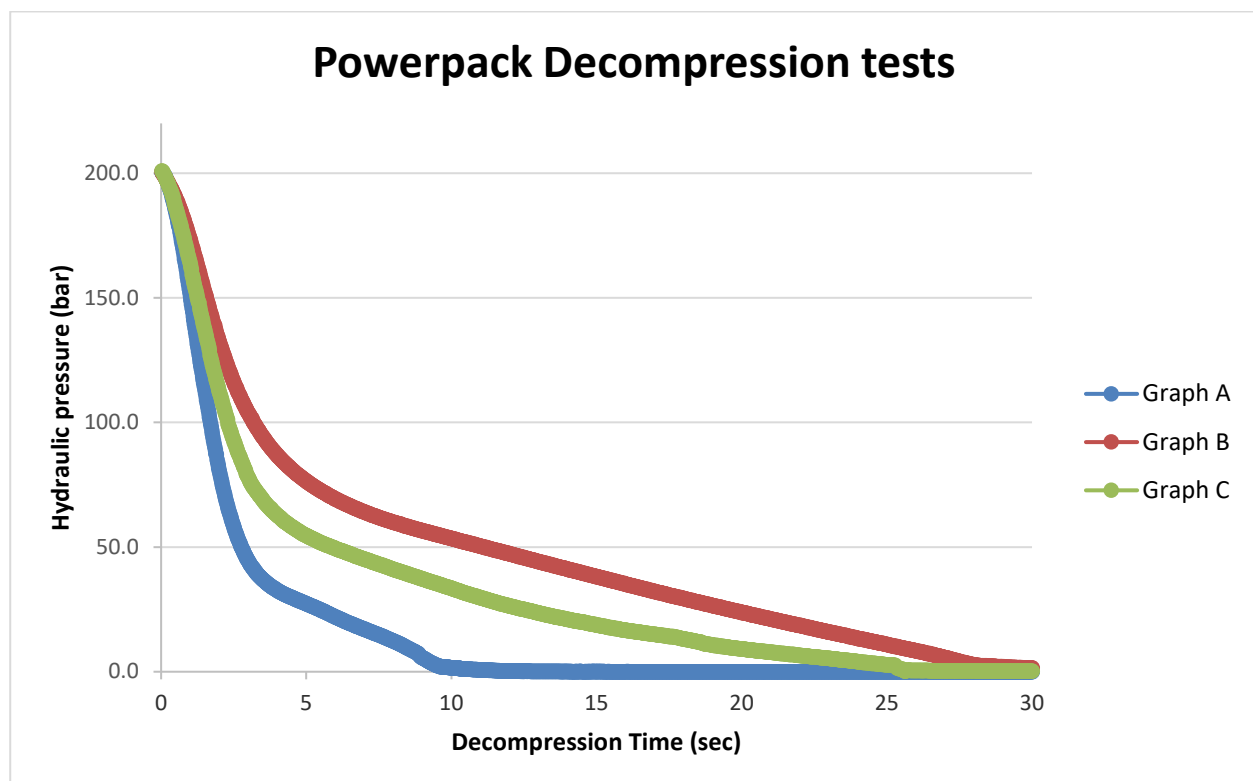


Figure 28: Power pack decompression graphs.

The graphs shown as examples in Figure 28 [51] have the potential of being the results of two different test permutations. The data could be the results of tests conducted on one Levelok power pack, or the other can be the case where there are three different Levelok power packs with different spindle and seat geometries in each power pack, giving results similar to three different decompression tests. These specific graphs as illustrated in Figure 28 [51] where the results of three different decompression tests were conducted on one Levelok power pack with three different initial settings.

As of yet, in either case, there is no method devised to determine which one of the decompression curves will be the most effective to administer the desired slide of a conveyance in the mineshaft after loading or unloading. In fact, this problem of the decompression cycle not performing to the required design was not even addressed by Horne Hydraulics [14]. Instead, their procedure was an iterative process that they performed at each commissioning of a Levelok system. They would swap out the different spindle and seat sets, with different geometrical sizes, of a Levelok power pack, on-site, and then perform different operational slide tests with the conveyance and then the best spindle and seat set was chosen according to the desired conveyance slide results obtained. This procedure was quite time-consuming and without the luxury of a clean workshop to disassemble and re-assemble a hydraulic power pack or have enough time for such a procedure during the commissioning of a system [1].

The other procedure that they followed when installation time was limited, was to do the tests on their test benches in the workshops, record the pressure data, and plot the decompression cycle curves [1]. The engineer would study the decompression curves and approve it, without any concrete evidence that the system would actually perform according to the system requirements.

This problematic procedure just described, was identified as one of the main reasons that the system had the shortcoming of not releasing as the design had required. Thus, the objective of Chapter 4 being one of the objectives of this study, was to develop a mathematical model to predict how the control output of the Levelok system's hydraulic power pack would affect the dynamics of a specific conveyance when the clamps are released.

With this information, it would confirm if the Levelok system hydraulic power pack will or will not perform according to design requirements before it is installed and commissioned for operation in the mine.

4.2 Testing algorithm construction

The first step in the construction of the mathematical conveyance displacement prediction model is to identify the inputs and desired outputs of the open-loop system. This model is defined as an open-loop system due to the fact that no sensor will give feedback on the displacement of the conveyance ("Conveyance slide") back to the controlling unit of the Levelok hydraulic power pack. Thus, the simple block diagram can be constructed as illustrated in Figure 29 [50]:

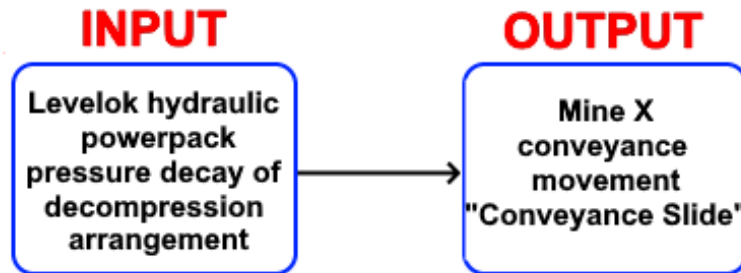


Figure 29: Block diagram defining the main input and output of the mathematical model [50].

The input of the system as shown in Figure 29 [50], can also be interpreted, as mentioned in Chapters 2 & 3, as the control of the open-loop system. The measured Levelok hydraulic power pack pressure decay values that constitute the system input, are measured in Bar with a recording frequency of 50 Hz. This sampling frequency is determined by the measuring equipment and will be discussed in Section 4.3 in more detail.

The approach that was taken to calculate the desired output conveyance predicted displacement was to characterize a "Controller", by manipulating the measured input "Control" values with specific calculated variables. Thus, as shown in Figure 30, the block diagram can be modified to obtain [50]:

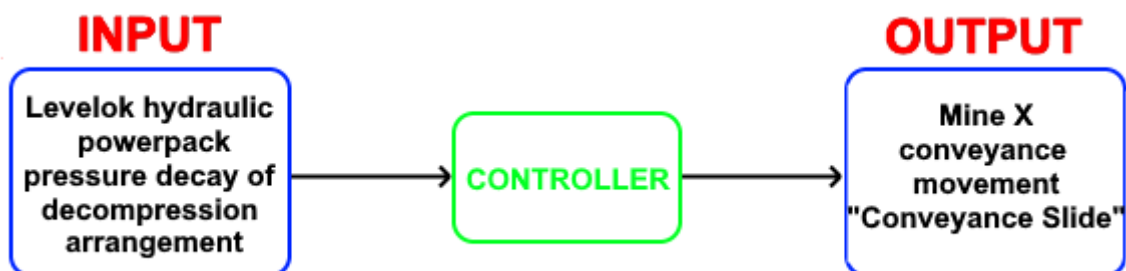


Figure 30: Modified block diagram illustrating the controller to manipulate the input values to obtain the desired output [50].

With a displacement of a mass as the output response, it was easier to implement this type of approach in a reverse manner. The reason for that is because of the more commonly known equations that can be used as a starting point of this characterization.

To calculate the displacement of a mass one can use one of the basic equations of motion, as represented in Equation 14:

$$\Delta X = V_i t - \frac{1}{2} a t^2 \quad (14)$$

Where $\Delta X = \text{Displacement [m]}$
 $V_i = \text{Initial velocity [m/s]}$
 $a = \text{Acceleration [m/s}^2\text{]}$
 $t = \text{Time [sec]}$

With the controlling entity being sampled with a specific frequency, the time steps for the calculations are automatically defined. The time step of a frequency of 50 Hz is calculated to be 0.02 sec. Thus, the equation of motion can be modified to obtain Equation 15:

$$X_f = X_i + V_i(t_f - t_i) - \frac{1}{2} a(t_f - t_i)^2 \quad (15)$$

Where $X_f = \text{Final displacement [m]}$
 $X_i = \text{Initial displacement [m]}$
 $V_i = \text{Initial velocity [m/s]}$
 $a = \text{Acceleration [m/s}^2\text{]}$
 $t_f = \text{Final time with a single time step increment [sec]}$
 $t_i = \text{Initial time [sec]}$

Before the Levelok hydraulic power pack's release sequence is initiated, a state of equilibrium can be considered. The conveyance is clamped with the Levelok system and is yet to move. Thus, the initial state of displacement at this moment in time is equal to 0. As the final displacement is calculated for each time step, it can be used as the new initial value to calculate the next increment of the displacement.

Considering Equation 15 there are two more variables involved to calculate the final displacement.

The initial velocity can also be calculated using one of the manipulated equations of motion, represented in Equation 16:

$$V_f = V_i + a(t_f - t_i) \quad (16)$$

Where

V_f = Final velocity [m/s]
 V_i = Initial velocity [m/s]
 a = Acceleration [m/s²]
 t_f = Final time with a single time step increment [sec]
 t_i = Initial time [sec]

The same assumption boundary condition that was considered for the calculation of the new final displacement for each time step can be considered for the calculation of the final velocity. The initial state of the velocity of the conveyance is 0 m/s. For every new time step calculation, the previous final velocity value can be used as the new initial velocity, for the calculation of both the new final velocity and displacement.

The acceleration of the conveyance is thus the only variable still outstanding for the calculation of both the final velocity and final displacement. To understand how the conveyance will accelerate after release, the dynamic behaviour of the system needs to be understood.

From Chapters 2 & 3, it is stated that the conveyance will start to “slide” as soon as the pressure decay in the Levelok hydraulic power pack has reached the value that is less than the calculated slip pressure. At this point, the conveyance (“mass”) will accelerate up (negative acc.) or down (positive acc.) depending on whether a payload was unloaded from, or loaded into the conveyance respectively.

With this information the boundary conditions can be set for the initial state of acceleration:

$$a_i = 0$$

because the conveyance has not yet started to move and the boundary conditions at the point of slip:

If Measured press. (P_m) < Slip press.

Then conveyance start to slide,

Else $a = 0$

Newton's second law of motion can be used to derive the equation for the calculation of the acceleration of the conveyance. This equation can then be used to complete the ***Then*** condition of the stipulated ***If***-statement boundary condition. Hence Equation 17:

$$\sum F_R = ma \quad (17)$$

Where F_R = Forces acting on conveyance displacement [N]
 m = Mass (Conveyance own mass & Payload) [kg]
 a = Acceleration [m/s^2]

Three forces are acting on the conveyance, which will affect the displacement and acceleration of the conveyance at each time step. These forces include the payload weight, the dynamic friction force caused due to the clamp shoes still pressing against the shaft guides at a certain pressure, and the winding rope resistance that will fluctuate due to the change of the end of rope mass.

With the sum of these forces, together with the manipulation thereof, the equation of the acceleration of the conveyance's displacement can be formulated, give Equation 18:

$$\sum F_R = ma \quad (17)$$

$$a = \frac{(m_p \times g) - F_{dynamic\ friction} - (X_i \times S_c)}{(m_p + m_c)} \quad (18)$$

Where a = Acceleration [m/s^2]
 m_p = Payload [kg]
 g = Gravitational acceleration [m/s^2]
 $F_{dynamic\ friction}$ = Dynamic friction Force [N]
 X_i = Initial displacement [m]
 S_c = Winding rope spring constant [N/m]
 m_c = Conveyance own mass [kg]

With these formulated equations for the displacement, velocity, and acceleration of the conveyance after the releasing sequence is initiated, the block diagram in Figure 31 [50] can be constructed and is an adjustment of the block diagram in Figure 30 [50], to define the "Controller" better.

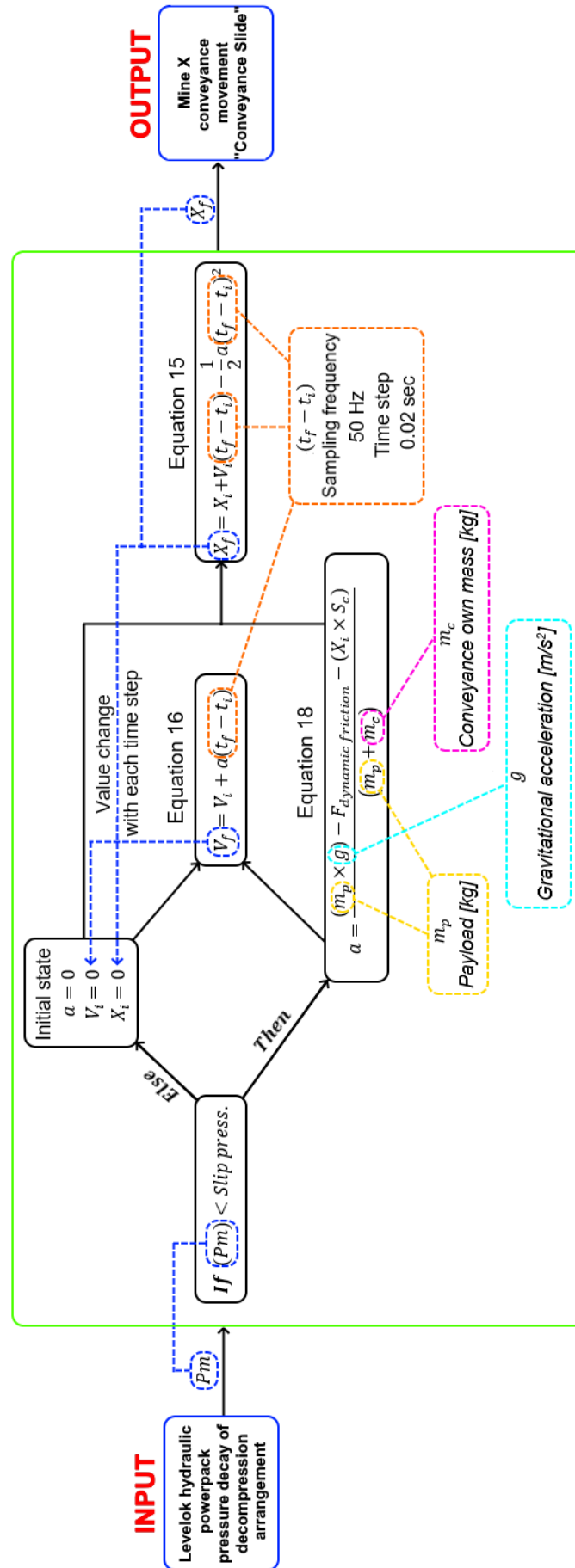


Figure 31: Block diagram defining a partial part of the "Controller" [50].

The block diagram in Figure 31 [50] illustrates the basic procedure to follow to determine the predicted conveyance displacement from the measured pressure data of the Levelok Hydraulic power pack's decompression cycle. This is done by utilizing basic equations of motion, Newton's 2nd law of motion, and force pressure relationships. There are still some variables that are not yet defined and need to be addressed to build on the basic work-frame.

The first of these variables form part of the **If**-statement. To complete this **If**-statement the calculation of the slip pressure is needed to compare it to the measured pressure. As mentioned, the slip pressure is the hydraulic pressure value where the conveyance starts to move when the Levelok system is released.

This displacement is caused by the loading or unloading of a payload weight. This payload weight is assumed to be evenly distributed between the number of clamps (n_c) installed in the system. The slip pressure is directly proportional to the payload weight and the payload weight is directly proportional to the friction force at the clamp shoes [3]. It is also important to note that the friction force and payload force are equal at the point of slip, as it is at this point where the conveyance is about to slide.

From the free body diagram in Figure 32 [50] [52], the friction force equation, Equation 19, can be formulated.

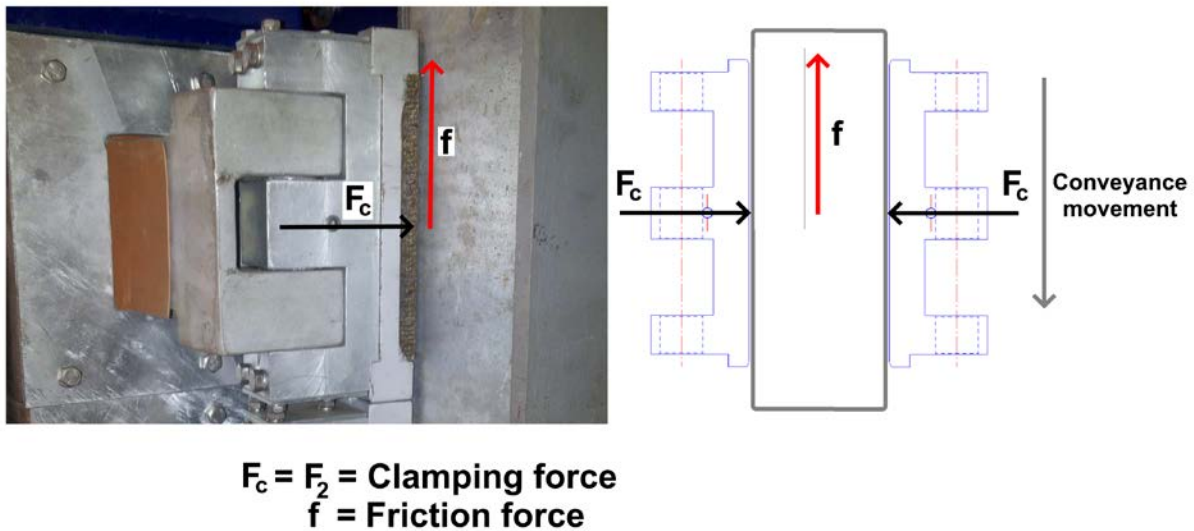


Figure 32: Friction & clamping forces free body diagram of Levelok clamp shoes clamping on a shaft guide [50] [52].

$$f = \mu_s \times 2 \times F_2 \quad (19)$$

Where f = Friction force of shoe on guide [N]
 μ_s = Static friction coefficient [Unitless]
 F_2 = Clamping force [N]

In Section 3.2, the free-body forces diagram in Figure 26 [50] [52] was used to define the clamping force, F_2 , of a Levelok hydraulic clamp. The formulation of the cylinder pressure force, F_1 , was also derived from basic pressure-forces relationships. With this information being substituted into the friction force equation, together with the before mentioned friction forces being equal to the payload forces at the point of slip, the equation defining the slip pressure can be obtained, as illustrated in the formulation of Equation 8:

$$F_2 = \frac{f}{2 \times \mu_s} \quad (19)$$

$$F_2 = F_1 \frac{\Delta X_2}{\Delta X_1} \quad (11)$$

$$F_1 = \pi \times \left(\frac{\phi_p}{2}\right)^2 \times P_s \quad (10)$$

$$f = \frac{(m_p \times g)}{n_c} \quad (19a)$$

$$\text{Slip press.} = \frac{m_p \times g}{\mu_s \times \Delta X_2 / \Delta X_1 \times n_c \times \left(\frac{\phi_p}{2}\right)^2 \times \pi \times 2 \times 10^5} \quad (8)$$

Where *Slip press.* = Measured in Bar. (hence the " $\times 10^5$ " in the equation)

m_p = Payload mass [kg]

g = Gravitational acceleration [m/s^2]

μ_s = Coefficient of static friction [unitless]

ΔX_1 = Moment lever arm from bearing to shoe on guide [m]

ΔX_2 = Moment lever arm from bearing to hydraulic cylinder [m]

n_c = Number of clamps [unitless]

ϕ_p = Piston diameter [m]

This equation is also used in Section 3.2, to calculate the point of slip at full payload.

All variables to calculate the hydraulic pressure at the point of slip for different payloads are known from WJ Engineering's general arrangement drawings & notes of the different components of the system and conveyances. The static and kinetic coefficients of friction however were unknown, and needed to be obtained from experiments conducted at one of the testing dock setups at WJ Engineering.

The full report describing the test procedures conducted and the results that were found is included in Annexure G [48]. These results on the different static and kinetic coefficients of friction for the different types of Levelok clamp friction shoe inserts are listed in Table 8 [48] [58]:

Table 8: Levelok friction shoe inserts static & dynamic coefficients of friction values [48] [58].

Friction shoe insert	Coefficients of friction	
	Static, μ_s	Dynamic, μ_k
Flat faced Hardox	0.25	0.23
Industrial lining Hardox	0.25	0.23
Industrial lining mild steel	0.27	0.25
Industrial lining ZA Gold	0.45	0.42
Industrial lining D9010	0.38	0.35

The coefficient of friction values of the mild steel friction shoe inserts, represented in Table 8 [48], are similar to the values found by Du Preez and Laubscher (2008), in their completed experimental test report, "*Friction coefficient confirmation test report*" [59].

The experiments reported in [59], were somewhat different from the heavyweight sliding tests conducted at WJ Engineering [48]. A hydraulic press was used to move a steel guide section that was clamped by a Levelok cage clamp. With a load cell, the force was measured which was required to move the steel guide. From these measurements, the friction coefficients were calculated using basic friction force relations.

With the defined coefficient of friction values, the equation for the dynamic friction force, in Equation 12, can also be formulated and the dynamic friction force calculated. The dynamic friction force can be defined as the friction force of the Levelok clamp friction shoe inserts still pressing against the shaft guides at a certain pressure after the conveyance is released. Thus, the dynamic friction force influences the acceleration of the conveyance as it slides into its new position in the shaft.

Similar steps can be followed as that of the methodology followed to formulate the slip pressure equation. Thus, the Dynamic friction force can be defined in Equation 20:

$$F_{dynamic\ friction} = \mu_k \times \frac{\Delta X_2}{\Delta X_1} \times n_c \times \left(\frac{\phi_p}{2}\right)^2 \times \pi \times 2 \times 10^5 \times P_m \quad (20)$$

Where $F_{dynamic\ friction}$ = Dynamic friction force [N]

P_m = Measured pressure values [Bar]

μ_k = Coefficient of kinetic friction [unitless]

ΔX_1 = Moment lever arm from bearing to shoe on guide [m]

ΔX_2 = Moment lever arm from bearing to hydraulic cylinder [m]

n_c = Number of clamps [unitless]

ϕ_p = Piston diameter [m]

The dynamic friction force is always implemented in the opposite direction of the conveyance displacement, as illustrated in Figure 32 [50] [52]. The dynamic friction force is a kinetic friction force, thus the assumption can be made that the dynamic friction force is equal to zero when the conveyance mass is stationary.

From these assumptions, the boundary conditions of the dynamic friction force can be defined with an **If**-statement as follow:

If Conveyance velocity $V_i < 0$

Then the Conveyance move upwards, thus " $-F_{dynamic\ friction}$ "

Else the Conveyance move downwards, thus " $+F_{dynamic\ friction}$ "

The other force that also can be seen as a friction force, that also influences the conveyance's acceleration, is the winding rope resistance force, $F_{rope\ resistance}$, defined in the formulation of Equation 12. From this equation formulation, the winding rope resistance force was defined as the product of the conveyance mass displacement, X_i , and the winding rope spring constant, S_c (assuming that there is no movement or change to the winding drum state while unclamping).

To formulate the wind rope spring constant equation, Equation 22, the rope stretch equation (Equation 1, Chapter 2 [29]) can be used together with Hooke's law (Equation 21). Consider a constant rope end mass carried with two winding ropes each with their own conveyance rope attachment:

$$F_s = S_c \times \Delta L \quad (21)$$

$$S_c = \frac{F_s}{\Delta L}$$

Where $F_s = \text{Spring force [N]}$
 $S_c = \text{Winding rope spring constant [N/m]}$
 $\Delta L = \text{Elongation (Rope Stretch) [m]}$

$$\Delta L = \frac{F \times L}{A \times E} \quad (1)$$

$$\therefore S_c = \frac{F_s}{\frac{F \times L}{A \times E}}$$

$$F_s = \frac{F}{2}$$

(The spring force is equal to half the tension in the winding rope due to a constant rope end mass carried by a double winding rope system)

$$\therefore S_c = \frac{2 \times A \times E}{L} \quad (22)$$

Where $S_c = \text{Winding rope spring constant [N/m]}$
 $A = \text{Metallic area of rope [m}^2\text{]}$
 $E = \text{Apparent modulus of elasticity of rope [Pa]}$
 $L = \text{Length of rope under load [m]}$

With the experiments conducted to define the values of the coefficients of friction and the formulation of the equations defining the friction forces that influence the acceleration of the conveyance mass after the slip pressure point, the block diagram in Figure 31 [50] can be revised.

The block diagram illustrated in Figure 33 [50], is the representation of the completed controller definition, transforming the measured high-pressure hydraulic pressure from a Levelok hydraulic power pack decompression cycle, into the prediction of a specific conveyance's displacement in a specific vertical mine shaft. This block diagram can be used as a methodology framework to construct a mathematical prediction model using, a PLC Matlab, GNU Octave [60], or any other analytical software package. For the scope of this dissertation, the framework will be used to construct a mathematical model in Excel.

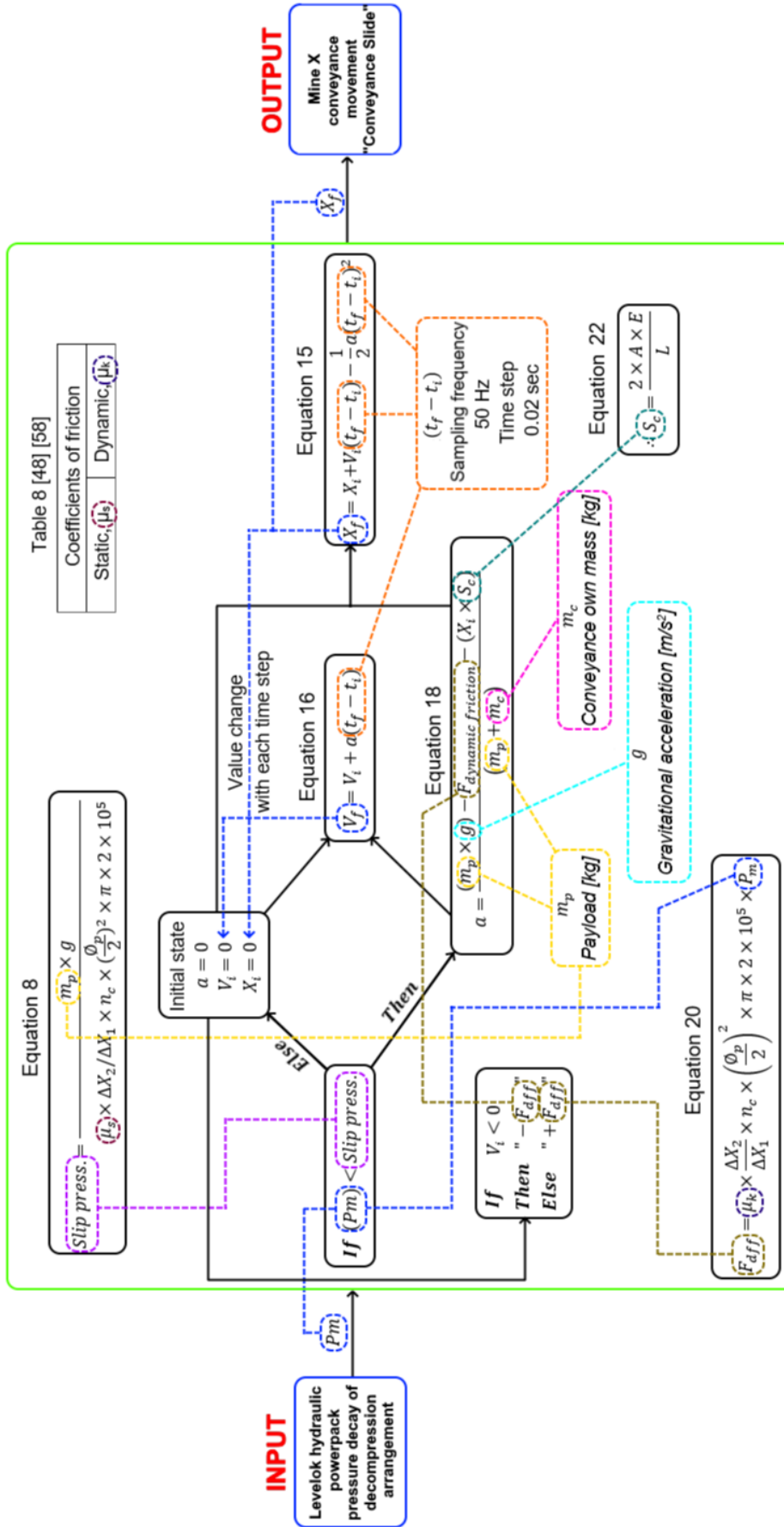


Figure 33: Revised Block diagram defining the complete "Controller", linking the measured pressure values to the conveyance's predicted displacement [50].

4.3 Testing equipment & workbenches

Using the block diagram in Figure 33 [50], to construct a mathematical model for the prediction of a conveyance's displacement after its Levelok arresting system is released, hydraulic pressure testing equipment is needed. This pressure equipment is needed to record the pressures in the high-pressure hydraulic line of any Levelok hydraulic power pack. Each Levelok power pack is equipped with a "Minitest" hydraulic testing point, as illustrated in Figure 34 [4].

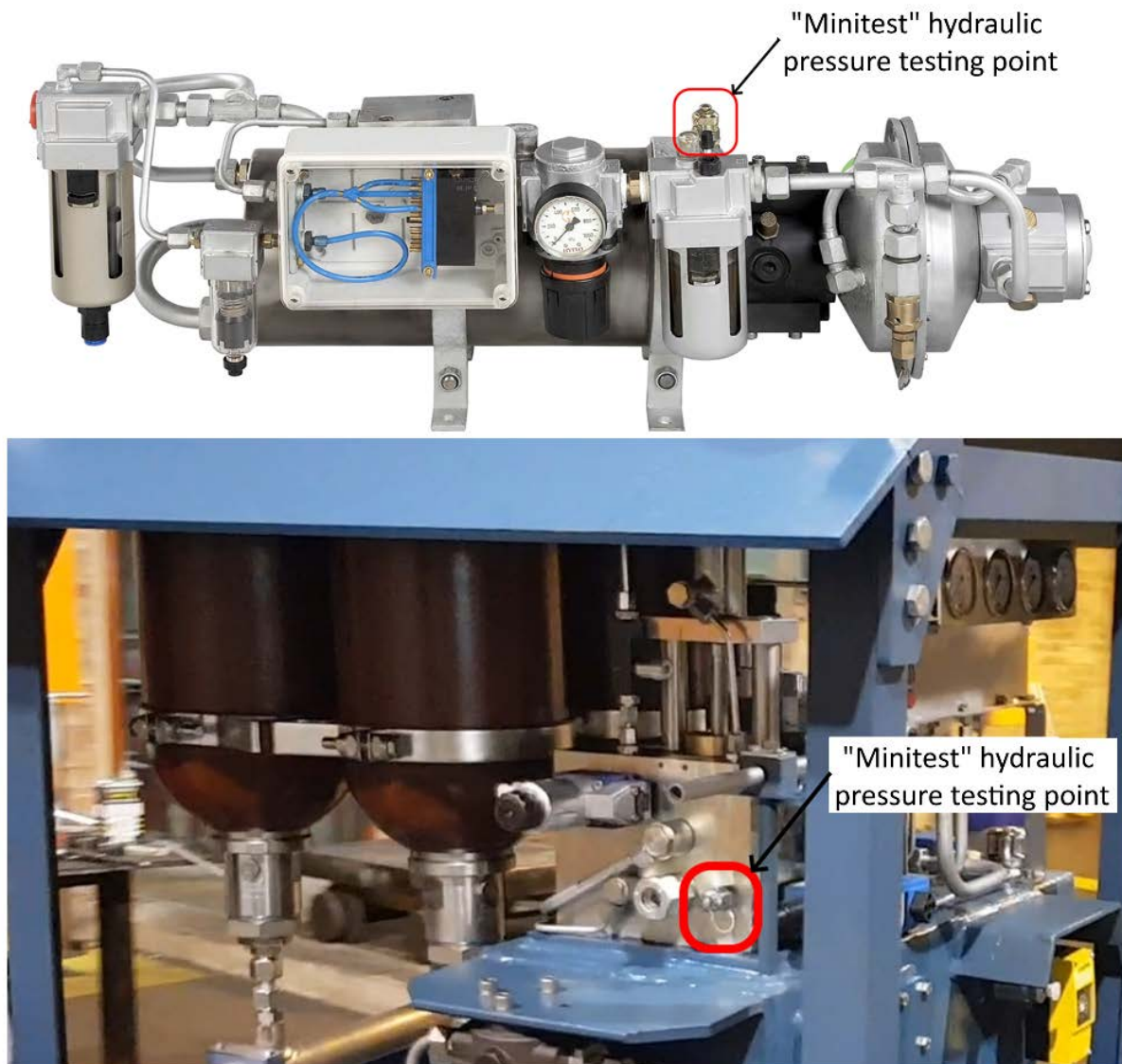


Figure 34: "Minitest" hydraulic testing points locations on different Levelok hydraulic power packs illustration [4].

Each Levelok clamp is also fitted with a “Minitest” hydraulic testing point, located at the back of the clamp, situated on the Clamplock valve unit. Figure 35 [4] illustrates this “Minitest” testing point location. This testing point is placed here, to enable the ability to measure the hydraulic pressure at each clamp separately.

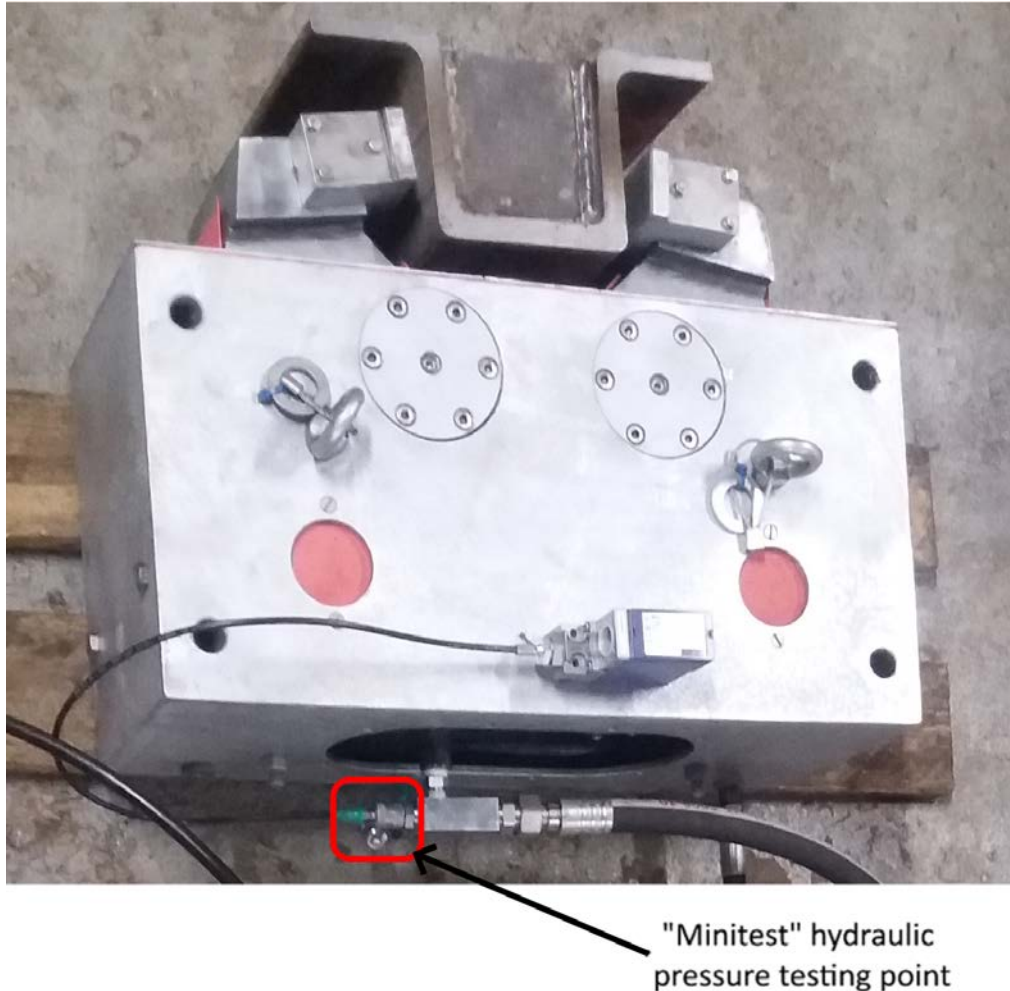


Figure 35: “Minitest” hydraulic testing points location illustration, connected to the Clamplock valve unit of a Levelok hydraulic clamp [4].

The high-pressure pressure decay of the decompression cycle can be data logged by pressure testing equipment that is connected to these “Minitest” hydraulic testing points. In Annexure G the eDaq [53], with required accessories, was used to fulfill this purpose. For the data logging of the input pressure data for the mathematical prediction model, the author decided to use the Ahlborn Almemo precision measuring instrument with a data logger function [61].

The reason why the Ahlborn Almemo precision measuring instrument [61] was chosen, is because it is a lightweight handheld unit that is easy to use, multiple tests can be completed in a very short time and setup does not take more than a minute. A 450 Bar maximum pressure rated pressure sensor is supplied with the data logger and is of sufficient range for the tests to be completed.

For the purposes of this dissertation and the mathematical model, the information of the datalogger that was needed was the recording frequency and the pressure recording range and accuracy. The recording rate of the pressure data was set to 50 Hz. The maximum burst pressure of the pressure sensor is 600 Bar. Pressure values within the operating range of the sensor, which is 0 – 400 Bar, are recorded with a maximum error of 0.1% [61]. Based on the system design specifications described earlier, the highest expected pressure to be recorded is 250 Bar, which is much lower than the 450 Bar rated maximum of the instrument.

The workbench, to complete the required tests on the Levelok power packs, was selected to be similar to that of the Levelok systems installed on the Mine X conveyances. The workbench illustrated in Figure 36 [4] is equipped with the same 4.5 Ton Levelok cage clamps as specified in Chapter 3. Multiple Levelok cage power packs were successfully tested previously by WJ Engineering employees using this test bench, confirming its suitability.

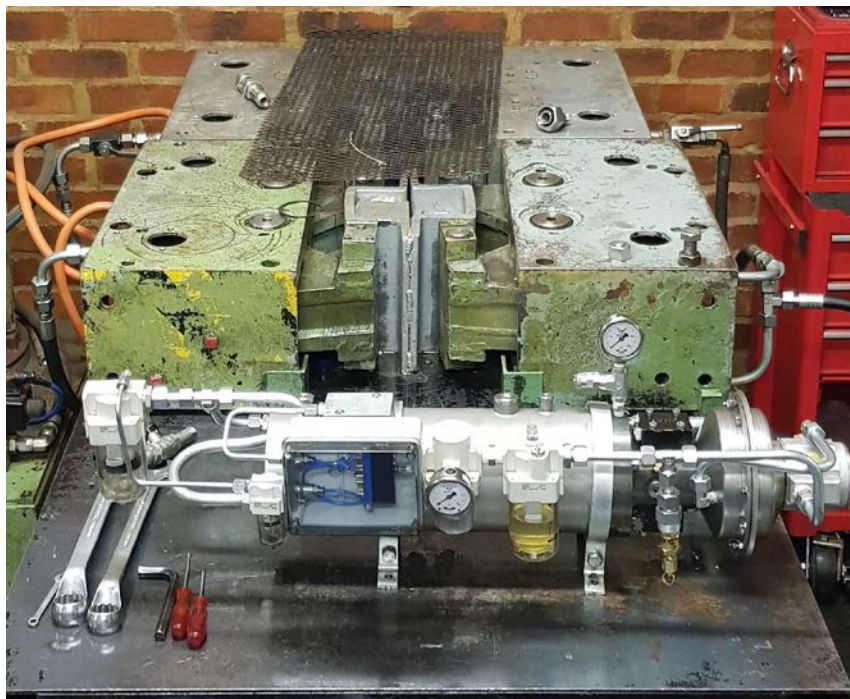


Figure 36: Levelok cage power pack testing workbench [4].

Multiple test runs were completed using the experimental setup illustrated in Figure 37 [50], and are described in Chapter 5.

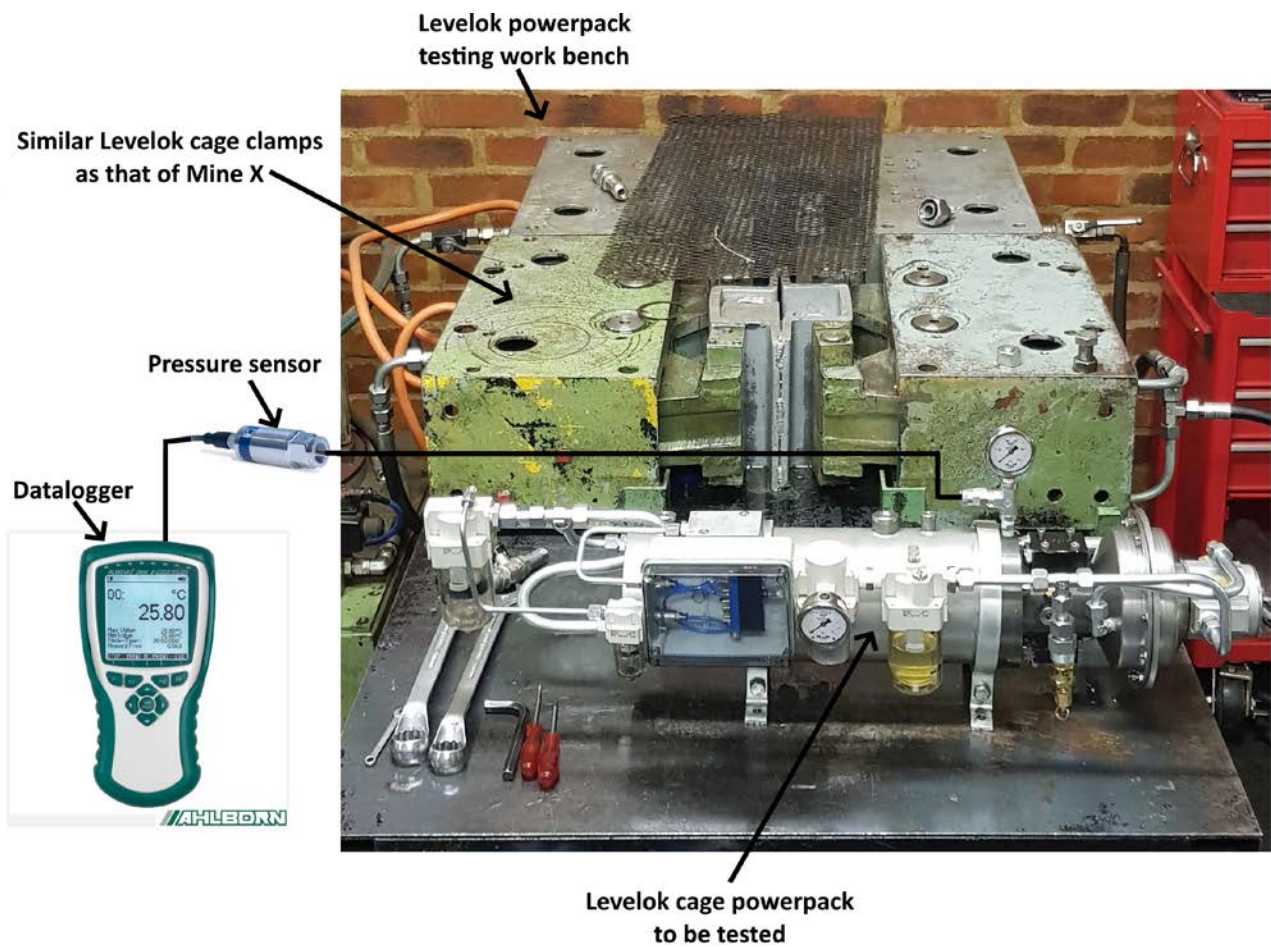


Figure 37: Experimental setup for the test of Levelok cage power packs [50].

4.4 Construction of the Levelok Power pack Decompression Cycle Conveyance Displacement Prediction and Assessment Mathematical Model using Microsoft Excel

As described in Section 4.2, Microsoft Excel was used to construct the mathematical model to predict the displacement of a conveyance released from a Levelok conveyance arresting system. The block diagram in Figure 33 [50] was used as the framework to construct an easy-to-use Excel program. An example of the test conducted with Levelok cage power pack serial number 219-09-18, using this Excel program is presented in Annexure H [62].

The mathematical prediction model developed and described in this chapter was completed using the design specifications of Mine X's Levelok systems and shaft characteristics, laid out in Chapter 3. The constant calculated variables are listed in Table 9, and its corresponding calculation sheet list is illustrated in Figure 38 [62]:

Table 9: Constant calculated variables of the mathematical model constructed for Mine X's Levelok systems [62].

Constant variables		
Static friction coefficient	0.27	
Dynamic friction coefficient	0.25	
Distance to piston	0.18	m
Distance to shoes	0.154	m
Piston diameter	0.1	m
Nr. of clamps	4	
Rope spring constant	59394.70	N/m
Payload	8000	kg
Cage own mass	13500	kg
Rope length	2986	m
Rope metallic area	8.061E-04	m ²
Elastic constant	1.10E+11	Pa
Rope stretch under payload	1.320	m
Rope spring constant check	59394.70	N/m
Slip pressure	39.52	Bar
Static friction force	39200.00	N/m

	A	B	C
1	Constant variables		
2	Static friction coefficient	0.27	
3	Dynamic friction coefficient	0.25	
4	Distance to piston	0.18	m
5	Distance to shoes	0.154	m
6	Piston diameter	0.1	m
7	Nr. of clamps	4	
8	Rope spring constant	$= (2 * B12 * B13) / (B11)$	N/m
9	Payload	8000	kg
10	Cage own mass	13500	kg
11	Rope length	2986	m
12	Rope metallic area	$= 0.457 * (0.042)^2$	m ²
13	Elastic constant	110000000000	Pa
14	Rope stretch under payload	$= (B9 / 2 * 9.8 * B11) / B12 / B13$	m
15	Rope spring constant check	$= + B9 * 9.8 / B14$	N/m
16	Slip pressure	$= + B9 * 9.8 / (B\$2 * B\$4 / B\$5 * B\$7 * 2 * 10^5 * (B\$6 / 2)^2 * 22 / 7)$	Bar
17	Static friction force	$= + B9 / 2 * 9.8$	N/m

Figure 38: Table 9 corresponding calculation sheet constructed in Microsoft Excel [62].

With the defined boundary conditions and calculation equations defined in the block diagram in Figure 33 [50], the running variables could be built into the Excel program [62].

CHAPTER 5

WORKSHOP AND AUDIT TESTS ON MK4 - MK5 LEVELOK SYSTEMS

5.1 The goal of conducted tests

The author facilitated numerous Levelok system audits on the Levelok cage systems installed at Mine X, as mentioned in Chapter 3. The result of these conducted audits was the identification of the main Levelok system shortcoming. During the clamp release of the Levelok cage systems, the conveyances would slide rapidly in the shaft and the change in rope end forces were not transferred gradually to the hoisting winding rope, causing the “yo-yo” effect of the conveyance’s displacement.

This phenomenon not only occurred with these MK5 Levelok cage systems of the Mine X shaft, but was also documented during audits on MK4 Levelok cage systems, and multiple different Levelok skip systems. It was also found that some of these systems would control the slide perfectly, but after repeated tests, the control output results of the perfect conveyance slide were not constant.

The supposition that was made from these findings, was that these different Levelok systems had certain components and technical liability similarities that needed to be addressed. If the problem was to be understood and solved with the MK5 systems installed at Mine X, the methodology followed could be adopted in all Levelok systems, to assure proper function.

In the course of this dissertation to understand the problem of the Levelok systems not releasing according to specification, numerous tests were conducted. These tests were conducted with viscosity ISO 32 [34] [37] hydraulic fluid and included the tests completed on-site during audits, and tests completed using the experimental setup as set out in Section 4.3, in Figure 37 [50]. All tests were done using the Levelok hydraulic power pack decompression testing procedure [6], as documented in Annexure F.

The recorded results were also analysed using the mathematical conveyance displacement prediction model to see how the different decompression graphs affect the conveyance displacement in the shaft during operation. The verification and validation of this mathematical model are addressed in Chapter 9 and are used in this chapter as a tool to better understand the controlling unit of the Levelok systems.

The results that were found during these different conducted tests are documented in this chapter and are discussed. These findings were then considered during the decompression cycle analysis & redesign.

5.2 Levelok power pack serial numbers

The Levelok power pack serial number is the unique identification number dedicated to each Levelok power pack manufactured and supplied to the different Levelok operational mines. These serial numbers are used to keep track of the history of the power pack, for assistance to the maintenance team during repairs. A section, that forms part of this recorded history, is all the tests conducted on the specific power pack.

In this dissertation, this serial numbering system was adopted for all tests conducted. This was done to assist with the identification of the power packs tested and to coincide with the logged history stored in WJ Engineering's file system.

The structure of a Levelok power pack serial number is defined in Figure 39 [63]. Serial number: 219-09-18 is used as an example.

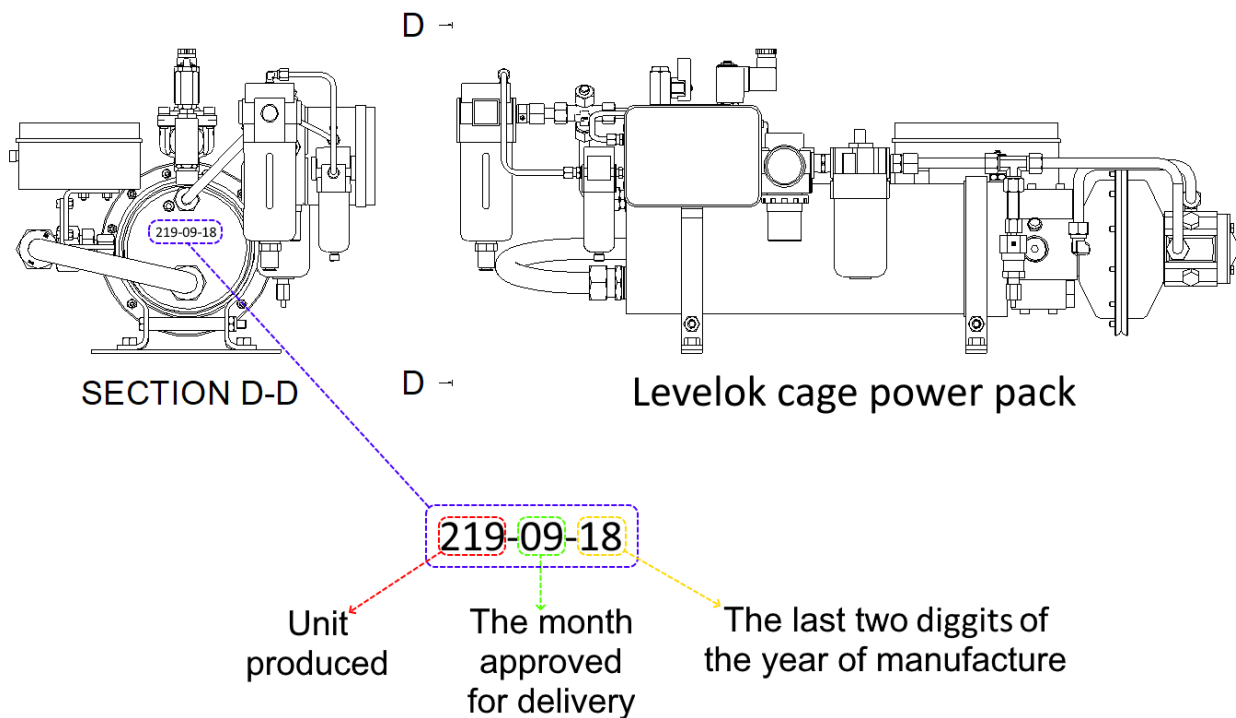


Figure 39: Levelok power pack serial number creation illustration [63].

5.3 MK4 & MK5 Levelok systems' differences and similarities

The results obtained from the multiple MK4 & MK5 Levelok systems' audit tests, presented some differences between the analysed decompression curves. To illustrate these differences, the decompression curve of the MK5 Levelok cage power pack (SN: 198-05-12) was plotted on the same graph as that of the decompression curve of the MK4 Levelok cage power pack (SN:174-12-97). This comparison is illustrated in Figure 40:

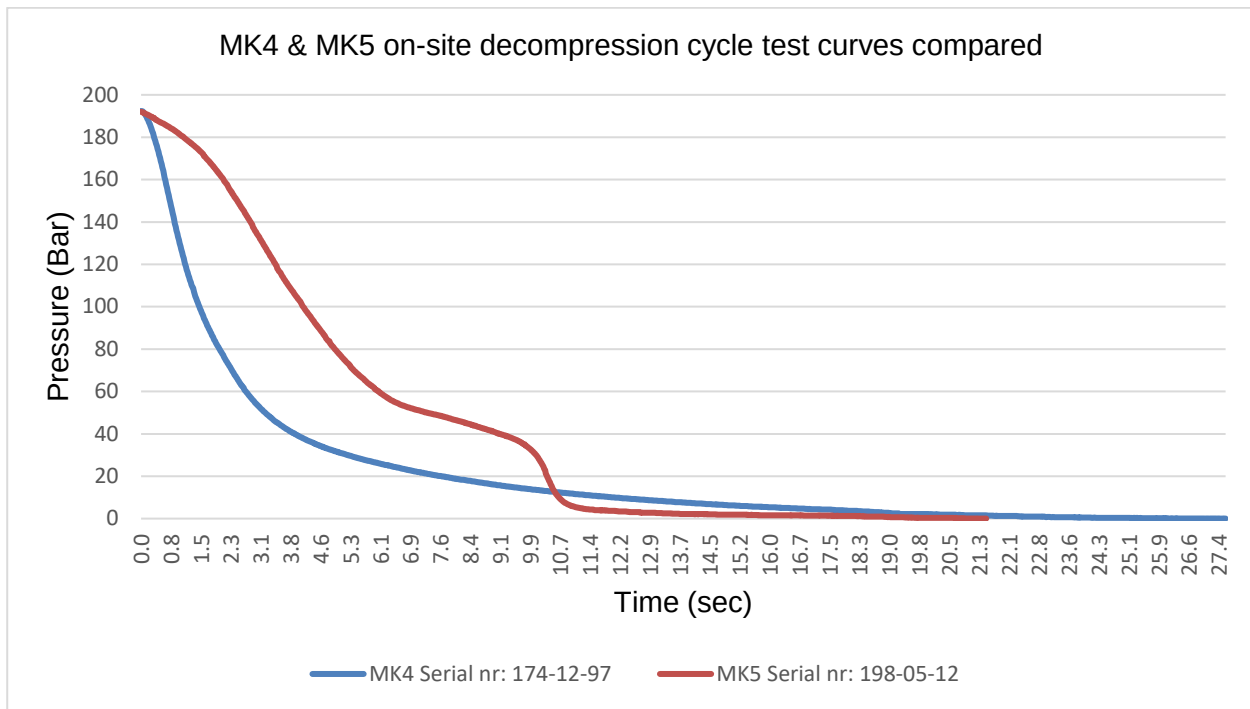


Figure 40: MK4 & MK5 on-site decompression cycle test curves compared.

This representation in Figure 40, the blue curve of the MK4 system is closer to the desired control output, as illustrated in Figure 19 (Section 2.3.3). The red curve of the MK5 system was quite unexpected. This result was surprising because of fact that, as discussed in Chapter 2, the controlling unit of the decompression curve is the decompression arrangement, and the decompression arrangements fitted to these two Levelok power packs were precisely identical.

The only difference between the designs of the MK4 & MK5 Levelok cage systems was the control philosophy. Together, with this design difference, there are certain electrical & pneumatic components added to the MK5 system. To investigate if these different components' operations affected the control output decompression curves, more inhouse tests were conducted on the MK5 Levelok cage power pack (SN: 198-05-12).

The red curve in Figure 41 represents the same on-site audit test as the red curve in Figure 40. The purple decompression curve illustrates the results of the workshop tests, with the same MK5 Levelok cage power pack (SN: 198-05-12) conducted on the workbench illustrated in the experimental setup of Figure 37 [50].

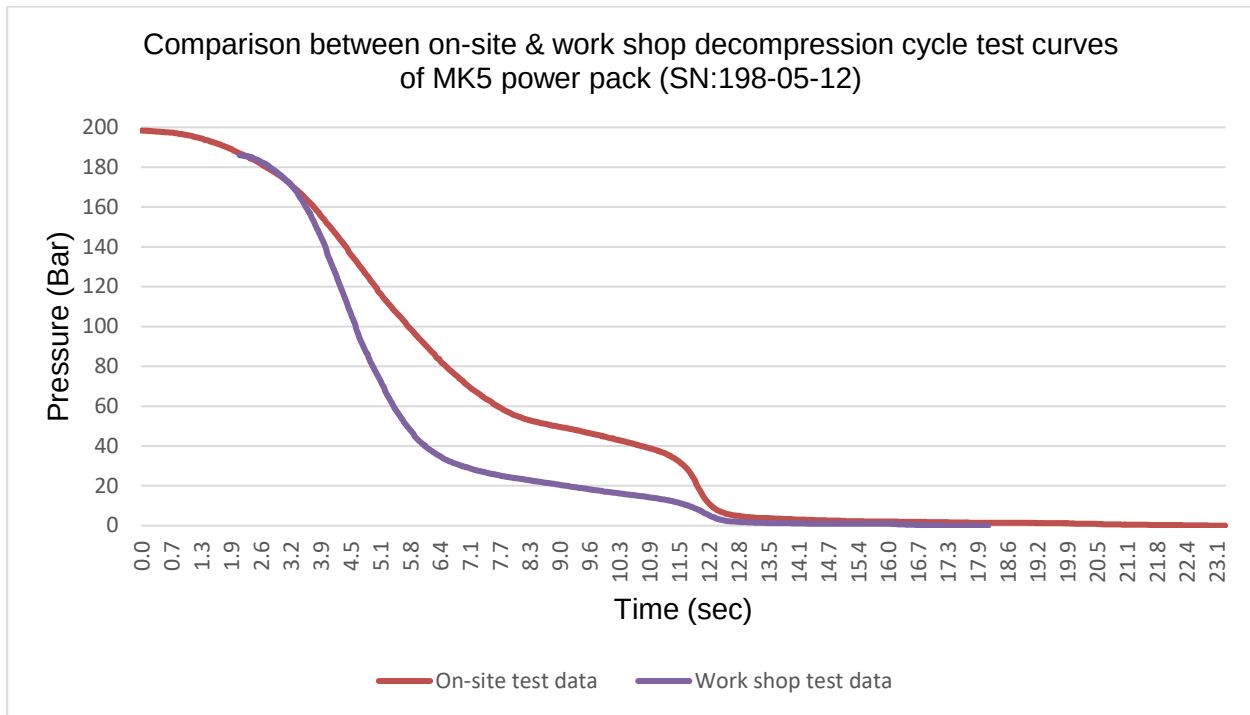


Figure 41: Comparison between on-site & workshop decompression cycle test curves of MK5 power pack (SN:198-05-12).

The only difference in experimental setup between the on-site audit & workshop decompression cycle tests on the MK5 Levelok cage power pack (SN: 198-05-12), was the pneumatic accumulator used on the cage system, during audit tests, to assure the clamps open fully.

With further tests, it was confirmed that the pneumatic accumulator was the cause of the difference between the decompression curves in Figure 41. The control philosophy of the MK5 system caused the solenoid valve of the pneumatic accumulator to open during the decompression cycle, causing a back pressure at the four Levelok clamps. This was solved easily by changing the control philosophy sequence and timing.

The other entity that was measured during these tests was the temperature of the hydraulic fluid. The findings showed that it had a small effect on the decompression cycle as well, but small enough to be found negligible.

Plotting these 3 curves (in their respective colours) that were discussed, on the same graph, showed what positive difference the adjustment to the MK5 system's control philosophy would have on the system's decompression cycle curve. Although the change would improve the decompression cycle, the green circle in Figure 42 also illustrates that in the first 3 seconds there was still an undesirable interference caused by another component of the MK5 system.

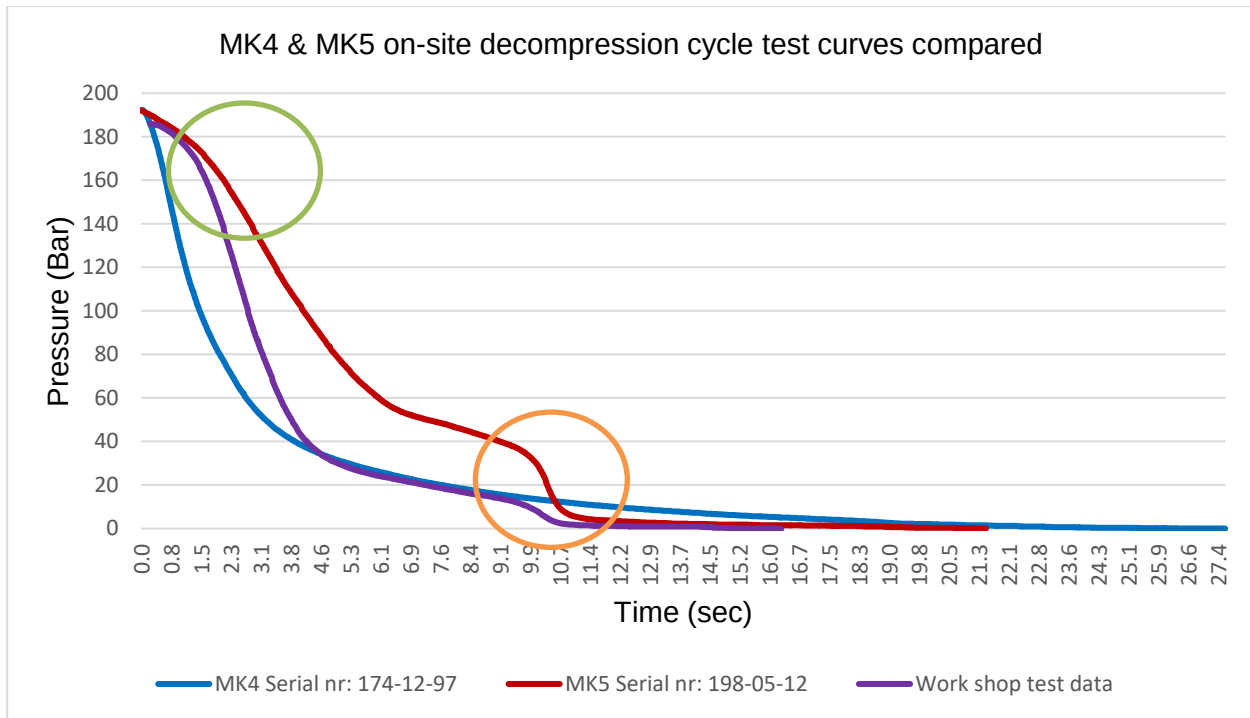


Figure 42: Comparison between on-site & workshop decompression cycle test curves of MK5 power pack (SN:198-05-12) & onsite audit tests of MK4 Levelok cage power pack (SN:174-12-97).

Referring to the information in Section 2.3.3, the decompression arrangement allows the high-pressure hydraulic fluid in the system to decay rapidly for the first few seconds of the decompression cycle. This feature is allowed, in order to make for speedier operations. With the safety factor for main clamping pressure to slip pressure being 2.36, calculations done in Annexure E [43], the main clamping pressure is 136% higher than the slip pressure. For the conveyance to start moving slip pressure must be reached. Thus, the faster decay in hydraulic fluid pressure, to get from main clamping pressure to slip pressure in the system, can reduce the operational shaft time.

From the illustrated red and purple curves in Figure 42, it was clear that the fast decay of hydraulic pressure was delayed. In fact, the blue curve of the MK4 Levelok power pack reached slip pressure, 89 Bar (Annexure E [43]), approximately 1.5 seconds faster than that of the best curve of the MK5 Levelok power pack.

The 1.5 sec that it takes longer for the MK5 decompression curve to reach slip pressure does not seem to be a lot, but this was the cause of the most interesting part of the results found. When the decompression curve values of the MK4 system on-site tests and the MK5 system workshop tests were simulated in the constructed mathematical conveyance displacement prediction model of Chapter 4, the real operational shaft time lost became clear.

The conveyance displacement simulations of the two different decompression datasets were plotted in the graph in Figure 43, for visualization purposes (Note: The maximum payload of 18 Ton on Mine X's conveyances was used for these predictions):

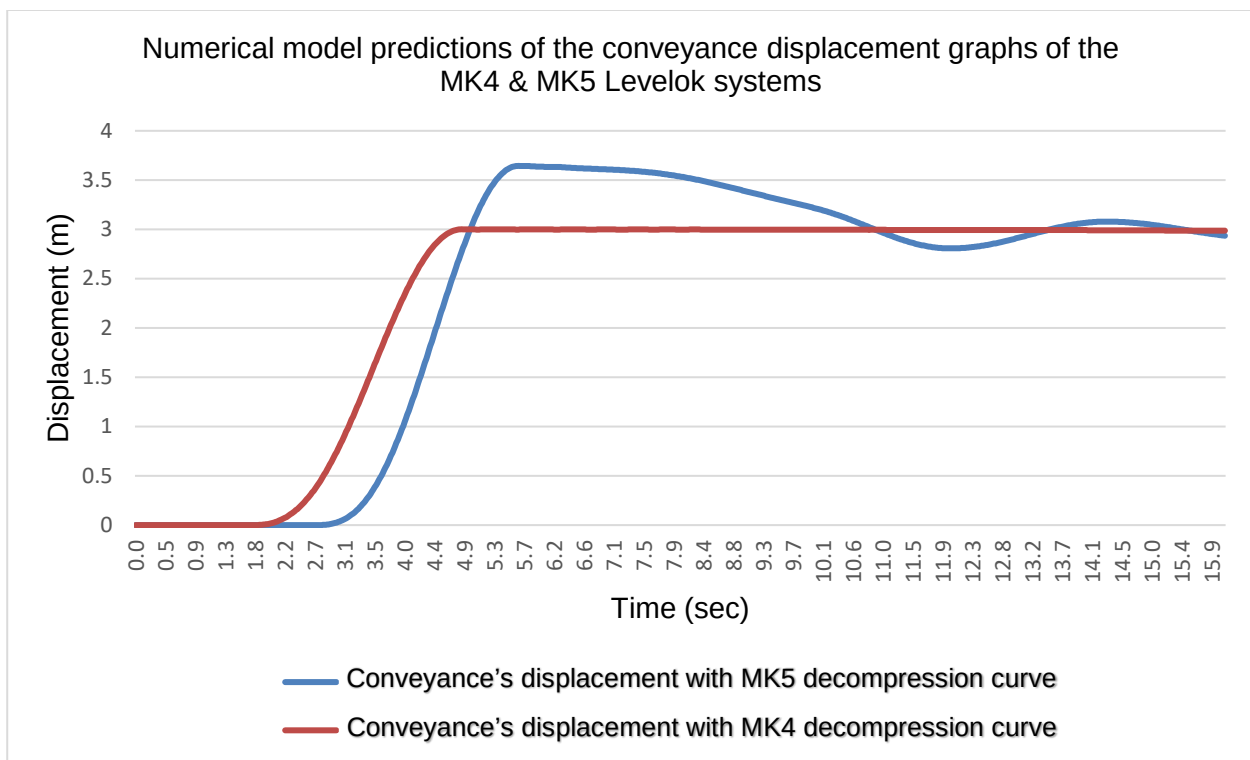


Figure 43: Numerical model predictions of the conveyance displacement graphs of the MK4 & MK5 Levelok systems

The simulated results of the MK4 decompression curve values showed that the conveyance would slide, take up the hoisting wire rope stretch gradually and come to a complete standstill in 2.88 seconds (as measured from the time of release).

In the case of the simulated results of the MK5 decompression curve values, the conveyance displacement was not nearly as stable. In fact, due to the quicker release of the conveyance, it accelerates faster causing it would overshoot the calculated 2.97 m rope stretch value and would take more than 16 seconds to stabilize before it can be hoisted away.

Following further investigative testing on the MK5 Levelok cage power pack (SN: 198-05-12), it was found that the component in question, causing the delay in the required fast pressure decline, was in fact the pneumatic assisted 12V solenoid valve. An example of this component and where it is located on the hydraulic power pack is illustrated in Figure 44 [63].

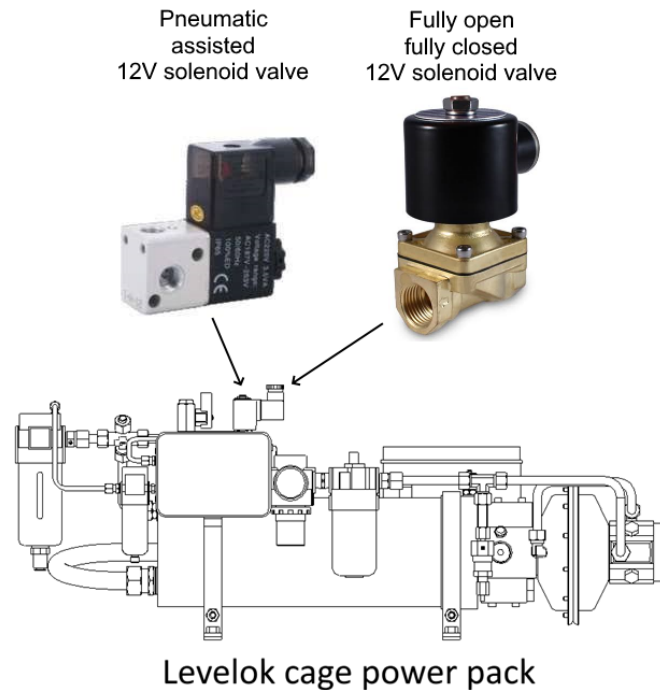


Figure 44: Illustration of the 2 different 12V solenoid valves used on an MK5 Levelok cage power pack [63].

As explained in Section 2.3.1, the pneumatic solenoid valve is actuated to release the pneumatic pressure in the power pack, to allow the decompression arrangement to release the clamping system. It was realized that the MK5 Levelok system was modified to use a pneumatic assisted solenoid valve, since the 12V solenoid was not strong enough to open the pneumatic valve on its own, it needed the assistance of the pneumatic pressure in the power pack to open the valve fully. The new valve thus caused an unforeseen resistance against the pneumatic flow release, during the decompression cycle.

It was also discovered that as the pneumatic pressure in the power pack dropped lower, the pneumatic assistance reduced as well, and thus the pneumatic valve would close more slowly, attaining more resistance against the pneumatic flow release. This was the reason for the uncharacteristic “bump” in the decompression curve, as indicated with the orange circle in Figure 42. The pneumatic accumulator served to further amplify this effect.

In some cases, due to this phenomenon, an excess of pneumatic pressure would still be trapped in the Levelok power pack, and cause the system to not release fully. The maximum hydraulic fluid pressure that was measured in the system, during audit tests at Mine X, due to this excess pneumatic pressure, was found to be 2 Bar.

With the use of the clamping force equation in Section 3.2, the clamping force, due to the 2 Bar hydraulic pressure still trapped in the system, could be calculated to be 1.835 kN per clamp. The total clamp force for Mine X's 4 clamp system equals to 7.34 kN, with a calculated holding capability of 1.98 Tons. This can be the cause of an extremely dangerous situation because with four clamps still clamping onto the shaft guides, with a 2 Ton holding capacity, it can cause a lot of damage to the shaft steelwork if the conveyance would be hoisted away.

With the exchange of the pneumatic assisted valve with the fully-open-fully-closed 12 V solenoid valve, as illustrated in Figure 44, this problem, with the consequences thereof, was addressed and solved, with the decompression curve rectified. This component behaviour would also be addressed in the control philosophy design of the new MK7 Levelok systems in Chapter 7.

5.4 Decompression cycle throttle check valve functional tests

The decompression arrangement of the MK4 & MK5 Levelok cage power packs is identical, as previously mentioned. This arrangement, with its different components and the functionality thereof, is explained in Section 2.3.1.1. The components in this complex assembly have their specific specifications and tolerances defined, to ensure that the desired decompression cycle output is achieved. These properties of these components are all fixed values, ordered from a supplier or machined in the machining workshop according to an approved for construction certified drawing. Thus, these part properties cannot be adjusted or altered after the decompression arrangement is assembled and installed to a Levelok power pack, except for one variable component.

The throttle check valve, shown in Figure 45, is used to control the hydraulic fluid volume flow in one direction while allowing for free hydraulic fluid volume flow in the reverse direction.

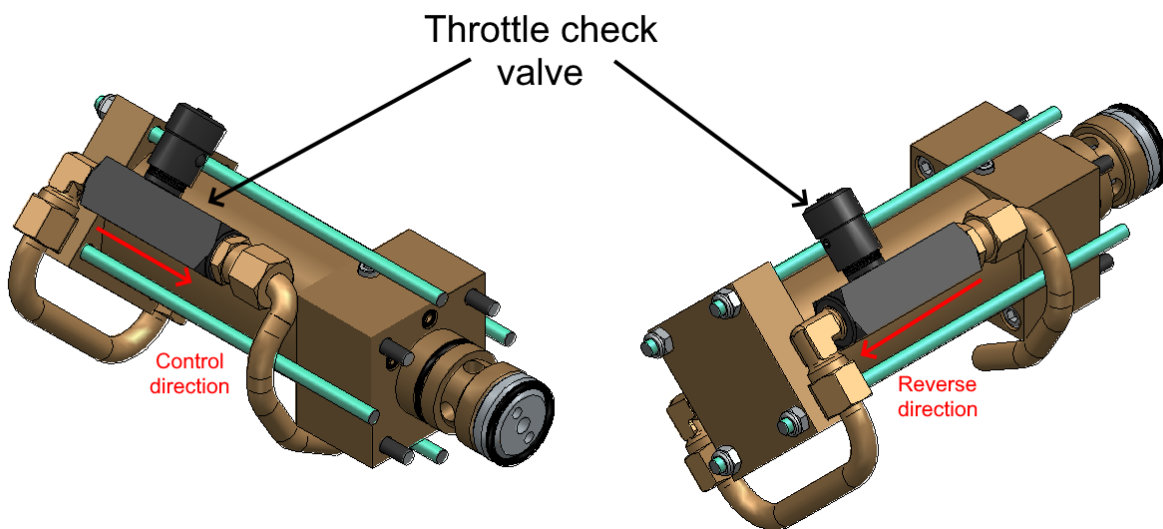


Figure 45: Illustration of the throttle check valve installed location, on the decompression arrangement [63].

Numerous decompression tests were conducted on a single MK5 Levelok cage power pack (SN: 239-06-2010) to investigate how the throttle check valve's variable settings would affect the decompression cycle output. These tests were conducted using the Levelok cage power pack experimental setup in the Levelok workshop, without the use of a pneumatic accumulator. The control of the MK5 Levelok cage power pack was also not altered with the recommendations made in Section 5.3. The throttle check valve was the only component that was adjusted for each test, to satisfy the goal of understanding how it affects the decompression cycle curve.

The variable knob of the throttle check valve is used to adjust its setting. Turned anti-clockwise, the valve setting is adjusted to let more volume flow through the check valve. Turned clockwise the valve setting is adjusted to attain more resistance against the hydraulic volume flow. The throttle check valve can be adjusted with a screwdriver, after removing one of the plugs on the Levelok cage power pack, as illustrated in Figure 46 [63]:

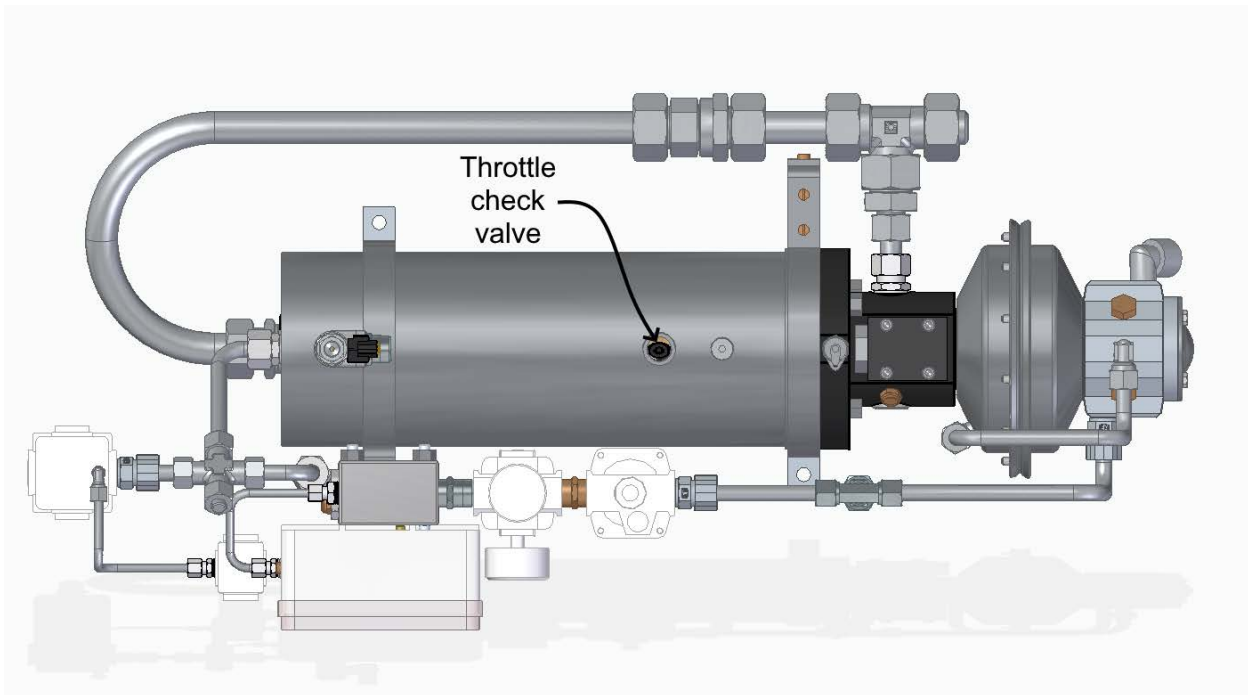


Figure 46: Illustration where the throttle check valve can be adjusted [63].

The throttle check valve tests were conducted by adjusting the variable knob half a turn for each decompression test. The first test was done with half a turn from the fully closed position. A total of 12 decompression tests were completed from the fully closed to the fully open position of the throttle check valve. The results of the 12 decompression tests are plotted in Figure 47. This testing procedure was completed in reverse as well, and the results again plotted in Figure 48.

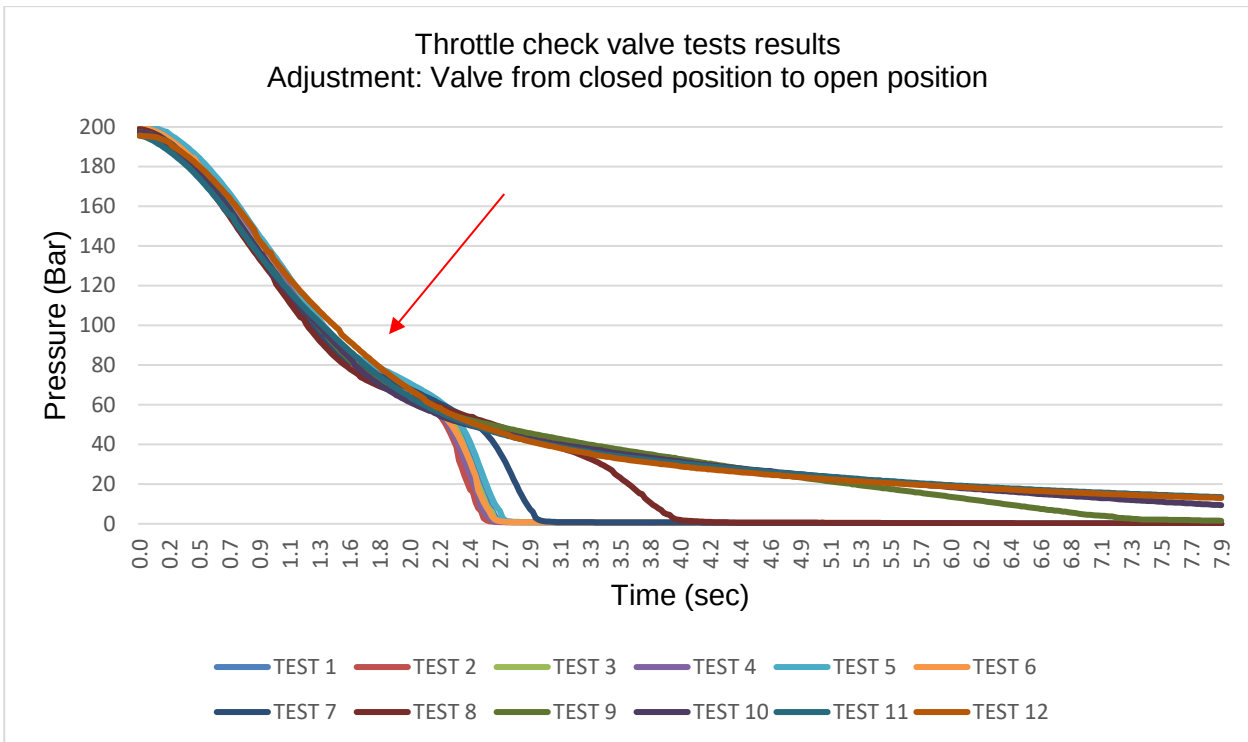


Figure 47: Throttle check valve test results. Adjustment: Valve from the closed position to the open position.

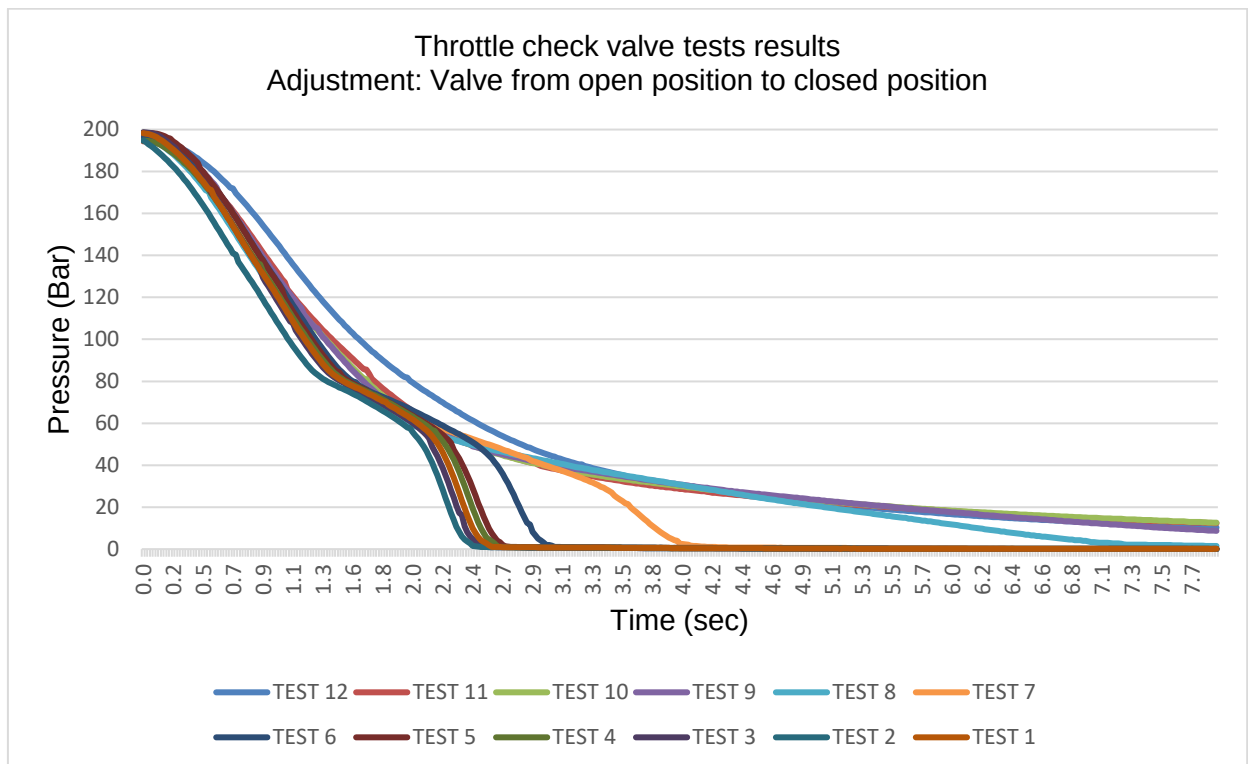


Figure 48: Throttle check valve test results. Adjustment: Valve from the open position to the closed position.

The throttle check valve test results represented in Figure 47 and Figure 48 confirmed repeatability, as expected. The throttle check valve did not affect the decompression cycle in the first 1,5 sec, but the setting did affect the total decompression cycle time. The decompression cycle time was extended with the increased resistance the throttle check valve induced on the hydraulic fluid volume flow. This effect is visible just after the point of slip, illustrated with the red arrow in Figure 47.

To visualize how the decompression cycle time affects the conveyance displacement after its Levelok arresting system is released, the 12 tests in Figure 47 and Figure 48 were divided into two groups:

- Tests 1-8, Unstable group
- Tests 9-12, Stable group

The average decompression cycle curves for each group were then used in the mathematical conveyance displacement prediction model. The conveyance prediction displacement results that were found for the two averages are represented in Figure 49 and Figure 50 (Note: The maximum payload of 18 Ton was used for these predictions):

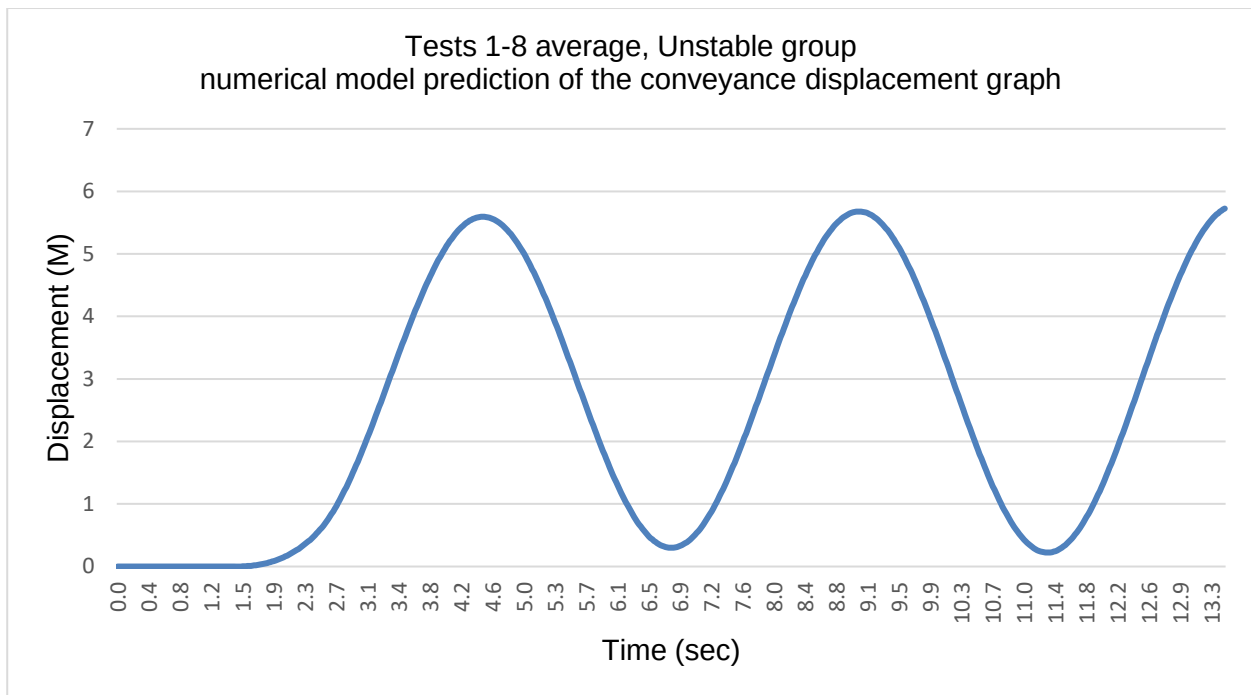


Figure 49: Numerical model prediction of the conveyance displacement graph, of the average decompression cycle curve of the Unstable group, Tests 1-8.

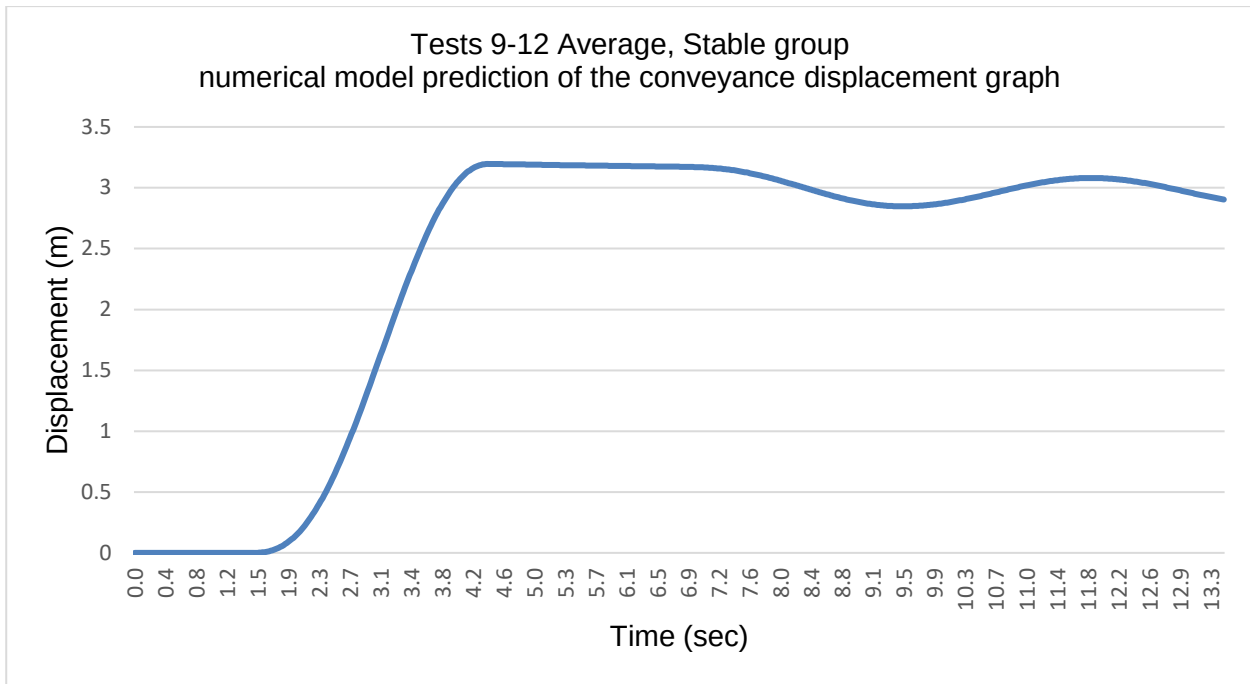


Figure 50: Numerical model prediction of the conveyance displacement graph, of the average decompression cycle curve of the Stable group, Tests 9-12.

The predicted displacement profile using the unstable group's average decompression cycle pressure values, would thus characterize a conveyance not sliding gradually to its new position in the shaft. The conveyance displacement in Figure 49 could be described as a “yo-yo” effect in movement, with a maximum hoisting rope stretch of almost 6 m. Thus, not only would there be extreme forces applied to the hoisting wire rope and the winder machine of the respective shaft, but a lot of operational shaft time would be lost and mining personnel involved would be placed in a particularly dangerous situation.

The stable group results in Figure 50, however, showed that with a throttle valve setting that extends the decompression cycle to a longer release time period, would have a more positive effect on the conveyance's displacement. The rope stretch of 2.9 m would be applied more gradually to the hoisting winder rope, minimizing the forces applied to it, saving time, and keep mining personnel safe.

5.5 Repeatability tests

The system audit tests, together with the discussions with different shaft engineers of Levelok operational mine shafts, revealed another problem. The MK5 Levelok cage system's release of an arrested conveyance did not operate with sufficient consistency. In some extreme cases, the Levelok system would allow the conveyance to slide perfectly, but then right after clamping and releasing of a system for a second time, the conveyance would "drop" and start to move up and down in the shaft ("yo-yo" effect). Another example of this inconsistency can be found in the first 2 seconds of the decompression curves of the MK5 Levelok cage power pack (SN: 239-06-2010), in Figure 48. The expectation was that the multiple decompression curves, when measured, would form one solid line, due to the fixed tolerances and decompression cycle properties.

For a more focussed investigation, several decompression tests were completed on a single MK5 Levelok cage power pack (SN: 216-05-2003). To investigate whether this MK5 Levelok cage power pack's decompression arrangement sustained a consistent decompression cycle output during repetitive operations, the decompression curve results needed to be comparable. To accomplish this objective, all properties of the hydraulic power pack were set beforehand, according to Mine X's *"Test settings for power pack"* sheet, found in the archived *"Levelok maintenance & operational manual for man, material cage clamping system"*, on the old Horne hydraulics server [9]. The decompression tests were conducted with no future adjustments to any of the components on the hydraulic power pack, and the decompression cycle results were plotted on the graph in Figure 51:

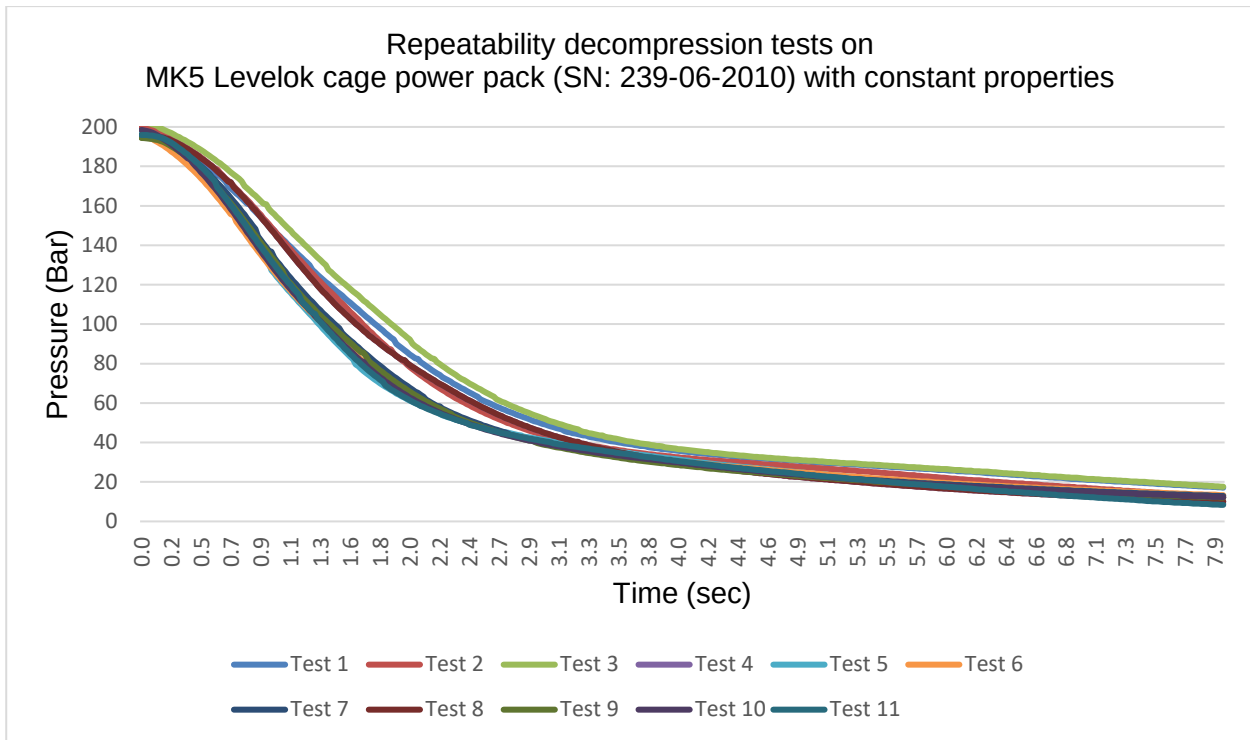


Figure 51: Repeatability decompression tests on MK5 Levelok cage power pack (SN: 216-05-2003) with constant properties.

These results also confirmed the inconsistency of the decompression arrangement of the MK5 Levelok cage power pack. The consequences of this inconsistency were evaluated by simulating a conveyance's displacement with the mathematical conveyance displacement prediction model. The best and worst decompression curves of Figure 51 were used to plot their respective conveyance displacement predictions, represented in Figure 52 (Note: The maximum payload of 18 Ton was used for these predictions).

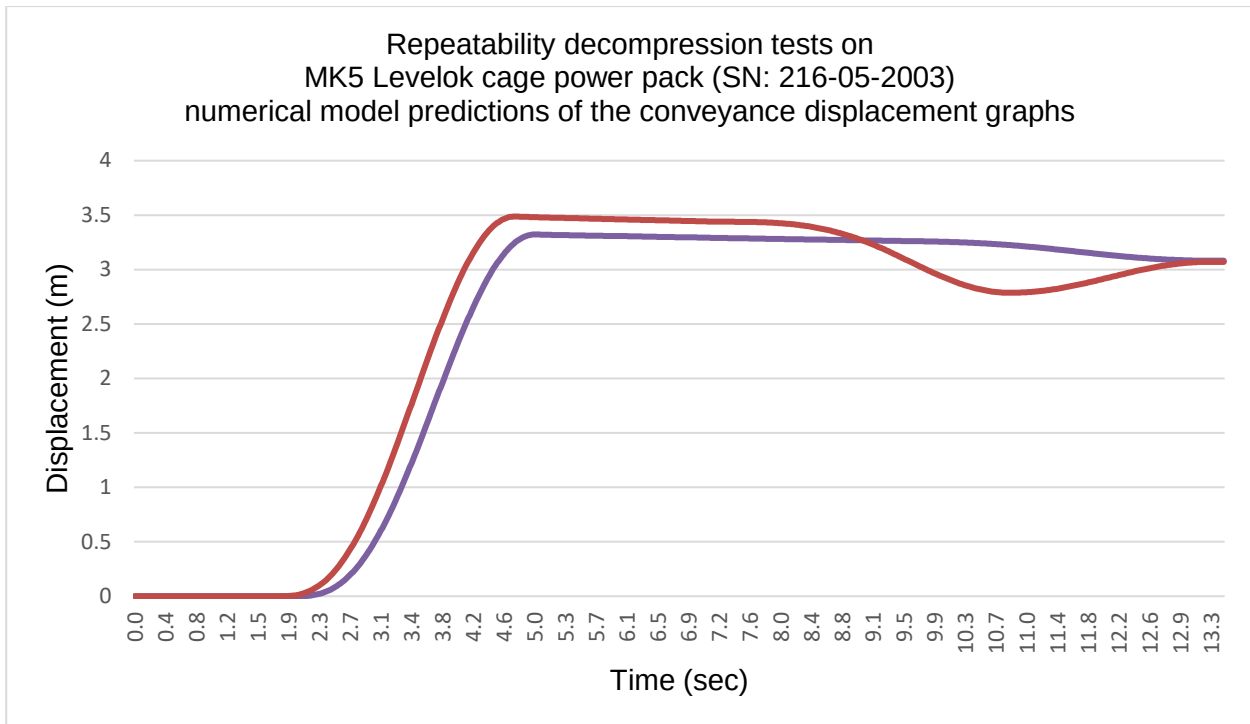


Figure 52: Repeatability decompression tests on MK5 Levelok cage power pack (SN: 216-05-2003) numerical model predictions of the conveyance displacement graphs.

These two plotted conveyance displacement predictions showed less instability than expected, but still created cause for concern. With reference to the derived equation in Section 2.3.4, Equation 7, the variable that is of utmost importance in, influencing the flow characteristics of the hydraulic fluid, is the size of the annulus (W) restricting the flow. The hypothesis, therefore, arose that the size of the annulus formed between the spindle and seat components of the decompression arrangement, was in some way altered during subsequent decompression cycle operations. This theory was therefore investigated more formally and the findings presented in Chapter 6 of this dissertation.

From a more practical point of view, some of the causes for the inconsistency of MK4 and MK5 Levelok cage systems that were found during the conducted audits were the use of contaminated hydraulic fluid or hydraulic fluid with different viscosity properties. Another cause was that of O-ring failures on the spindle, and the reason for this failure was also investigated and addressed in Chapter 6.

5.6 Spindle & seat annulus size

The two main components of the decompression arrangement of any Levelok hydraulic power pack are the spindle and seat. The dynamics between these two components and their ability to control the decompression output were discussed in Section 2.3.3. Due to the importance of these components, all the critical dimensions thereof were recorded before the decompression arrangement was installed to a Levelok power pack for testing. As mentioned in Section 5.6, the critical dimension of utmost importance is the size of the annulus (W) between the spindle and seat. The illustration in Figure 53 defines this dimension visually:

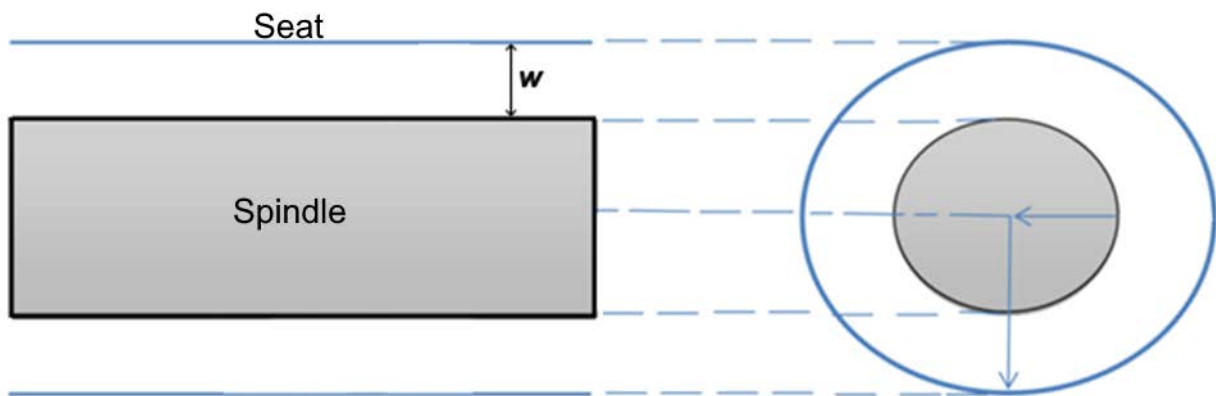


Figure 53: Narrow annulus between spindle and seat illustration [24].

According to the information gleaned from Horne hydraulics drawings, and from the preserved notes of Peter Horne, the annulus size (W) was defined to be between 0.035 - 0.045 mm. This was not the case after the analysis of the recorded data on the critical dimensions of several MK4 & MK5 Levelok cage power packs. Instead, 9 different annulus sizes were found between 28 power packs tested.

The cause of this inconstancy can be due to numerous reasons. This could have been the result of a QA system at fault, faulty measuring equipment, or even temperature changes in the manufacturing workshop [3]. Also, no documentation was found, staffing the reasons why certain alterations were made. The actual reasons will probably never be known.

Nevertheless, the tests conducted in this study showed that the annulus size (W) of 0.035 - 0.045 mm was too small. The measured results of the decompression cycle tests for the annulus size 0.35 mm, 0.05 mm, 0.055 mm, 0.06 mm, 0.065 mm, 0.07 mm, 0.075 mm, 0.085 mm, and 0.10 mm are plotted in Figure 54. The corresponding Mine X conveyance displacement prediction curves, simulated with the mathematical conveyance displacement prediction model, is represented in Figure 55 (Note: The maximum payload of 18 Ton was used for these predictions):

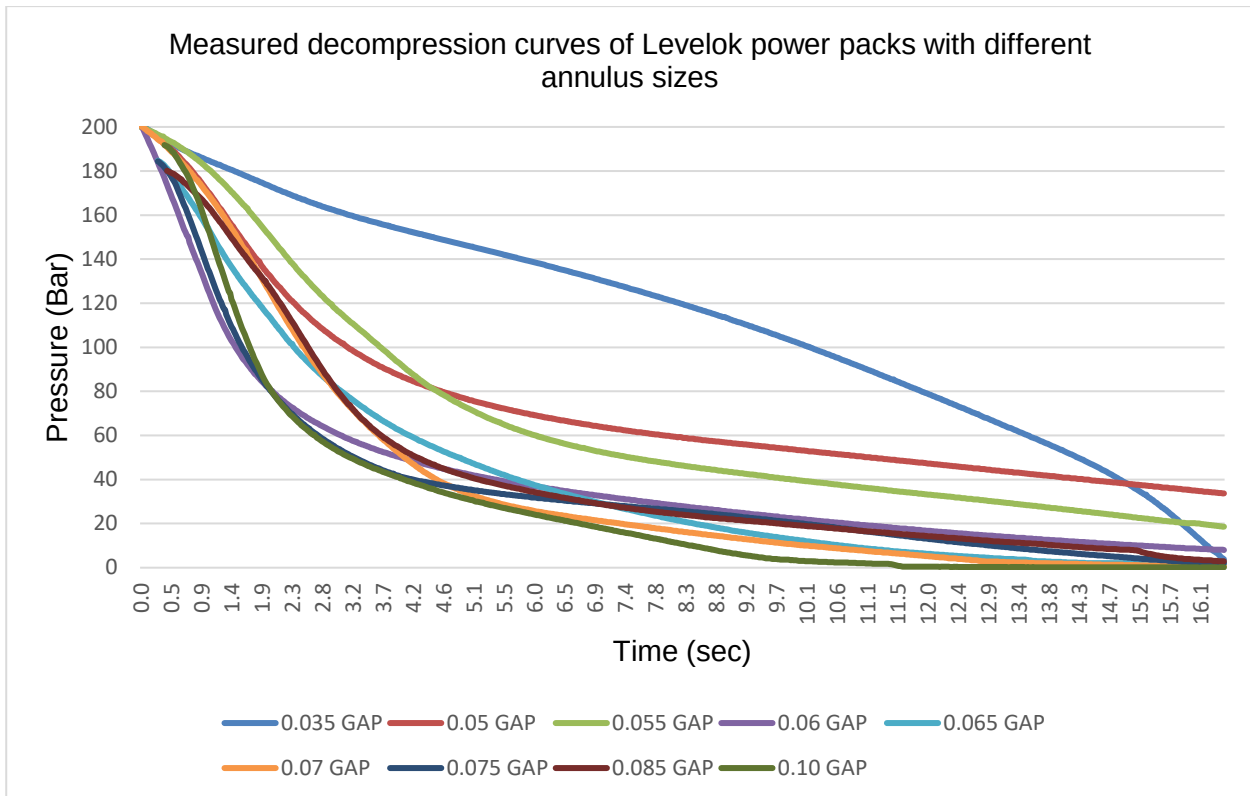


Figure 54: Measured decompression curves of Levelok power packs with different annulus sizes.

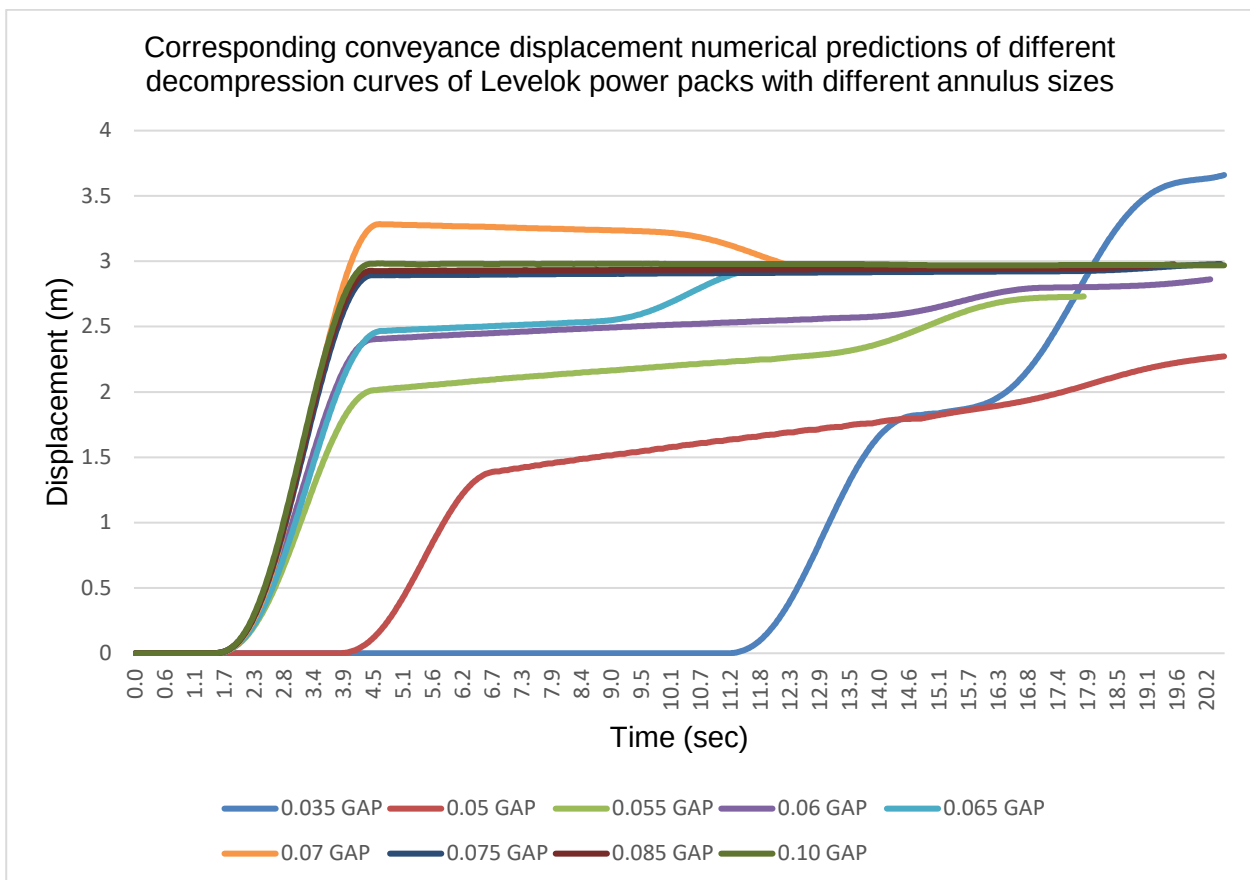


Figure 55: Corresponding conveyance displacement numerical predictions of different decompression curves of Levelok power packs with different annulus sizes.

The numerical predictions of the conveyance movement shown in Figure 55, show that the recommended annulus size that was needed to stabilize a conveyance during release, thus obtaining the best “slide” with a full payload mass, was 0.07 - 0.10 mm.

The follow-up on-site system audit tests that were completed on the Levelok systems at Mine X, installed with Levelok cage power packs with the modified annulus size, gave more insight into this crucially important variable. The mineshaft can be particularly wet on certain days, and thus due to the water on the guides in the shaft, it was found that the kinetic coefficient of friction would be lower than the 0.25 value calculated in experiments conducted in Annexure G [48]. There was no change to the static coefficient of friction in these conditions since the clamps would press all water between the shaft guides and clamp shoes away, during the static high-pressure clamping procedure.

The larger annulus sizes together with the lower kinetic coefficient of friction would cause instability in the displacement of the conveyance after release, as illustrated in Figure 56 (Note: The maximum payload of 18 Ton was used for this predictions):

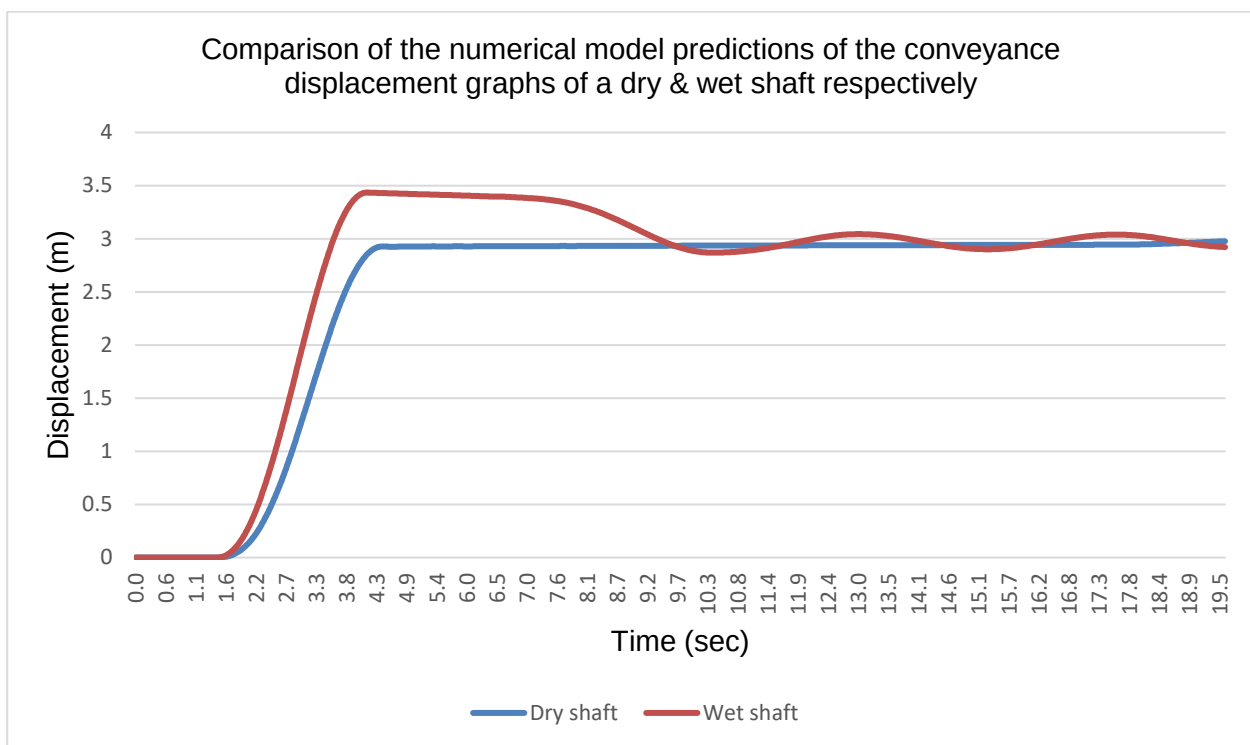


Figure 56: Comparison of the numerical model predictions of the conveyance displacement graphs of a dry & wet shaft respectively.

The recommended annulus size was then altered to be in the range of 0.07 - 0.08 mm, to satisfy the dynamics of a conveyance in a wet or dry vertical mine shaft.

The decompression curve of the MK5 Levelok cage power pack (SN: 215-05-2003), using this altered recommended annulus size of 0.075 mm in its decompression arrangement, together with its corresponding conveyance prediction curves for a wet and dry mine shaft are plotted on the same graph, in Figure 57 (Note: The maximum payload of 18 Ton was used for this predictions):

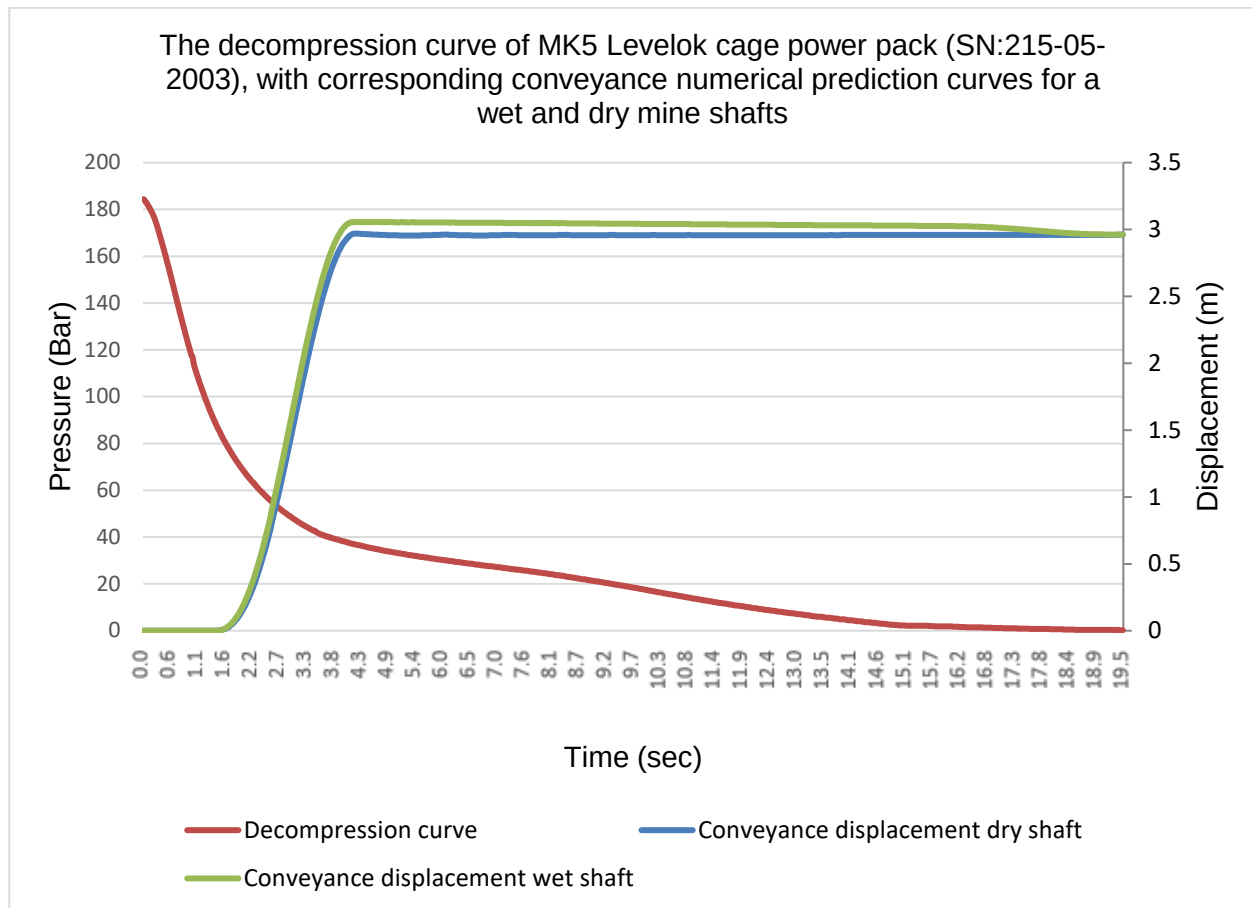


Figure 57: The decompression curve of Levelok cage power pack (SN:215-05-2003), with corresponding conveyance numerical prediction curves for wet and dry mine shafts.

5.7 Summary of completed tests

The results obtained from the multiple completed decompressions cycle workshop and audit tests on the MK4 and MK5 Levelok systems, with their corresponding numerical prediction conveyance displacement graphs, presented valuable information. This information, assisted in the better understanding of the dynamics of the decompression cycle, and the control output thereof.

The control philosophy, together with the control components of the MK5 Levelok system was examined and tested and was found to have some undesirable effects on the decompression cycle curve. The responsible components were identified and will be altered in the new design methodology represented in Chapter 7.

The function of the throttle valve component on the decompression cycle arrangement was described, and better understood. The plotted decompression curves showed that the throttle valve is the controlling component of the decompression cycle time. These plotted decompression curves also presented a phenomenon that created cause for concern. A more focused investigation was implemented, to determine the cause of this phenomenon.

The decompression cycle repeatability tests confirmed the inconsistency of the decompression arrangements pressure output. The hypothesis, therefore, arose that the size of the annulus formed between the spindle and seat components of the decompression cycle arrangement, was in some way altered during continuous operation. This theory was therefore investigated more formally and the findings presented in Chapter 6 of this dissertation.

The importance of the annulus size formed between the spindle and seat components of the decompression cycle arrangement as illustrated in the results plotted from the completed decompression tests on multiple Levelok cage power packs. The numerical predictions of the conveyance movement showed that the recommended annulus size that was needed to stabilize a conveyance during release, thus obtaining the best “slide” with a full payload mass, in a wet ore dry mine shaft, was 0.07 – 0.08 mm. This crucially important dimension is to be implemented in both the new design methodologies represented in Chapters 7 and 8.

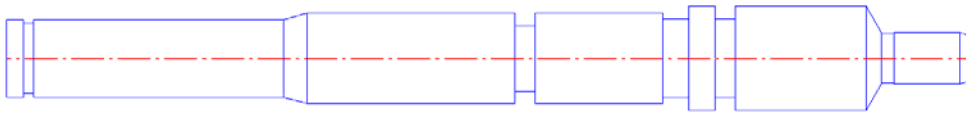
CHAPTER 6

DECOMPRESSION CYCLE ANALYSIS & REDESIGN

6.1 The MK4 & MK5 decompression arrangement problems

The Levelok arresting system's design, methodology, and control philosophy have seen significant changes over the last 40 years of development [1]. These improvements to the Levelok system, addressed specific client specifications, and caused for components being added to and removed from the system. The greater effect of these changes can be seen on the components of the decompression arrangement of the Levelok cage power pack. An example of these components that have changed in its geometry and functionality is the decompression arrangement spindle, as illustrated in Figure 58 [64] [65]:

MK1-MK3 Decompression arrangement spindle



MK4-MK6 Decompression arrangement spindle



Figure 58: Decompression arrangement spindle geometry design change illustration [64] [65].

With the MK1-MK3 and MK6 Levelok cage man, material systems discontinued, all later design improvements have been added to the MK4 & MK5 Levelok cage systems. As discussed in Chapter 3, even with these added improvements, the system did not yet fully deliver on the promises of its advantages.

The decompression tests conducted in Chapter 5 highlighted system problems regarding certain components added to the MK5 Levelok cage system. More importantly, some concerns regarding the decompression arrangement were uncovered. These concerns included the failure of the O-rings on the spindle, the inconsistency of the decompression cycle output, and the size of the annulus between the spindle and seat. As presented in the remainder of this chapter, these concerns were analysed, addressed and the results were used to develop a methodology, by which the new improved MK7 decompression arrangement was designed.

6.2 The O-ring failures on the spindle

Coetzee (2016) [20] was employed by Anglo Ashanti as a Levelok maintenance specialist at their Moab Khotsoeng and Koponang mining operations before he was approached by the officials at Mine X. His experience with both types of Levelok systems (cage & skip systems), brought it to WJ Engineering's attention that the decompression arrangement of the Levelok man, material cage system is unreliable due to O-rings failing on the spindle itself. With undesirable leakage occurring in the decompression arrangement, it causes erratic system behaviour that does not comply with the specific design requirements. There are two O-rings on the spindle, as illustrated in Figure 59:

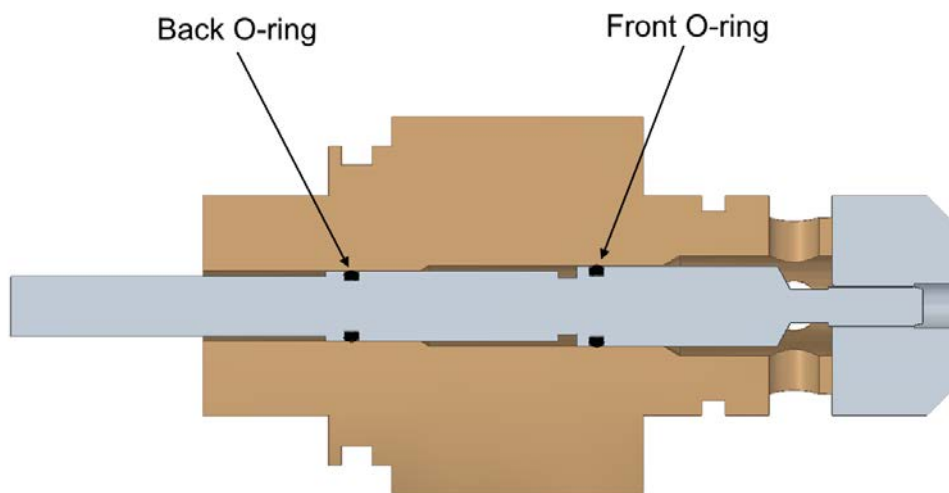


Figure 59: Illustration of O-rings on the spindle.

The O-ring failure on the spindle of a Levelok cage power pack was easily identifiable. During the clamping procedure of the Levelok system, trapped air is released through one of the button silencers on the pump body. This air flows through a cavity, from the decompression arrangement's piston chamber leading to the button silencer, as illustrated in Figure 60. This trapped air is released out of the decompression arrangement assembly when the decompression arrangement's piston compresses the spring to push the spindle into the seat. When the back O-ring on the spindle fails, the hydraulic fluid flows into the piston chamber and is pushed through the cavity, creeping out at the button silencer. Thus, hydraulic leakage at the button silencer is a sign of the failure of the back O-ring.

Hydraulic leakage does not occur with the failure of the front O-ring, instead, during the clamping procedure, the power pack will never reach the main clamping pressure. The front O-ring's function is to help the spindle to stay seated against the seat, and if this O-ring is to fail, premature leakage occurs between the spindle and seat. If the Levelok power pack keeps on pumping and never reaches the main clamping pressure, it may be a symptom of the failure of the front O-ring.

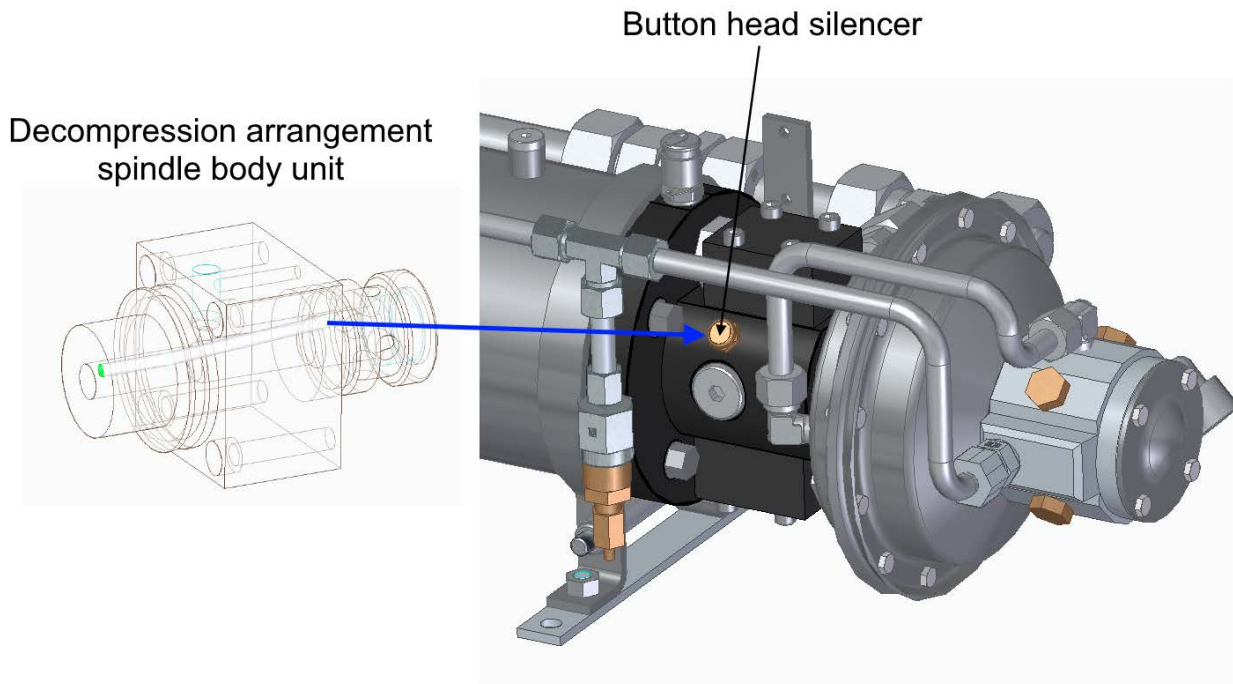


Figure 60: Illustration of the cavity in the spindle body leading to the button silencer on the pump body.

One cause of these O-ring failures was found while examining a spindle body that was cut in half utilizing a wire-cutting machine unit and analysing the corresponding component drawings. During the assembly of the decompression arrangement, both the front and back O-rings would be damaged due to a sharp edge inside the spindle body. This sharp edge is located at the intersection of the balancing fluid cavity and the last chamfer in the spindle chamber in the spindle body, as illustrated with the red circle in Figure 61 [66]:

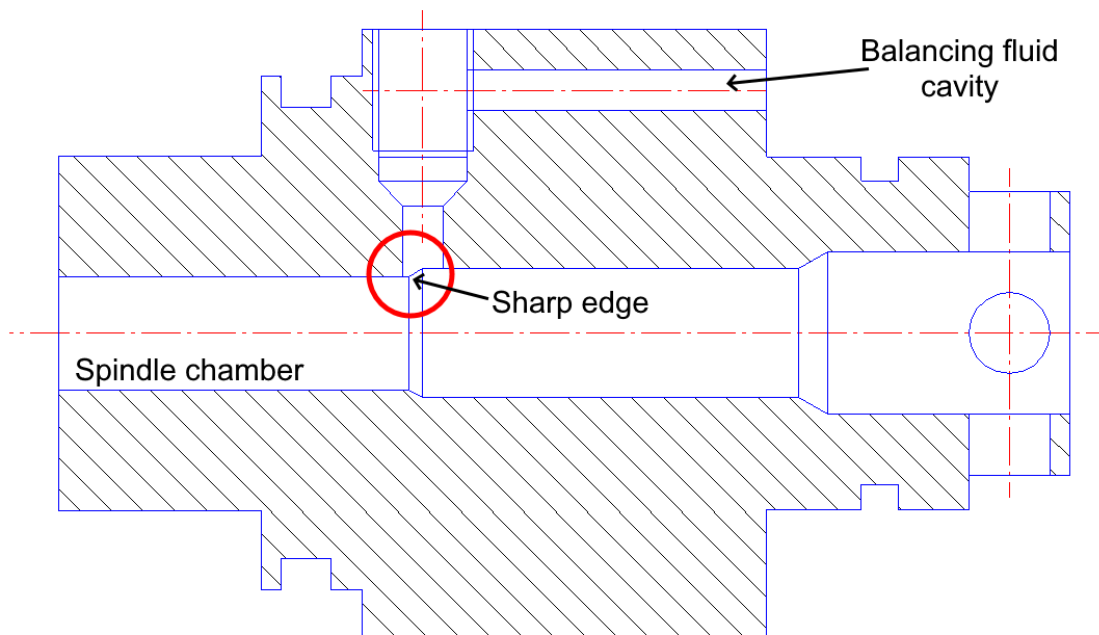


Figure 61: Illustration of the location of the sharp edge formed in the spindle body during machining [66].

The other cause of O-ring failures was found in the type of material used in the manufacturing of the O-rings. The specification of the rubber material used determines the A-shore hardness properties [68]. The hardness of the O-ring material defines the hydraulic pressure limit the O-ring can control. Utilizing a piston gap (ΔD) of 0.1mm (between the spindle and the spindle body), together with the maximum operating pressure of 210 Bar, in the graph represented in Figure 62 [67], the A-shore hardness needed for the O-rings material can be defined to be a minimum of 90 shore.

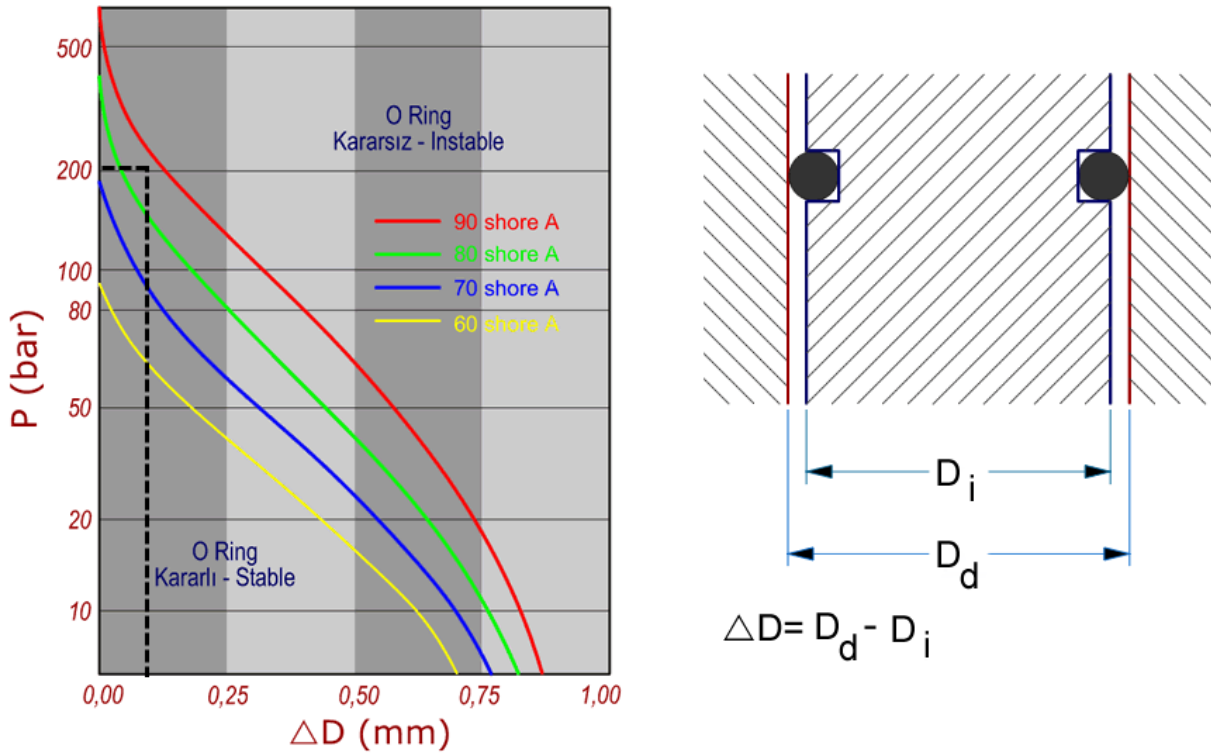


Figure 62: Piston gap to be evaluated under operation pressure, diagram and graph illustration [67]

The old MK4 and MK5 decompression arrangement spindle O-rings were measured with an A-shore hardness tester and were found to be too soft, ranging from 60 to 80 shore.

With this newly gathered information on the causes of the O-ring failures, improvements could be made to the decompression arrangement to assure reliability thereof. Thus, this information was used in the new MK7 decompression arrangement design in Section 6.5.

6.3 The misalignment of the decompression arrangement components

The repeatability results conducted in Chapter 5 revealed the inconsistency of the decompression cycle output of the decompression arrangement. The supposition that was made for the cause of this inconsistency was that the size of the annulus formed between the spindle and seat components of the decompression arrangement was in some way altered during the different decompression cycle operations.

The size of the annulus being 0.07- 0.08 mm, does not leave a lot of space for any misalignment, especially for the moving components of the decompression arrangement. The assembly diagram represented in Figure 63 [47] [69] lists the components that can affect the alignment of the spindle and seat.

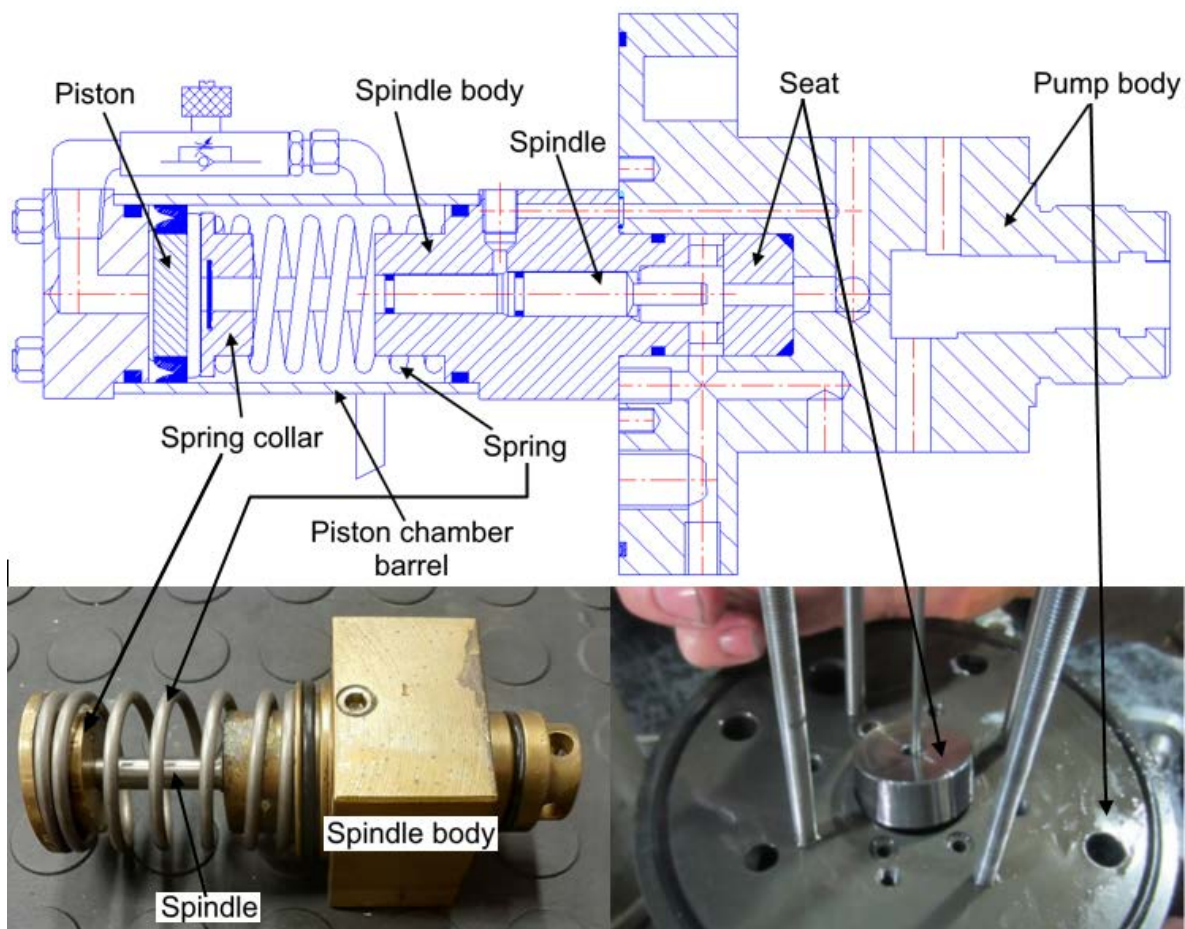


Figure 63: Decompression arrangement components, responsible for the alignment of the spindle & seat [47] [69].

Figure 63 [47] [69] also illustrates that the seat and spindle body does not attach in any way, the same for the piston and spring collar components. The seat is placed in the pocket of the pump body and the spindle body with attached components follows. The piston barrel is placed over the spring, up against the spindle body, where after the piston is placed in the barrel. The cap, with threaded rods and nuts, holds the whole decompression arrangement assembly together.

After the inspection of all the individual component drawings and machining tolerances thereof, it was found that, due to all the loose components, the machining tolerances added up to a bigger value than the size of the annulus. A misalignment can be calculated to a maximum of 0.13 mm, by just analysing the machining tolerances of the spindle, seat, and pump body as illustrated in Figure 64 [65] [66] [70] [71]. (Due to NDA, precise dimensions could not be published, thus to demonstrate tolerances the first digit of each dimension was replaced with an X):

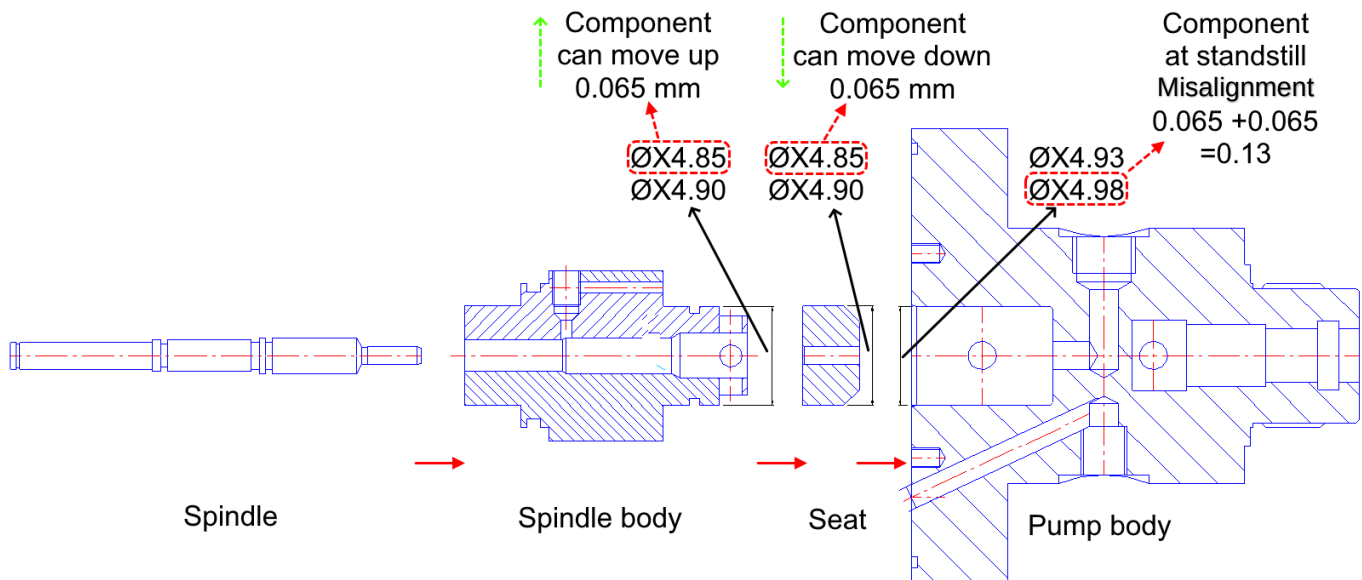


Figure 64: Illustration of the calculation of the maximum misalignment of the main components of the decompression arrangement [65] [66] [70] [71].

According to these findings, the spindle and seat would not always be concentric to one another. The position of the components could change after each decompression cycle and this relative movement was probably the cause of the inconsistency of the decompression cycles.

6.4 Volume flow analysis case studies setup and required parameters

The misalignment of the decompression arrangement components could have an immensely undesirable effect on the flow characteristics of the hydraulic fluid. The decompression cycle is defined by the flow of the hydraulic fluid through the narrow annulus created between the spindle and seat. With the misalignment, it could cause the spindle and seat to not always be concentric to one another, which is the desired position of the two components during operation (Case study 1), as illustrated in Figure 65 [50]:

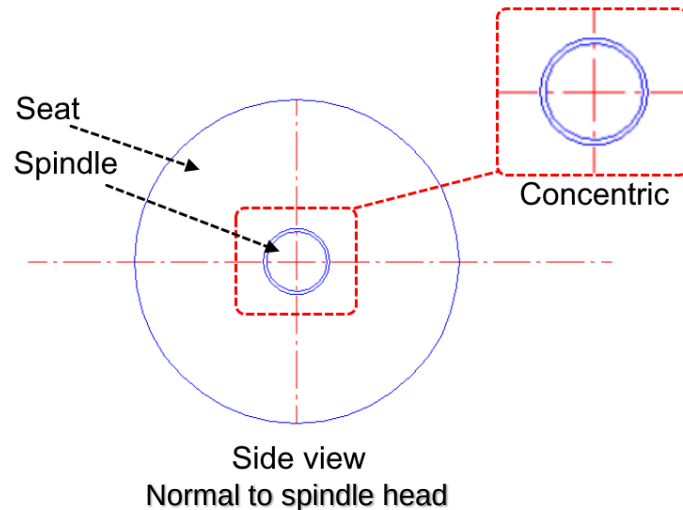


Figure 65: Illustration of concentric spindle and seat (Case study 1) [50].

The annulus size is set to be a constant 0.07 mm when the two components are concentric to one another. With the misalignment of the decompression arrangement components, an offset of the spindle would be possible (Case study 2), as illustrated in Figure 66 [50]. This offset can cause the annulus size to reach a maximum of 0.14 mm.

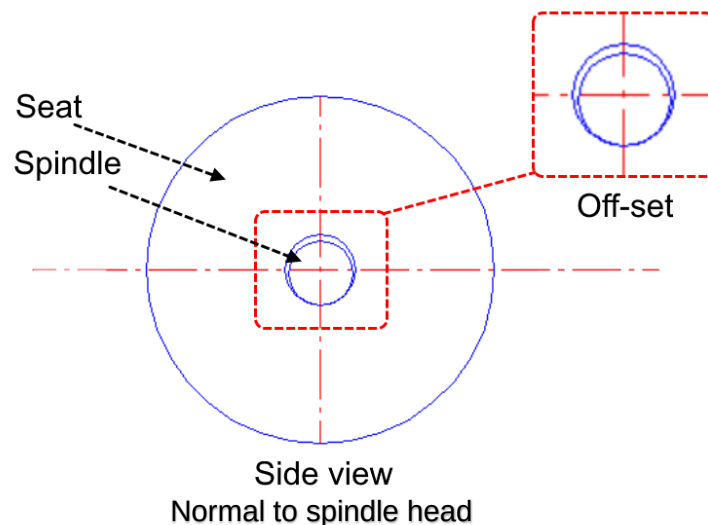


Figure 66: Illustration of off-set spindle and seat (Case 2) [50].

Section 2.3.3 explained the step-by-step process of how the dynamics of the spindle and seat mechanism define the flow characteristics of the hydraulic fluid. This explanation states that the narrow annulus length is at a maximum during Step 3 of the decompression cycle process (See Figure 22). At this point, the friction of the flow restriction caused by the narrow annulus is at its maximum. Also, with reference to Figure 19, this is the period of the decompression cycle where the slip pressure point occurs, and alternately the displacement or “slide” of the conveyance as well. The repeatability tests conducted in Section 5.5 also concluded that the inconsistency of the decompression arrangement during this period of the decompression cycle showed cause for concern.

It was therefore decided that through the decompression arrangement's operation, the positions of the spindle and seat during this period of the decompression cycle, were the most important locations of these components. Thus, all volume flow characteristics calculations and flow analyses simulations conducted on the narrow annulus, utilizing the FloEFD CFD package [72] incorporated in Solid Edge [44], was done with the layout of the decompression arrangement as illustrated in Figure 67:

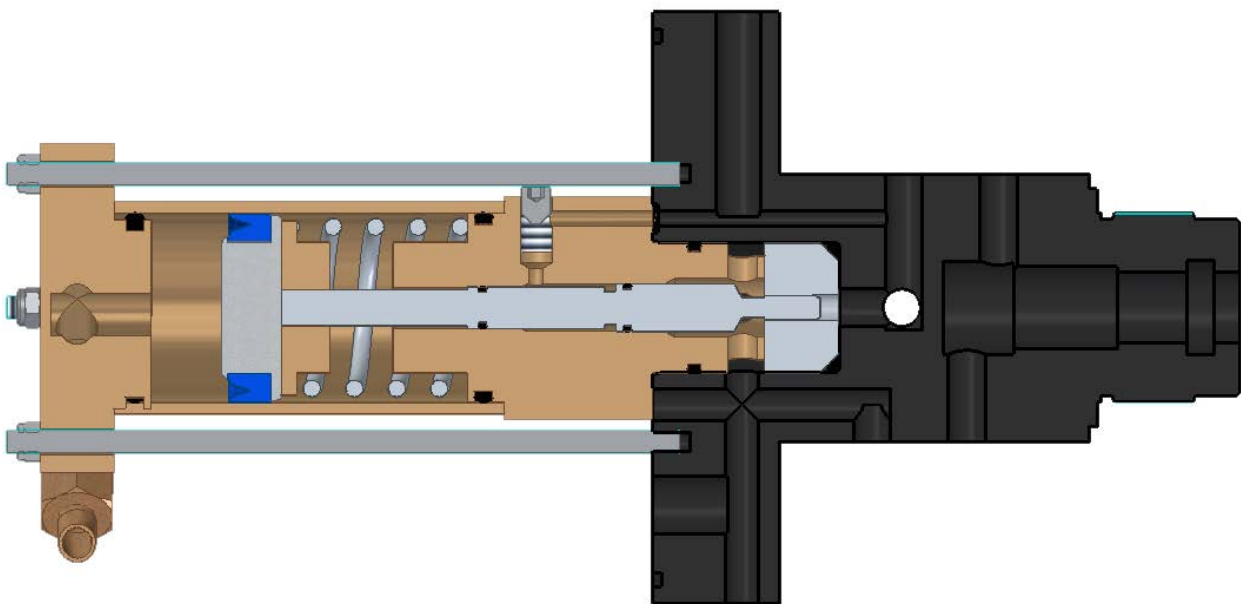


Figure 67: Solid Edge CAD model used for the flow analyses simulations.

To better understand how the flow characteristics in the annulus were affected by the misalignment of the decompression arrangement components, the two case studies represented in Figure 65 and Figure 66 [50] were studied and compared using this decompression arrangement layout represented in Figure 67.

The equation for volume flow rate, of which the hydraulic fluid flow through the narrow annulus, was derived from first principles in Section 2.3.4, Equation 7. To calculate the volume flow rate of the two cases to compare, certain parameters were needed to be identified. The critical dimensions needed are represented in Figure 68:

Equation 7

$$\dot{Q} = -\frac{\pi R \Delta p W^3}{12 \mu l}$$

$\dot{Q}$ = Volume flow rate [m^3/s]

R = Orifice inner diameter of the seat [m]

Δp = Pressure drop [Pa]

W = Size of the annulus [m]

μ = Hydraulic fluid viscosity [m^2/s]

l = Annulus length [m]

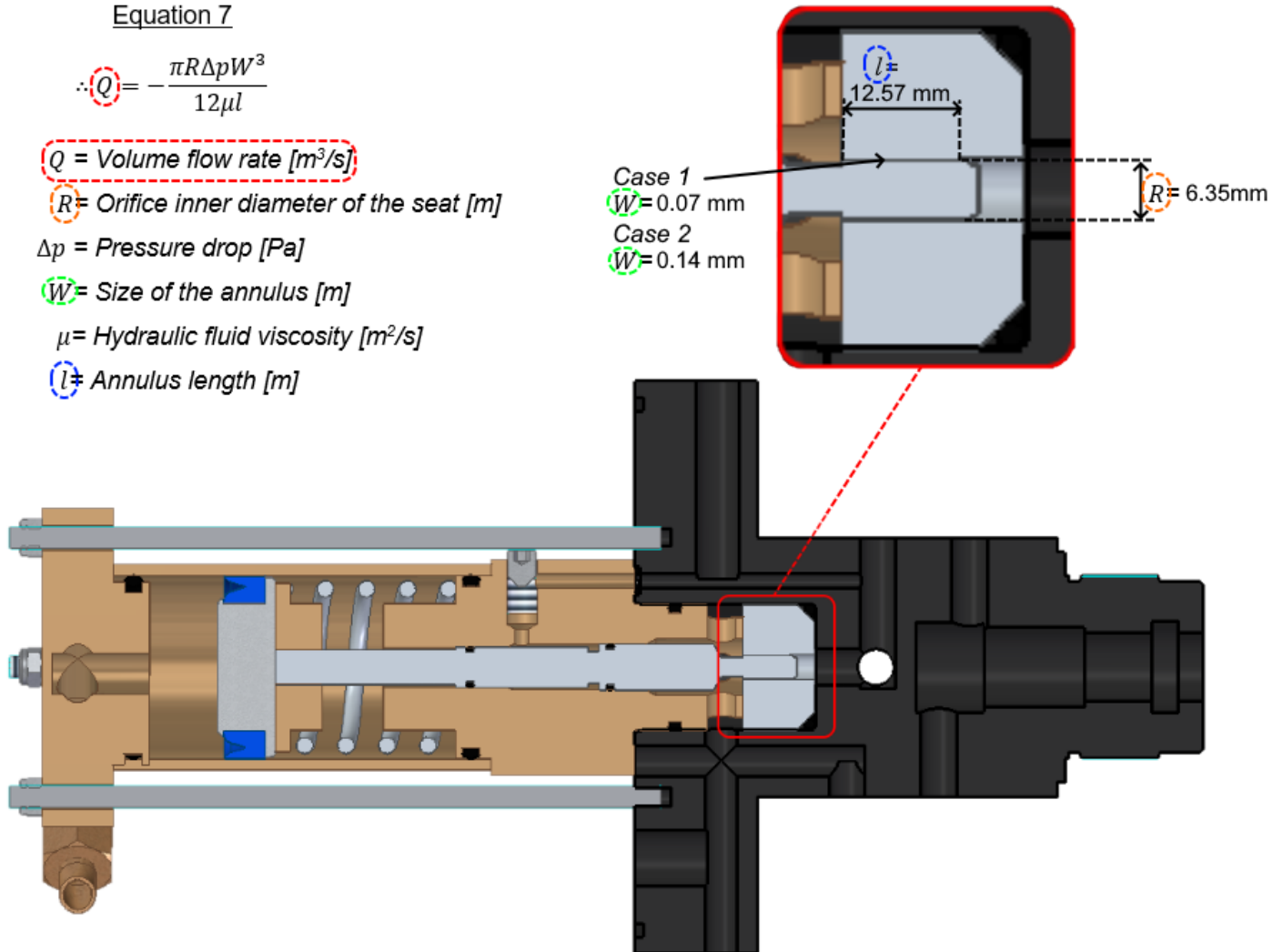


Figure 68: Visualization of the critical dimensions needed for the calculation of the volume flow rate of the hydraulic fluid through the narrow annulus.

The viscosity of the ISO32 Hydraulic fluid used in the Levelok power pack is 32 cSt, but defining a new liquid to be used in the FloEFD analysis, more fluid properties were required. These properties of the ISO32 Hydraulic fluid are represented in Annexure B and Table 10 [34] [37] [73].

Table 10: Properties of ISO32 Hydraulic fluid [34] [37] [73].

ISO 32 Hydraulic fluid properties		
Density	857	kg/m^3
Viscosity	0.027	$\text{Pa}\cdot\text{s}$
Specific heat	2.15	$\text{J}/\text{kg}\cdot\text{K}$
Thermal conductivity	0.128	$\text{W}/(\text{m}\cdot\text{K})$

The pressure drop over the narrow annulus was calculated by first defining the boundary conditions of the simulation setup in FloEFD. The decompression arrangement layout, as illustrated in Figure 67, was mentioned to occur right before the pressure point of slip, which was calculated to be 88.96 Bar using Equation 8 in Section 3.2. Thus, the assumption made was that this calculated slip pressure was indeed the system pressure at this specific time step. The other assumption that was made at this specific time step, was that of the pressure value of the hydraulic fluid release side of the decompression arrangement. This pressure value was determined to be equal to atmospheric pressure, as the pneumatic pressure in the Levelok cage power pack's hydraulic fluid reservoir would have been released completely.

From these assumptions made, the pressure drop over the narrow annulus was calculated to be equal to 8.795 MPa, and the boundary conditions of the simulation setup in FloEFD defined in Figure 69:

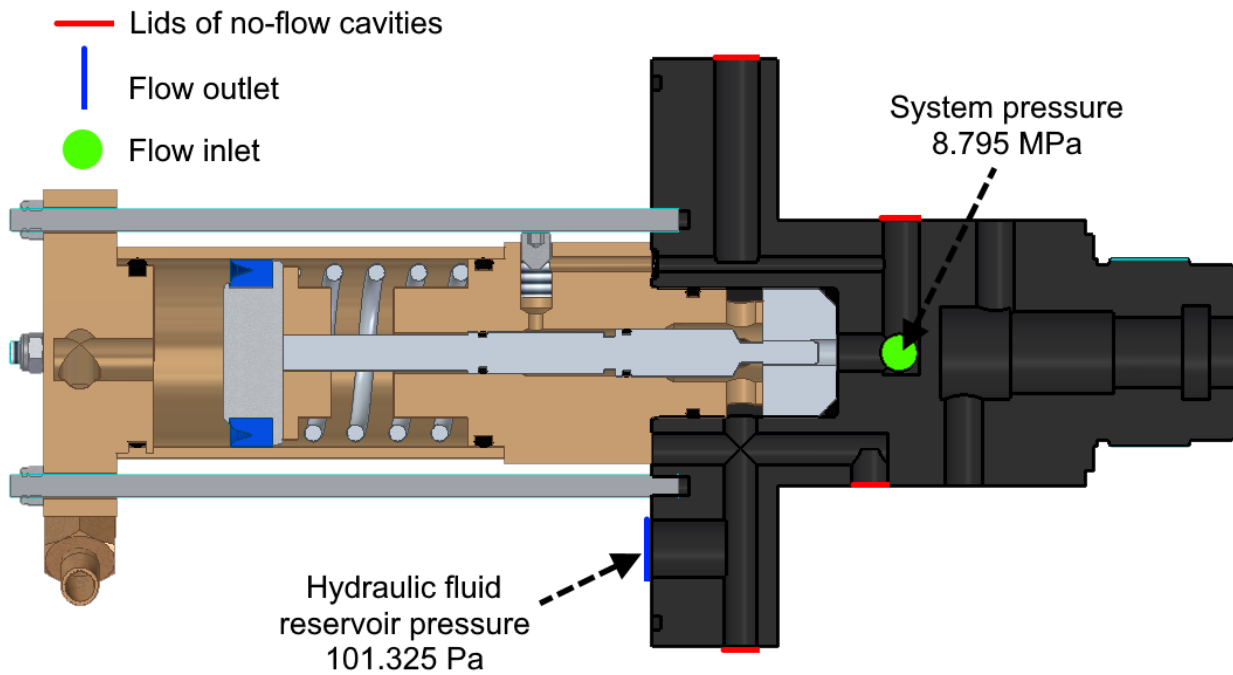


Figure 69: Boundary conditions of the simulation setup in FloEFD.

The boundary conditions of the simulation setup as defined in Figure 69, were used for all simulations conducted on both case studies. The only parameter that was changed during the Case study 2 simulations was the spindle position. The spindle, with its O-rings, was moved down 0.07mm to mimic the cause of misaligned decompression arrangement components.

6.5 Volume flow analysis case studies results

6.5.1 Case study 1

The results that were obtained from the FloEFD simulations conducted on the Case study 1 model setup, are illustrated in Figure 70. The flow trajectories in this figure represent the main volume flow from the high-pressure inlet, through the constant narrow annulus formed between the spindle and seat, into the decompression body discharge chamber, after which it flows down the outlet cavity leading to the hydraulic fluid reservoir. The colour distribution that is displayed on these flow trajectories demonstrates the pressure deterioration, caused by the friction of the narrow annulus, inflicted against the flow of hydraulic fluid. The 8.795 MPa high-pressure hydraulic fluid (Red) is discharged into the hydraulic fluid reservoir at atmospheric pressure (Blue). The spindle is the only visualized component in this illustration, hereby assisting in the best visualization of these flow trajectories.

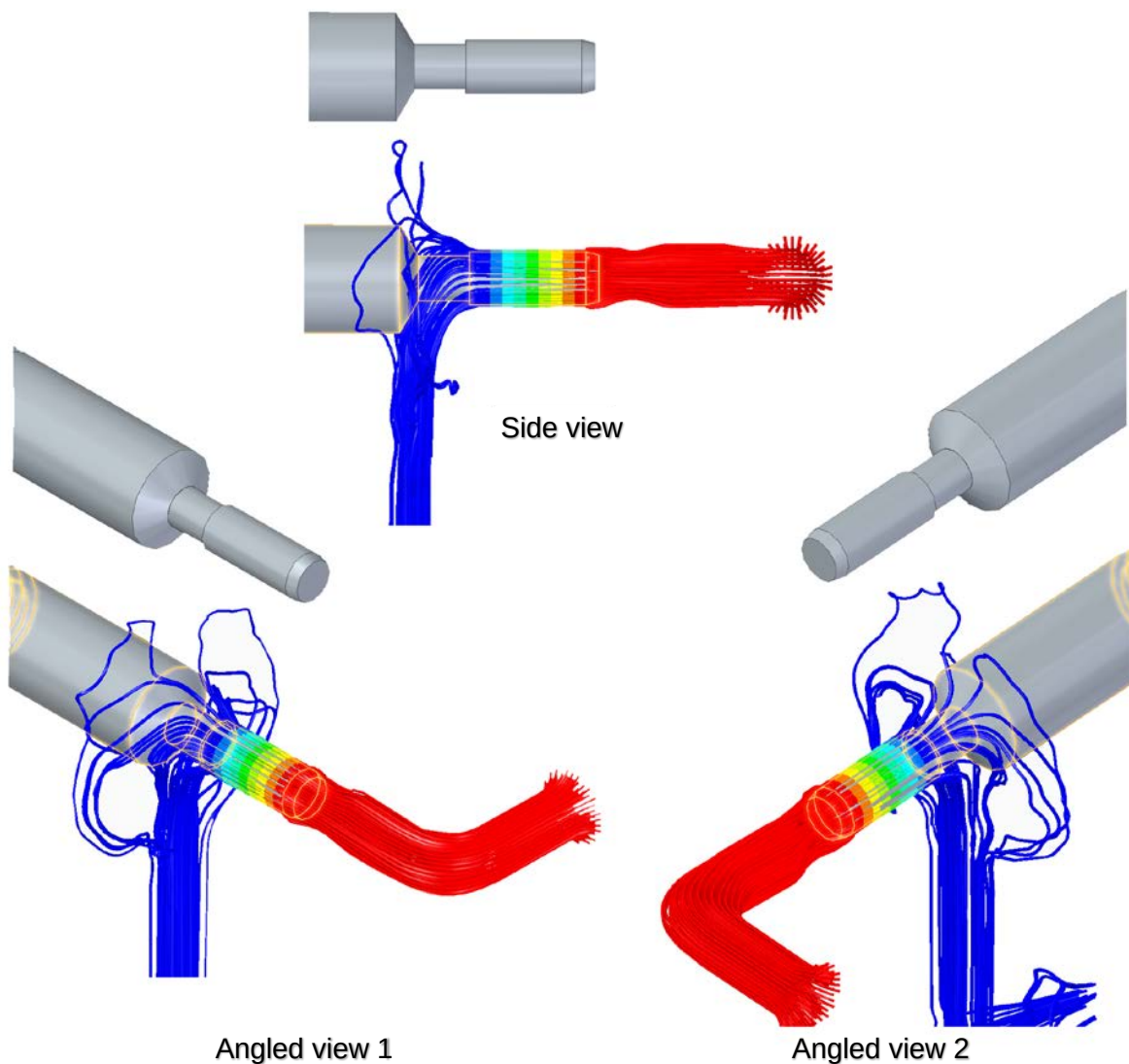


Figure 70: Case study 1 FloEFD hydraulic flow around the spindle visualized results.

The flow trajectories displayed in Figure 71, illustrate the same volume flow trajectories with their corresponding pressure colour distribution as that of Figure 70. The magnified two-dimensional side view of the spindle head attains a better visualization of the pressure distribution across the length of the constant 0.07 mm narrow annulus.

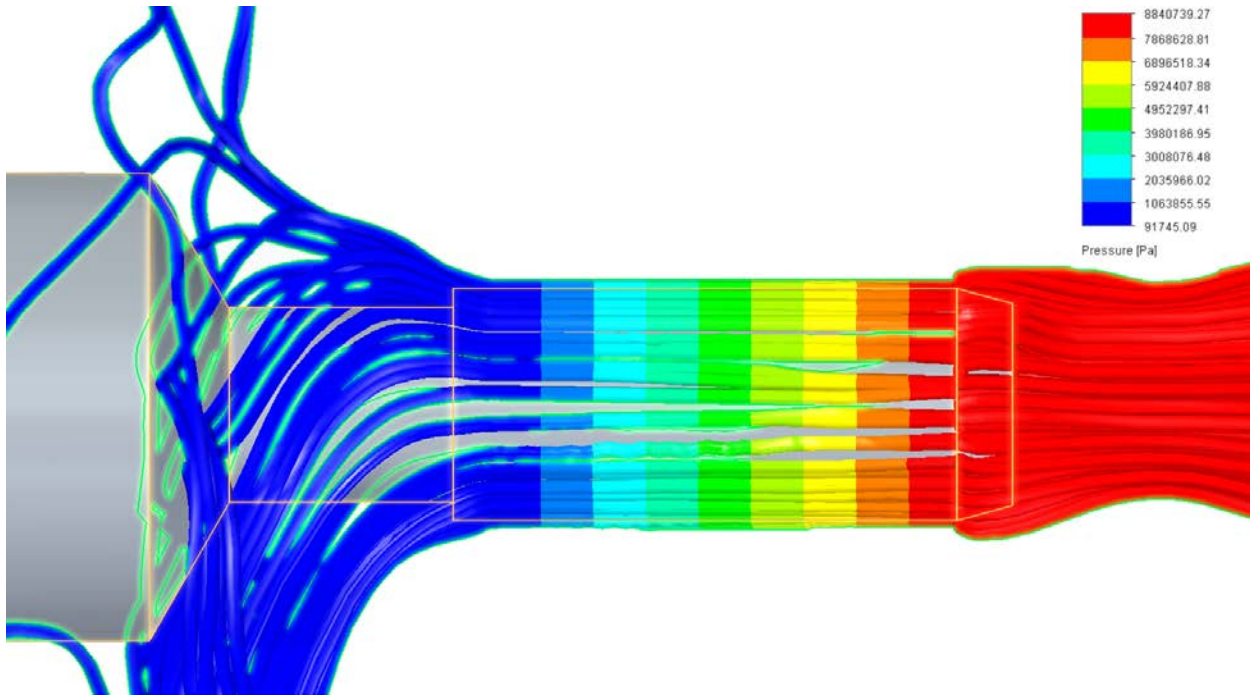


Figure 71: Case study 1 FloEFD pressure distribution across the spindle visualized results.

These results that were obtained from these conducted flow simulations are that of a static simulation model. A more accurate step-by-step iteration process analysis could have been conducted, to simulate how the decompression cycle output is achieved from the dynamic interaction between the decompression arrangement components. However, this was not the objective of the flow simulations.

This static simulation model was used to address the concerns regarding the causes of misalignment of the decompression arrangement components, by comparing two important aspects found with that of the results obtained from the static simulation model of Case Study 2. The first of these aspects was an observation made and the other the calculation of the volume flow rate across the narrow annulus length.

The results displayed in Figure 70 and Figure 71, illustrate the symmetry of the flow trajectories across all planes and uniformity thereof over the entire area of the spindle head. The volume flow rate was calculated to be $0.012467 \text{ m}^3/\text{s}$ utilizing Equation 7. This value was confirmed with the results obtained from the FloEFD simulations, by measuring the volume flow rates at the inlet and outlet boundary conditions.

6.5.2 Case study 2

The results that were obtained from the FloEFD simulations conducted on the Case study 2 model setup, are illustrated in Figure 72. The corresponding magnified two-dimensional side view illustration in Figure 73, is used to better visualize the pressure distribution across the length of the misaligned spindle head with a 0.07 mm offset. To assist with the objective of comparing the results with that found in Case study 1, these results were presented with a similar view layout and coloured pressure distribution as was previously used.

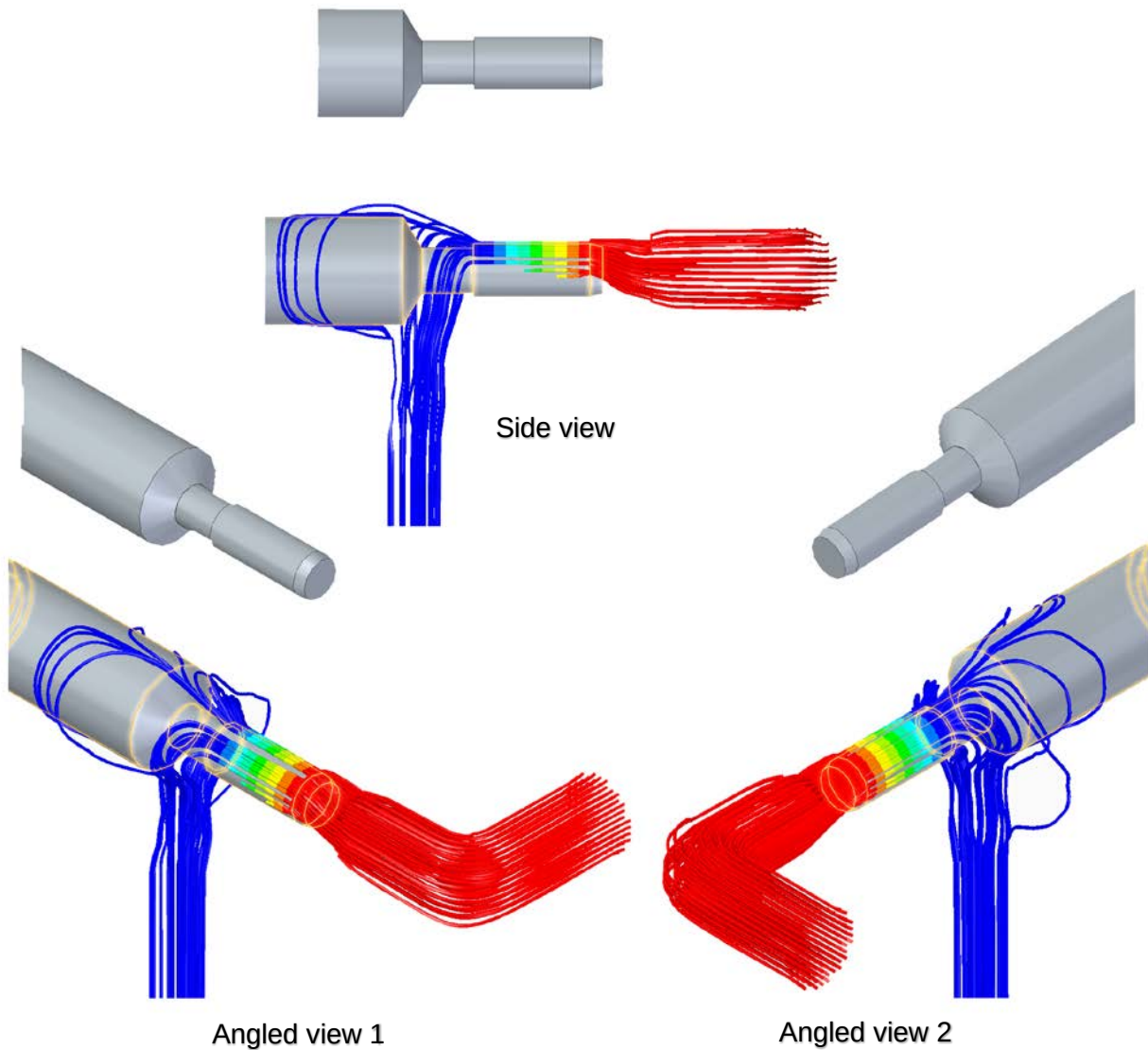


Figure 72: Case study 2 FloEFD hydraulic flow around the spindle visualized results.

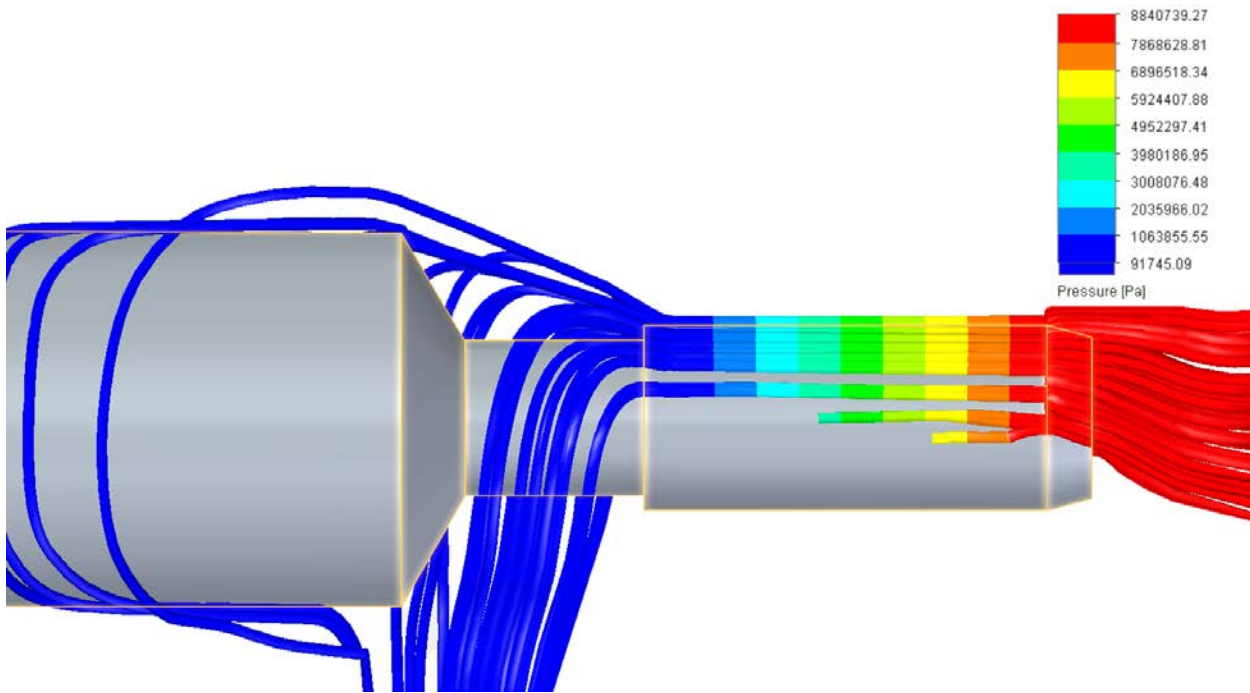


Figure 73: Case study 2 FloEFD pressure distribution across the spindle visualized results.

The flow trajectories illustrated in Figure 72 and Figure 73, follow a similar flow path as that of the flow trajectories displayed in Figure 70, but with one distinct difference. The symmetry of the flow trajectories across all planes and their uniformity over the entire area of the spindle head is broken. The majority of the hydraulic fluid volume flow follows a path over the top of the spindle head into the spindle body discharge chamber. This maldistribution of flow is due to the maximum 0.14 mm annulus gap that was formed, due to the misalignment of the decompression arrangement components.

The other concern that was identified from these results was the calculated flow rate. Due to the enlarged annulus gap at the top of the spindle head, its equivalent friction inflicted against the hydraulic fluid volume flow was decreased. Thus, the volume flow rate of the hydraulic fluid through the narrow annulus of a misaligned spindle inside the seat was calculated and confirmed to be eight times more than the volume flow rate of the same hydraulic fluid through the narrow annulus of a concentric spindle and seat arrangement.

6.6 New MK7 decompression arrangement design

The information and results that were obtained from the simulations and analyses conducted in this chapter, together with the test results presented in Chapter 5, were used in the concept drafting and subsequently the design of the new MK7 decompression arrangement.

The cross-section and isometric view of the general arrangement of the new MK7 decompression arrangement assembly is illustrated in Figure 74 [63]. In this illustration, the main focus areas are numbered. These marked areas are the key points that make the MK7 decompression arrangement unique, and are discussed:

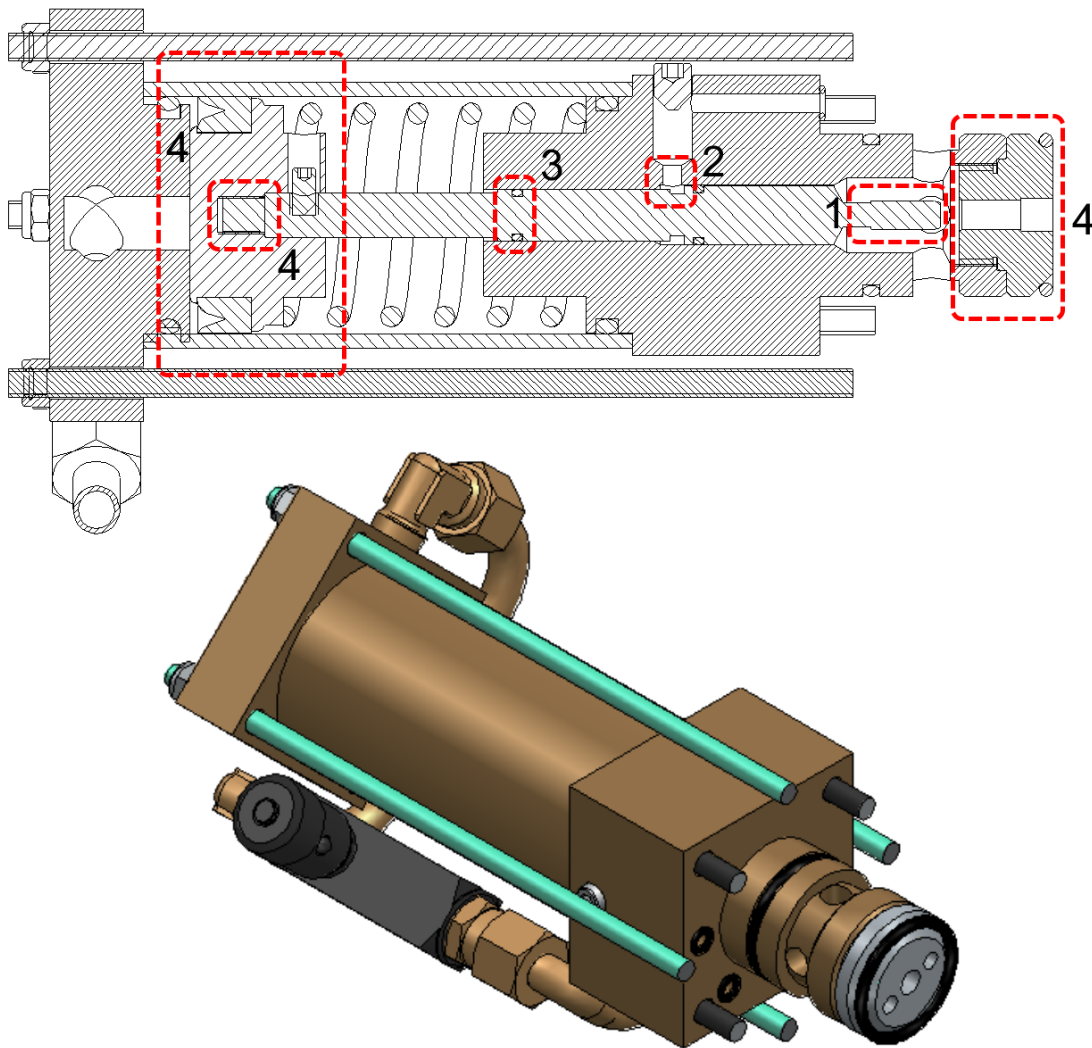


Figure 74: The cross-section and isometric views of the general arrangement of the new MK7 decompression arrangement assembly [63].

1. Narrow annulus size.

The multiple workshop and audit decompression cycle tests conducted in Section 5.6, and analysed with the conveyance displacement prediction model of Chapter 4, yielded the recommended annulus size of 0.07 - 0.08 mm. The spindle and seat geometries were altered to satisfy this requirement.

2. The sharp edge in the spindle body addressed.

The sharp edge, discussed in Section 6.2, that was located at the intersection of the balancing fluid cavity and the last chamfer in the spindle chamber in the spindle body, was eliminated. The spindle and spindle body was extended in length by a few millimeters, to allow the balancing fluid cavity to move away from the chamfer, without interfering with the functionality of the features.

3. The O-rings reclassified

The selected O-rings to be used in the MK7 decompression arrangement were all defined to have a material A-shore hardness of 90 shore. This decision was made due to the applied pressure to all O-rings during operation, which would be equal to the system operating pressure of 210 Bar, as specified in Table 6 [43].

4. The alignment of the decompression arrangement components.

The results obtained from the FloEFD CFD simulations presented in Section 6.5, emphasized the importance of the appropriate alignment of the decompression arrangement components. To achieve this desired alignment, and to ensure the spindle would move concentrically to the seat in a consistent manner, a few component adjustments were made. The spring collar and piston were redesigned to form one solid component. The spindle was extended and threaded to enable it to screw into the new piston-spring-collar component and be locked with a grub screw. By extending the spindle body and threading it, as well as threading the seat, it enabled these two components to be fixed to one another. With all these modifications, the new MK7 decompression arrangement was transformed into a secure and robust assembly, with all components assisting with the desired concentric alignment of the spindle in the seat.

This new MK7 decompression arrangement was one of the results of the knowledge obtained during this study. This new invention has been patented in WJ Engineering's name with patent reference number PA165722/ZA. Simultaneously, it was announced that all MK4 and MK5 Levelok cage power packs to be upgraded to the new MK7 and MK7s Levelok cage power packs, respectively, in order to address previous operational and safety concerns.

CHAPTER 7

MK7 & MK7S DESIGN

7.1 Introduction to new MK7 Levelok cage power pack range.

The objectives of this study included the investigation and understanding of the Levelok conveyance arresting system and the functionality of all the components thereof. The most important subsystem being the decompression arrangement assembly controlling the decompression cycle of the Levelok system. Numerous tests were conducted to identify the shortcomings of this critical mechanism, and based upon the test results improvements were made to ensure a more reliable and consistent decompression cycle output.

The new MK7 decompression arrangement assembly is the main feature distinguishing the MK7 & MK7s Levelok man, material cage power packs from their predecessors. The MK7 Levelok cage power pack is a unit only controlled by pneumatics, with the same control philosophy as that of the MK4 Levelok cage power pack. The MK7s Levelok cage power pack is the replacement of the MK5 Levelok cage power pack, incorporating a more complex electronic interlock control philosophy. This entails essential electronic equipment and accessories, not only installed on the Levelok hydraulic clamps and pneumatic accumulator but onto the Levelok cage power pack as well. The physical differences between the MK7 and MK7s power packs are illustrated in Figure 75 [63], and the corresponding clamping and unclamping procedures are represented in Annexure A [11].

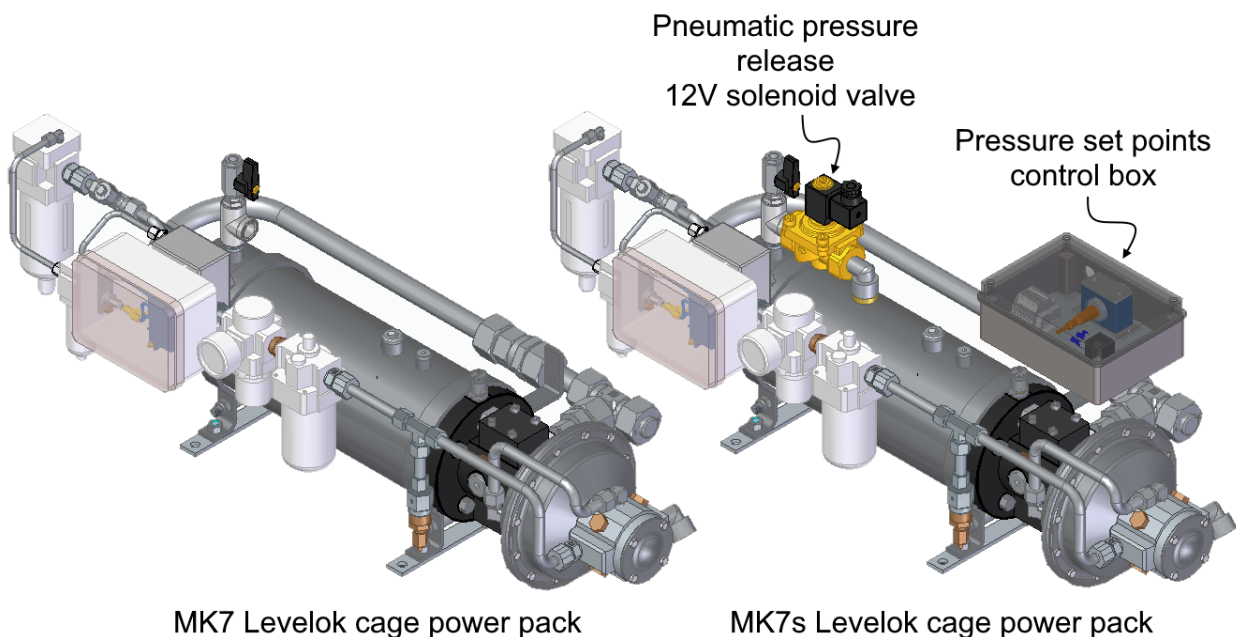


Figure 75: Illustration of the differences between the MK7 & MK7s Levelok cage power packs [63].

7.2 Client requirements and specifications for MK7s Levelok cage power pack

The MK7s Levelok cage power pack is the unit to be used in the Levelok cage man, material arresting systems installed on the two cages at Mine X. This power pack unit was specified according to the design specifications and system requirements discussed and decided upon between the engineering management of Mine X and WJ Engineering.

These design specifications and system requirements of Mine X's Levelok cage man, material arresting systems, are listed in Table 6 [43] of Section 3.2, and Table 7 [11] of Section 3.3, respectively. The information listed in these tables not only assisted with the selection of the recommended power pack to be used in the system but will also be used to identify which signals need to be transmitted from the conveyance to the winder driver display.

The initial step to assure all specifications and requirements of the hydraulic power pack and system is met, is to construct the hydraulic system circuit diagram of the complete system.

7.3 Hydraulic system circuit diagram

The hydraulic system circuit diagram of the MK7s Levelok system is fundamentally based upon the hydraulic system circuit of the old MK5 system. The system improvements and alterations that were made were done so as to satisfy the client's specifications and requirements as listed in Table 6 [43] Table 7 [11]. The Levelok system 4 clamp layout at Mine X and its corresponding MK7 hydraulic system circuit diagram are illustrated in Figure 76 and Figure 77 [74], respectively:

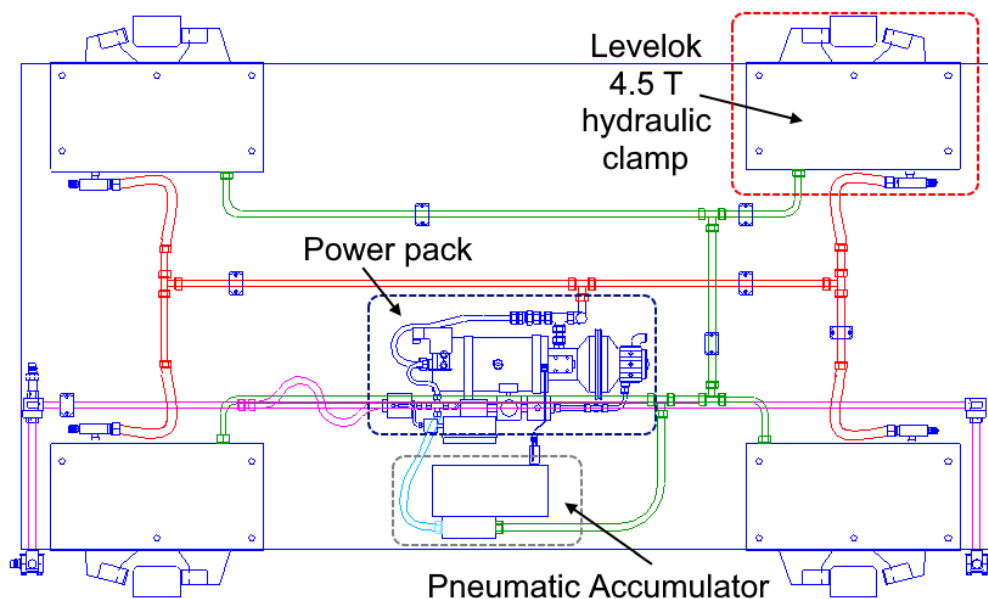


Figure 76: The 4 clamp Levelok system layout of the Mine X installed systems [74].

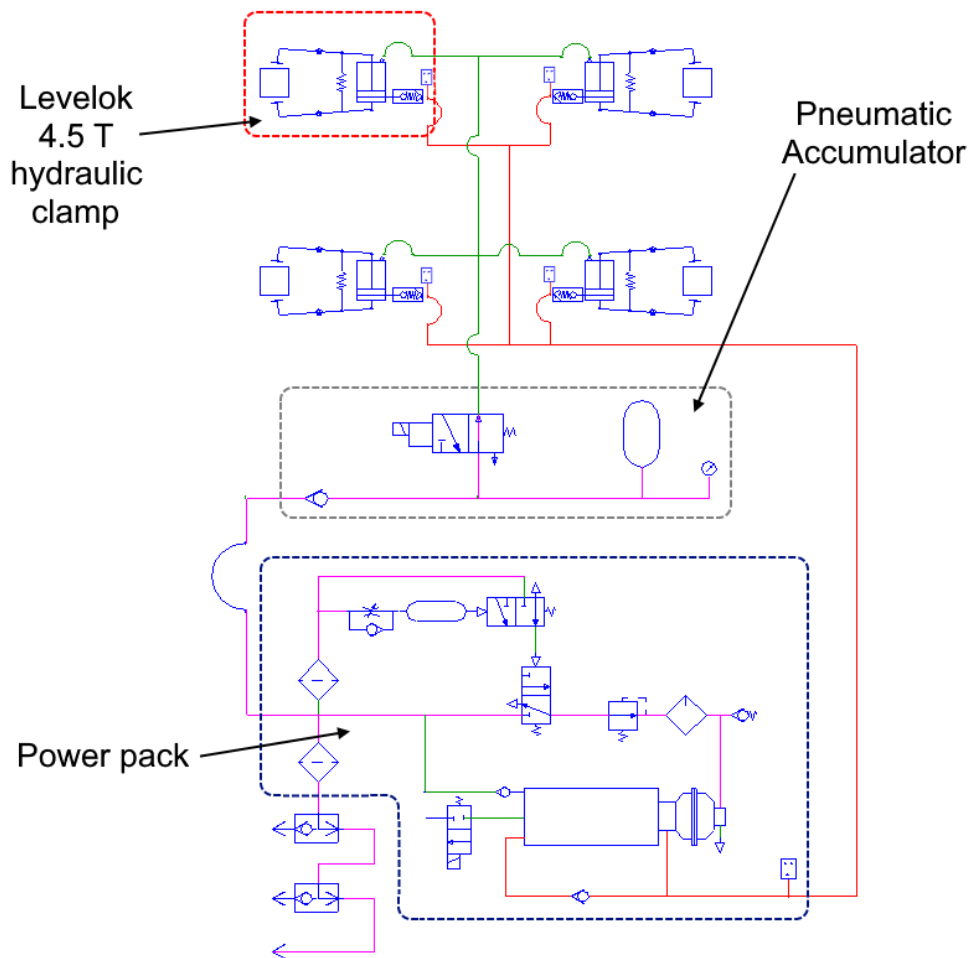


Figure 77: The MK7s hydraulic system circuit diagram [74].

To simplify the Levelok system layout and corresponding hydraulic system circuit diagram illustrated in Figure 76 and Figure 77 [74], all high-pressure hydraulic lines are coloured red, the pneumatic supply line to the power pack and the pneumatic accumulator is coloured magenta and the pneumatic line controlling the non-actuating side of the hydraulic clamps coloured in green. The Levelok hydraulic clamp unit is circled in red, the MK7s Levelok cage power pack unit in blue, and the pneumatic accumulator in grey on both diagrams. All other components and piping are installed separately onto the cage conveyance.

7.4 Components and 3D model design

The hydraulic system circuit diagram in Figure 77 [74], is used for assistance in selecting the required components to construct the 3D models of the three main components of the MK7s Levelok man, material cage arresting system. These 3D models are then used to draft machining details of the different sub-components for fabrication and machining.

7.4.1 4.5 Ton Levelok hydraulic clamp

The calculations completed in Chapter 3 & Annexure E [43], confirmed that the 4.5 Ton Levelok hydraulic clamps were an appropriate choice, according to the design specifications and system requirements. It was based on these findings that the decision was made to utilize the 4.5 Ton Levelok hydraulic clamps as is. Thus, the full design review of these clamps was not part of the scope and objectives of this dissertation. However, some changes to the control philosophy were made to accommodate these clamps.

These changes included the signals for the indication on the winder driver display, signifying the Levelok clamps have been released fully from the shaft guides. These signals are important to the interlocking circuit of the Levelok system, and also form part of the system requirements. On the old MK5 Levelok systems proximity switches or micro switches were used to send these signals, via the JT communication system, to the winder display. These components proved to be highly unreliable, not only due to possible wet conditions in the shaft but also due to the magnetic fields formed from all the high voltage cables that are also laid down the shaft. The decision was made to replace these displacement switches with programmable pressure switches connected to the individual clamp lock valves on the Levelok hydraulic clamps. The illustration in Figure 78 [5] [47] [74], shows this modification on the clamps and the corresponding alterations made to the hydraulic system circuit diagram.

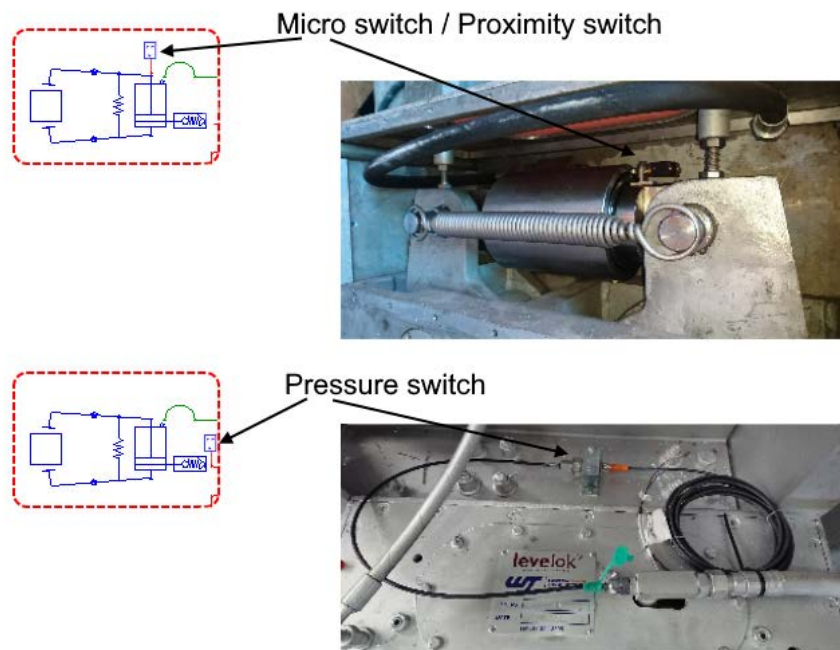


Figure 78: Illustration of equipment used to send a signal indicating clamps are fully open [5] [47] [74].

The pressure indication transmitting a pressure under 2 Bar proves that there is no hydraulic fluid in the actuating side of the Levelok clamp cylinders. This is a safe and reliable indication for full Levelok clamp release, and the conveyance is cleared to be hoisted. The 3D isometric model of the 4.5 Ton Levelok hydraulic clamp, constructed in Solid Edge, is illustrated in Figure 79 [75].

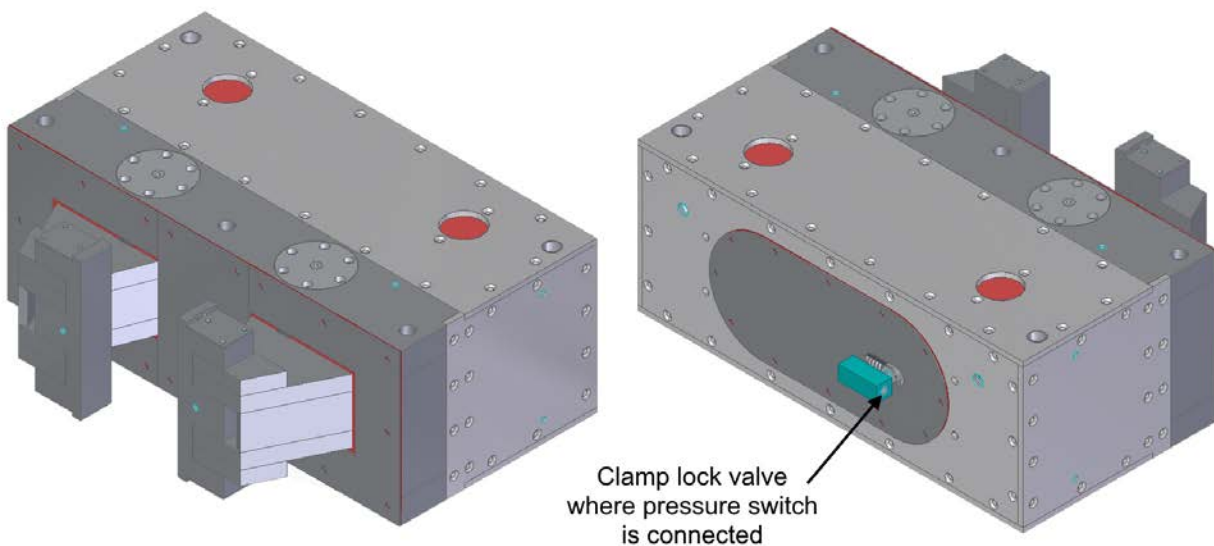


Figure 79: Isometric views of the 4.5 Ton Levelok hydraulic clamps used in the Mine X installed systems [75].

These clamps are fitted with double-acting cylinders, meaning the actuating side of the cylinders are hydraulically operated, but the reverse action is assisted with a pneumatic accumulator. The pneumatic pressure is used to assure clamp release, and to do so smoothly.

7.4.2 Pneumatic accumulator

The test conducted in Chapter 5, Section 5.3, revealed the negative effect the pneumatic accumulator had on the decompression cycle output when its pressure was released prematurely into the system. The purpose of the pneumatic accumulator is not to assist with the decompression release, but rather to assure the clamps are fully retracted from the shaft guides after release has been completed.

The old MK5 Levelok pneumatic accumulator made use of a pneumatically operated 2 to 3-way valve controlling the pressure release. The pneumatic pressure controlling this valve was piloted from the pressurized hydraulic reservoir tank of the MK5 Levelok cage power pack. As soon as the pressure in the cage power pack was released to initiate the decompression cycle, the piloted pneumatic pressure to the 2 to 3-way valve would fall away and the valve would open too early. The illustration in Figure 80 [5] [77], displays the isometric views of the MK5 Levelok pneumatic accumulator with its components as discussed, together with its corresponding hydraulic circuit diagram.

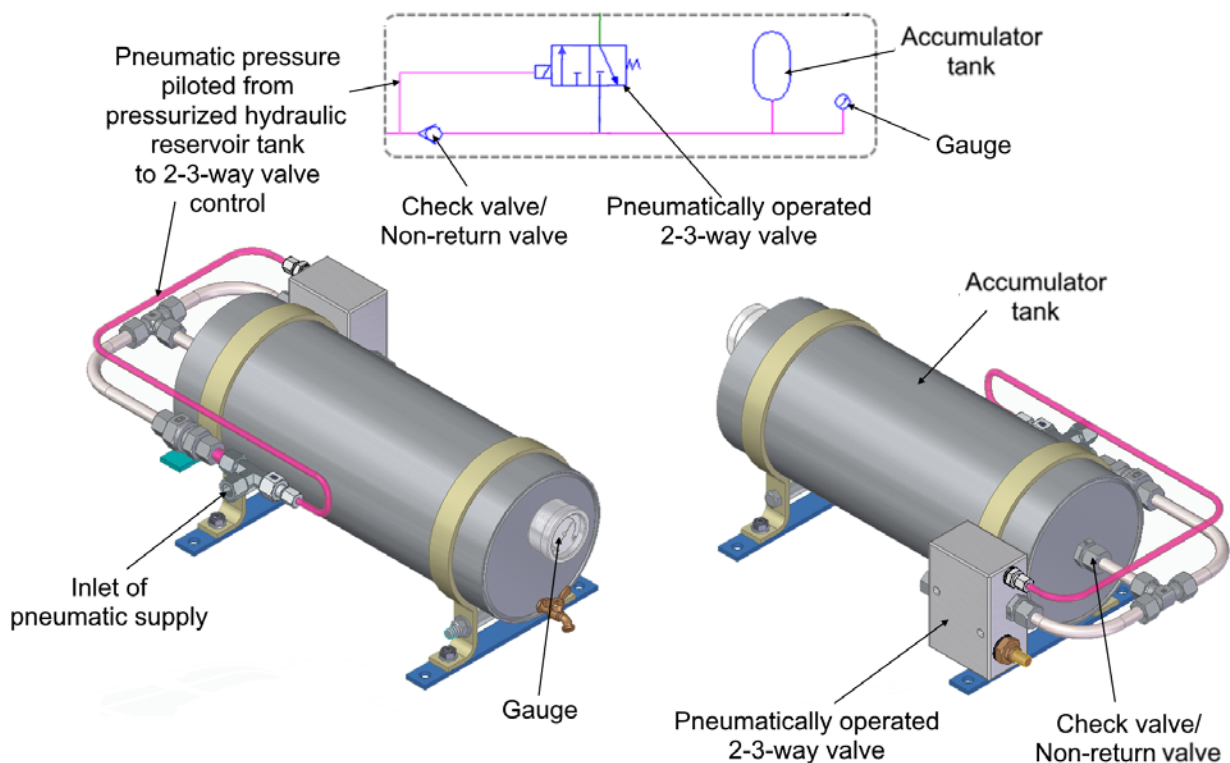


Figure 80: MK5 Levelok pneumatic accumulator with the corresponding hydraulic circuit diagram [5] [77].

A solution was found to counter this unintended behaviour of the Levelok pneumatic accumulator and was implemented in the MK7s system. The pneumatically operated 2 to 3-way valve was exchanged with a 12V DC solenoid 2 to 3-way valve. This allowed the pneumatic accumulator to receive a signal from the MK7s Levelok cage power pack signifying the end of the decompression cycle, before the 2 to 3-way valve would open to release its pressure to the clamp cylinders.

These alterations to the control philosophy assured the pneumatic accumulator would release its assistance pneumatic pressure to the clamp cylinders after the decompression cycle was completed. The illustration in Figure 81 [74] [76], displays the MK7 Levelok pneumatic accumulator with its components as discussed, together with its corresponding hydraulic circuit diagram.

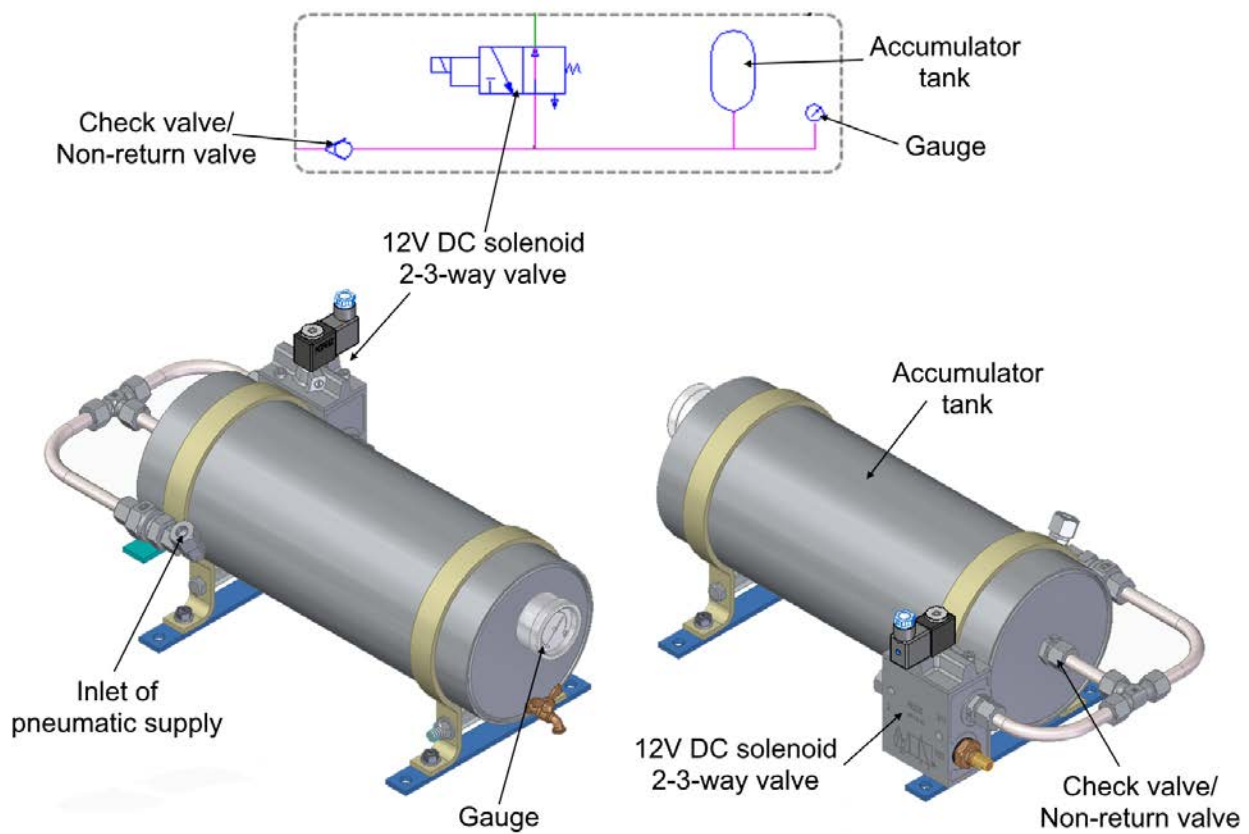


Figure 81: MK7s Levelok pneumatic accumulator with the corresponding hydraulic circuit diagram [74] [76].

7.4.3 MK7s Levelok cage power pack

Throughout this dissertation, the main focus has been the Levelok cage power pack. This included the research completed on the purpose and functionality of this complex pneumatically controlled hydraulic unit. The different types of Levelok cage power packs that have been developed over the years were experimentally tested and analysed. From the results obtained, the main shortcomings of the Levelok cage power packs were identified and addressed. As mentioned, the new MK7 decompression arrangement design was one of the outputs based on the knowledge obtained during this study and is the main feature distinguishing the MK7 & MK7s Levelok man, material cage power packs from their predecessors.

This crucial assembly with the unchanged pump body unit with all its accessories (the same as that of the old MK4/MK5 Levelok cage power packs), completed the internal components of the MK7s Levelok cage power pack. The illustration in Figure 82 [63] [74], illustrates how the decompression arrangement assembly is covered with the hydraulic fluid reservoir (the size was confirmed in Chapter 3, to be efficient), and how these components are assembled. Figure 82 [63] [74] also demonstrates where this assembly is located in the hydraulic circuit diagram of Figure 77 [74].

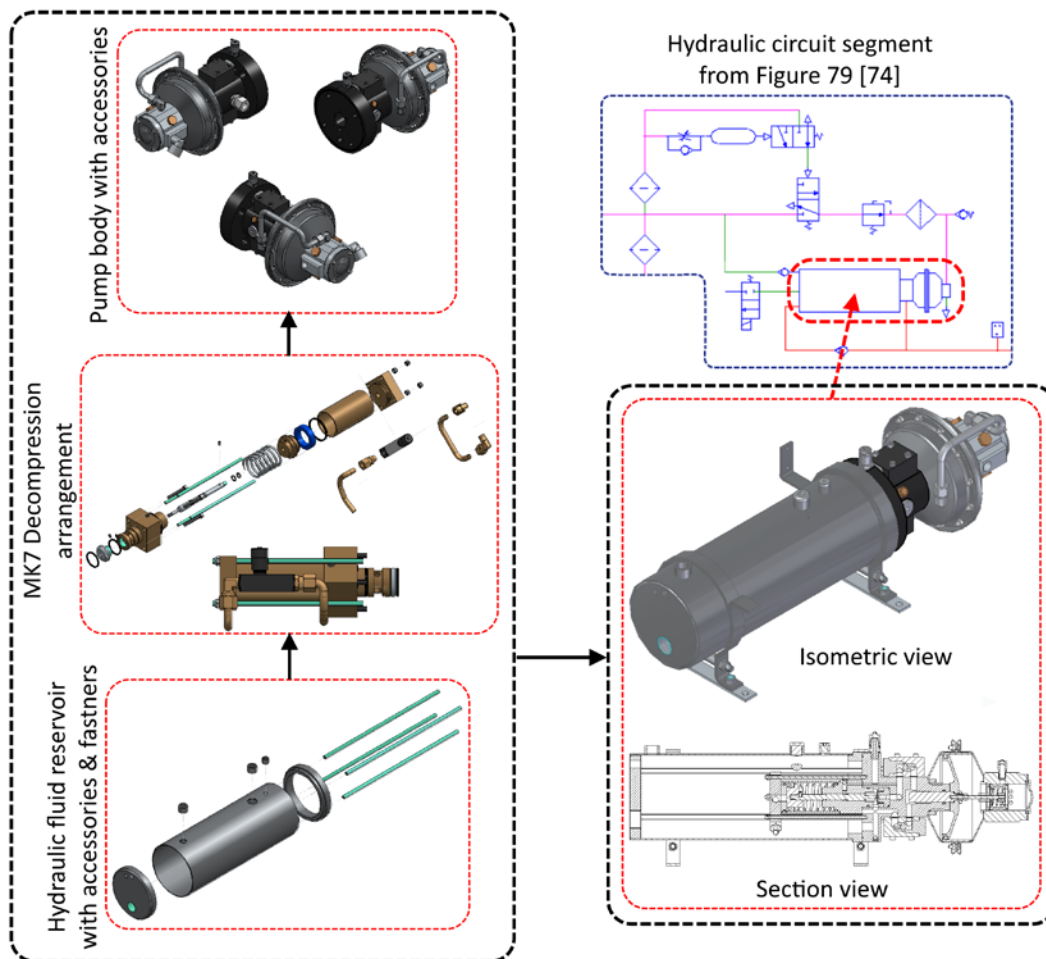


Figure 82: MK7s Levelok cage power pack internal components assemble [63] [74].

The detailed explanation laid out in Section 2.3.1, explains how the decompression arrangement assembly and the pump body function together to complete the objectives of clamping and unclamping of the Levelok system. To attain these objectives, Section 2.3.1 also explains how pneumatic pressure is utilized to activate these two components and how it is transported from the pneumatic supply, through all the airline components (while describing their different functions) and then through to the different ports of the power pack where pneumatic pressure are needed.

The airline was identified as the subassembly installed on the Levelok power pack unit to regulate the required pneumatic pressure. It was discussed that the airline of the MK6 Levelok cage power pack was slightly different from that of the MK4 & MK5 airlines, but that the components and their functions were still similar, as illustrated in Figure 12 [4] [30] [31] of Section 2.3.1.

With the design of the MK7 Levelok cage power pack range, it was decided, based upon the availability of the components and the robustness of the components itself, that the old airline schematic of the MK4 & MK5 systems would be used. However, the decompression tests conducted and the results thereof, documented in Section 5.3, identified the pneumatic assisted 12V DC pneumatic pressure release valve as the component that caused a delay in the required fast pressure decline in the first few seconds of the decompression cycle. With the exchange of this pneumatic assisted valve with a fully-open-fully-closed 12 V solenoid valve, the decompression curve would be rectified. Thus, this exchange was decided upon during the selection of the required components for the MK7 Levelok cage power pack range airline assembly.

The illustration in Figure 83 [63] [74], associate these different components of the airline to their respective symbols in the hydraulic circuit diagram segment from Figure 77 [74], and shows how the airline is fitted to the base assembly of Figure 82 [63] [74]:

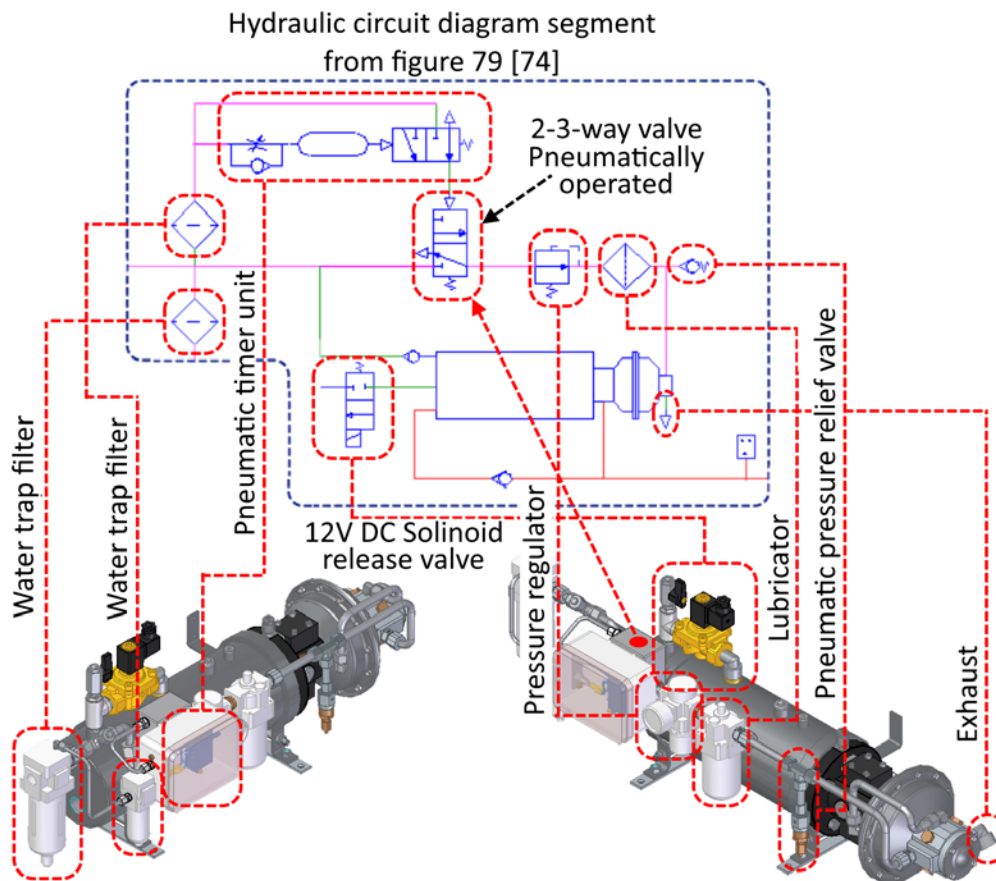


Figure 83: Illustration of the airline components referenced to their respective symbols in the hydraulic circuit diagram segment [63] [74].

In Section 2.3.1, it was explained that when the pneumatic pressure supply is connected to the conveyance, the pressure reaches the Levelok cage power pack via pneumatic piping. The pneumatic pressure is first directed into the fluid reservoir of the power pack, with the objective of pressurizing it, and the hydraulic fluid inside of it. With this pressurization of the hydraulic fluid in the fluid reservoir, hydraulic fluid is pushed through the fluid reservoir outlet to the actuating side of the clamp cylinders, via hydraulic piping installed to the Levelok power packs and onto the conveyance as illustrated in Figure 77 [74].

As mentioned, this is to allow for the “The fast approach” of the Levelok clamps before high-pressure clamping. Figure 84 [63] [74] with its reference to the hydraulic circuit diagram in Figure 77 [74], illustrates the hydraulic piping and fittings added to the MK7s cage power pack, to assist with this important “The fast approach” function.

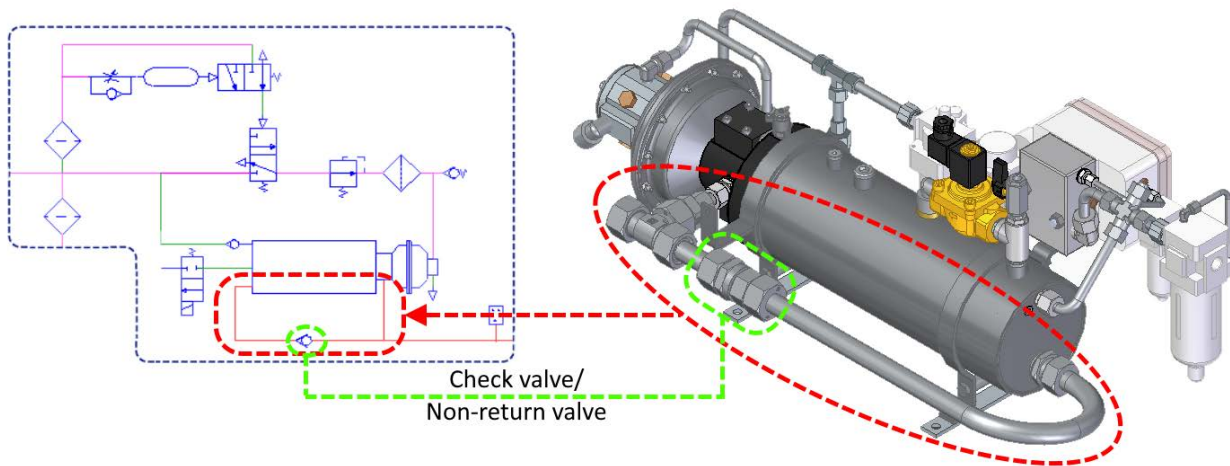


Figure 84: Illustration of the hydraulic piping and fittings added to the MK7s Levelok cage power pack, to assist with “The fast approach” function [63] [74].

The Levelok cage power pack is used to transfer pneumatic pressure into hydraulic pressure. The pressure ratio between these pneumatic and hydraulic pressures of the MK7 range of power packs is 1:60. The illustration in Figure 84 [63] [74], also defines the position of the high-pressure check valve fitting. This is the component that allows the low-pressure hydraulic fluid to pass through, allowing “The fast approach” function, but also protects the hydraulic fluid reservoir from these high-pressures generated from the Levelok cage power pack, that would flow in the opposite direction.

The final component to be addressed from the hydraulic circuit diagram in Figure 77 [74], is the pressure switch in the high-pressure hydraulic line circuit. This pressure switch is used to satisfy the system requirement of supplying a signal at 180 Bar system pressure to the communication system of the conveyance.

The MK5 Levelok cage power pack was fitted with a normal diaphragm pressure switch. During numerous audit and workshop tests conducted, it was found that these types of pressure switches were unpredictable and unreliable. Also, this type of pressure switch only consists of one switch point, and with the exchange of the release valve on the pneumatic accumulator to a 12V DC operated 2 to 3-way valve, two switch points would be required.

The MK7s Levelok cage power pack was fitted with an IO-Link pressure switch from IFM Electronics, which has proven itself to be more consistent and reliable and consists of two switch points. This usage of these switch points will be discussed in detail in Section 7.5.

The illustration in Figure 85 [47] [73] [74], shows the difference between the diaphragm and IO-Link pressure switches, where it is located on the hydraulic circuit diagram and where the minitest fitting is located on the Levelok cage power pack where the pressure switch is connected.

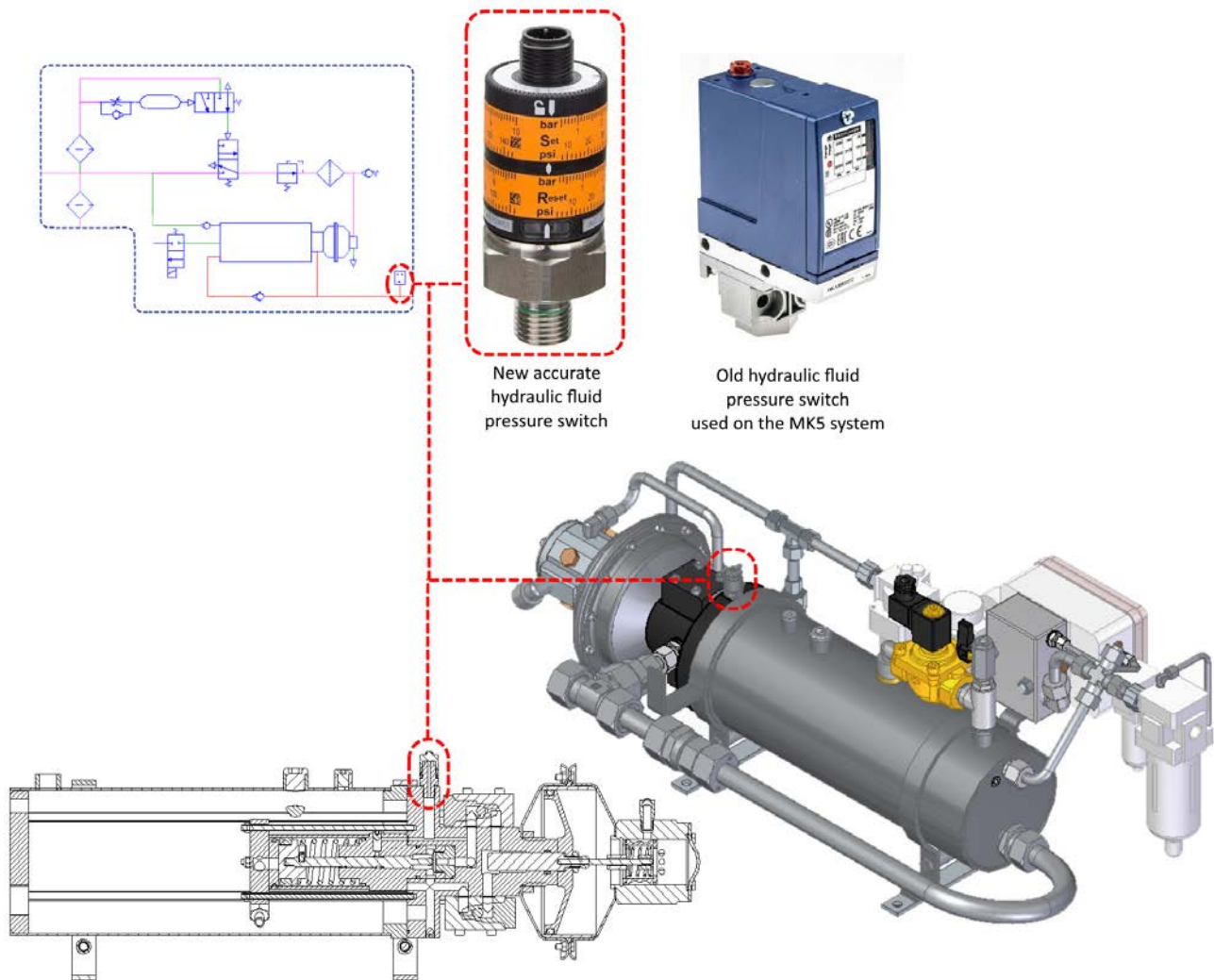


Figure 85: Illustration of the pressure switches used on the MK5 & MK7s Levelok systems, together with the illustration of the location of attachment on the Levelok cage power pack [47] [63] [74].

7.5 Control design & interlock circuit signals

An electrical interlock is a feature that makes specific system components or procedures dependant on specific electrical signals communicated to the system control. The OEM of the Levelok system is not responsible for the interlock system, but is required to supply the required signals to be used by mining personnel to construct these interlock circuits in the winder house control panels.

The 12 V DC electrical control design of the MK7s Levelok man, material cage system, together with its required interlock output signals were constructed from the defined design specifications and system requirements of Mine X's Levelok systems.

In this section, each of these requirements and specifications is addressed with its corresponding Levelok component involved, and are then used to combine and structure an MK7s Levelok man, material cage system electric circuit diagram.

7.5.1 4.5 Ton Levelok hydraulic clamp

The system requirement of each Levelok clamp to be fitted with a programable pressure switch for pressure measurement in the individual clamp cylinders was set for the use of two functions. The first is to use these signals for the indication of individual clamping functionality purposes on the winder driver display. The other was to use these signals in the interlock circuit of the winder machine, to assure all clamps are disengaged from the shaft guides completely before the winder brakes can be released for hoisting. This interlock is constructed to protect equipment, shaft steelwork, and personnel.

These four signals supplied by the individual pressure switches are obtained by a positive setpoint signal set at 2.2 Bar. The JT communication system on the conveyance receives these signals and sends it to the winder house PLC. A logic diagram of this control is illustrated in Figure 86 [50].

The pressure switch numbering system in this logic diagram was adopted from Mine X's numbering system, and works as follow:

PS = Pressure switch, **C** = Clamp, **N** = North, **S** = South, **L** = Left *and* **R** = Right

Thus,

PSCNL = Pressure switch Clamp North Left

This indicates the pressure switch signal received from the Levelok clamp on the back end, left side of the conveyance when facing the conveyance with the winder house behind you.

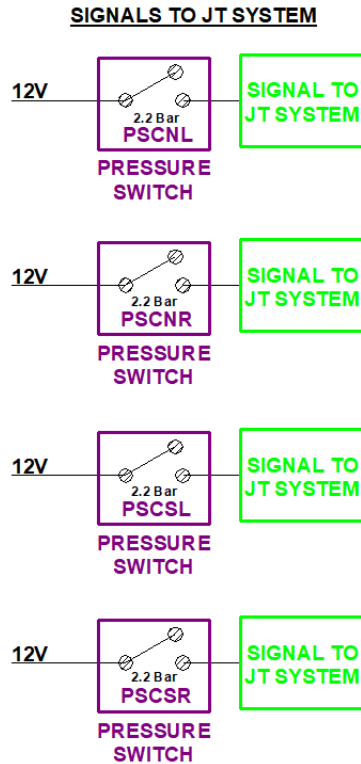


Figure 86: Logic diagram of the setpoints of pressure switches of each individual clamp, sent to the JT communication system [50].

7.5.2 Pneumatic accumulator

There are no signals required from the pneumatic accumulator to the system control or the interlock circuit. However, with the exchange of the pneumatic operated release valve to a 12V DC operated 2 to 3-way valve, as discussed, a signal from the MK7s Levelok cage power pack signifying the end of the decompression cycle is required to allow the pneumatic accumulator to release its pressure to the clamp cylinders. This is why a second switch point is required from the main pressure switch fitted to the power pack.

This signal of signifying the end of the decompression cycle is received from a positive setpoint on the main pressure switch, set at 12.5 Bar. The logic diagram for the pneumatic accumulator is constructed in Figure 87 [50].

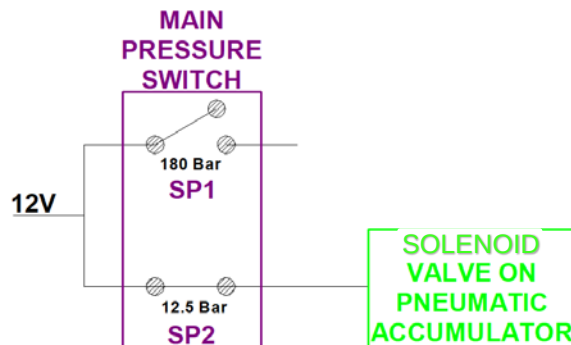


Figure 87: Logic diagram of activating the solenoid release valve on the pneumatic accumulator [50].

7.5.3 MK7s Levelok cage power pack

The system requirement, of supplying a signal when the system hydraulic pressure reaches 180 Bar, was set to enforce safety protocols and generate interlocks to assure the safety of all personnel during the use of the Levelok system. This signal is obtained from the main pressure switch fitted to the MK7s Levelok cage power pack, as illustrated in Figure 85 [47] [73] [74].

This signal, that is sent to the JT conveyance communication system, is used for:

- the activation of the safety lights installed on the conveyance for use during Levelok system operation,
- an extra indication on the winder driver display,
- and is added to the interlocking circuit of the winder machine, to assure the release of the Levelok system before the winder brakes can be released for hoisting.

The set point of this signal from the main pressure switch is set at 180 Bar, as specified in the design specifications. The logic diagram for the Main pressure switch fitted to the Levelok cage power pack, is constructed in Figure 88 [50].

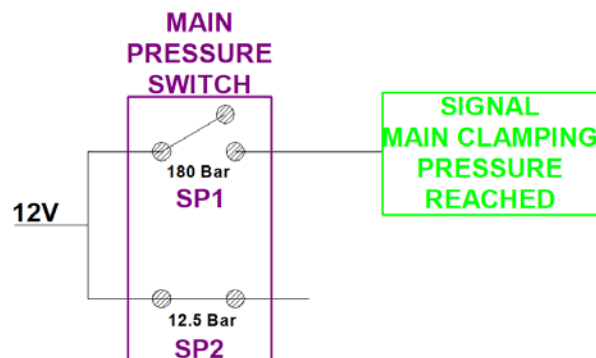


Figure 88: Logic diagram of signaling main clamping pressure reached [50].

The unclamping of the Levelok system was discussed in Section 2.3.1, and in the clamping and unclamping procedures set out in Annexure A [11], where it is defined that a Levelok release button is pushed on the onsetter's control panel to send a signal to the JT conveyance communication system, to initiate the unclamping procedure. A positive 12 V DC voltage, set on a timer, is sent to the solenoid release valve on the Levelok power pack (See Figure 83 [63] [74]) for one minute. This same timed voltage supply is used for the solenoid release valve on the pneumatic accumulator.

7.5.4 MK7s Levelok man, material cage system electric circuit diagram

The logic diagrams in Figures 86 to 88 were used to assist with the design of the MK7s Levelok man, material cage system electric circuit diagram, which is illustrated in Figure 90 [78]. This is a normal 12 V DC system, all red and blue coloured lines represent the positive and negative wire connections, respectively, supplying all instruments with electrical current. The black and green coloured lines represent all signal connections.

The black connections represent all the signals supplied to the JT conveyance communication system for indication and interlock purposes. These include all the signals sent from the programmable pressure switches connected on each Levelok clamp (See Figure 86 [50]), together with the 180 Bar main system pressure signal from the main pressure switch's set point one (See Figure 88 [50]). These are all normally open connections, meaning positive signals are received as soon as the state of each setpoint of the instruments is true.

The signal from setpoint two of the main pressure switch, represented by the green wire connection, is also a normally open connection. This connection was inverted to a normally close connection using a 12 V DC 25A 5-pin relay. The reason for this inversion, is to ensure that the pneumatic accumulator will release after the main pressure in the system has dropped under the 12.5 Bar set point requirement, as illustrated in the logic diagram in Figure 87 [50]. Thus, the state of the main pressure switch instrument needs to be false to sustain power to the 12 V DC solenoid valve on the pneumatic accumulator.

The two 12 V DC solenoid release valves, the GHD release valve on the Levelok power pack and the M1 release valve on the pneumatic accumulator, are connected to a timer supply from the JT conveyance communication system.

This design requires two junction boxes. Junction box one is only fitted with terminals for power and signal distribution, whereas Junction box 2 is fitted with terminals, a pressure switch, and a relay installed to the MK7s Levelok cage power pack as illustrated in Figure 89 [63].

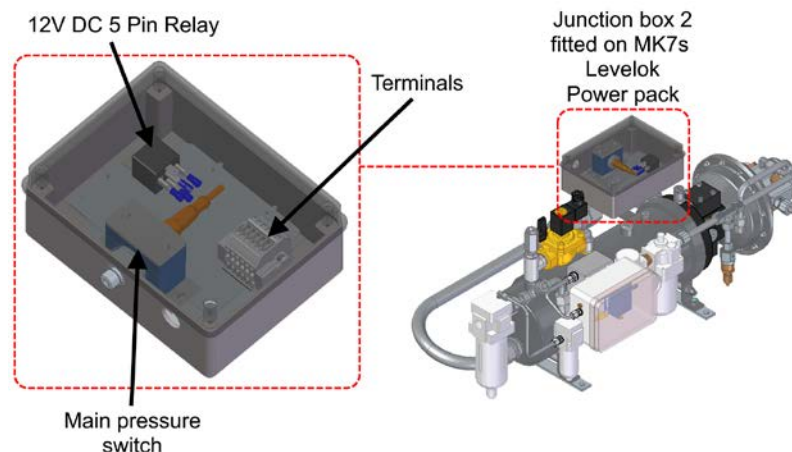


Figure 89: Junction box 2 installed to an MK7s Levelok cage power pack [63].

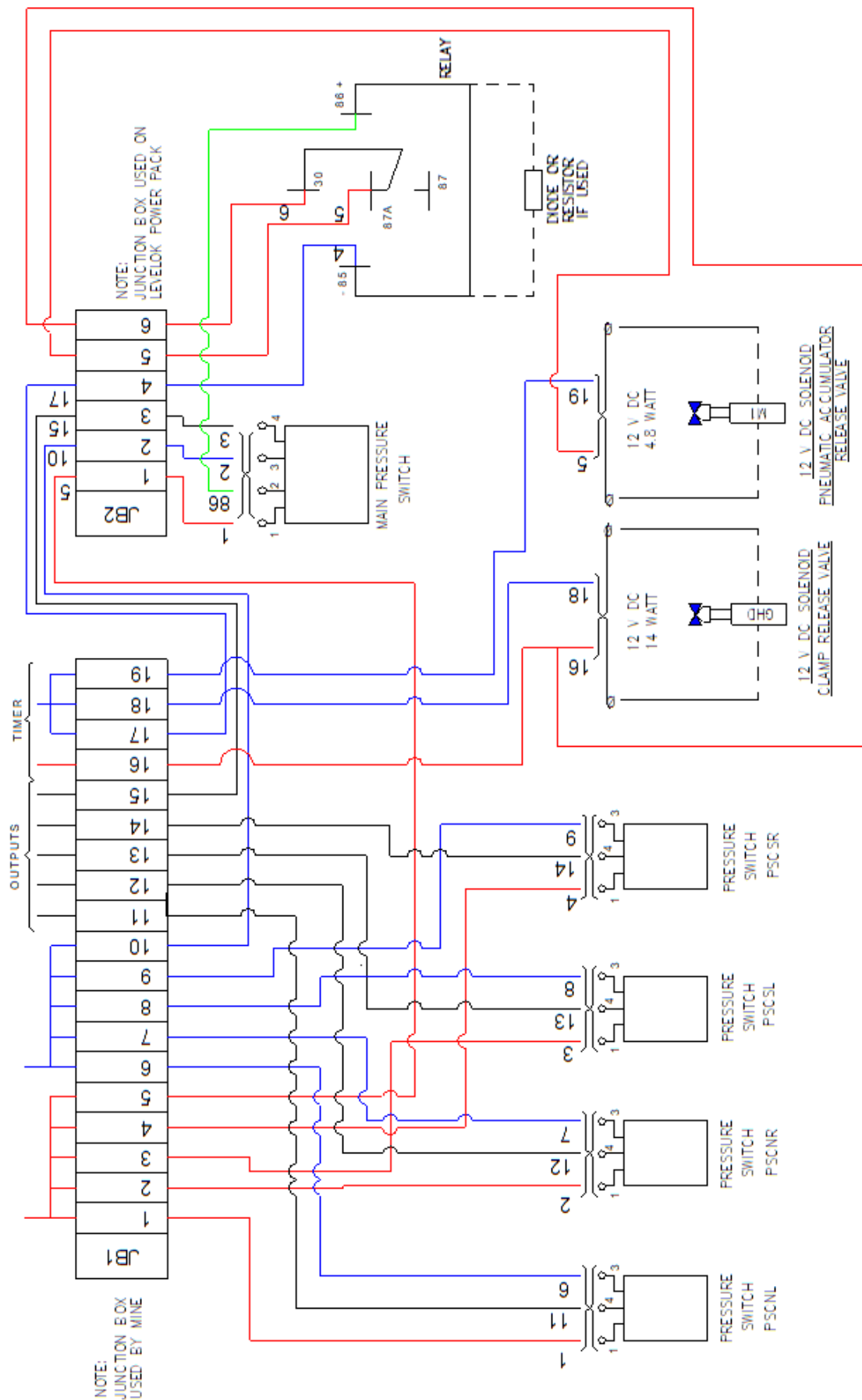


Figure 90: The MK7s Levelok man, material cage system electric circuit diagram [78].

CHAPTER 8

MK7 ELEC DESIGN

8.1 Introduction to new MK7 Elec Levelok cage power pack.

The MK7 Elec Levelok cage power pack was designed by request of the engineering management of Mine X. Their ever-increasing problem of supplying clean, water-free pneumatic pressure to all Levelok operated shaft levels, at a minimum gauge pressure of 4 Bar, forced them to explore other sources to operate the Levelok systems without the use of pneumatics.

The MK7 Elec Levelok cage power pack is a more complex 24 V DC operated unit, with no pneumatic pressures required. This unit relies upon a 24V electrical motor and hydraulic gear pump to generate hydraulic fluid pressures which are stored in four 10 liter hydraulic accumulators. This Levelok cage power pack consists of manifold blocks installed with solenoid operated directional valves, check valves, throttle valves, and a decompression cycle arrangement, which supplies the Levelok cage system with high and low-pressure hydraulic fluid for the clamping and unclamping sequences. The clamping and unclamping procedure of the MK7 Elec Levelok cage power pack is described in Annexure A [11].

The control philosophy is somewhat similar to that of the control philosophy of the Levelok skip power pack, with the main difference being, that all the MK7 Elec Levelok cage power pack unit's electrical components and signals are operated with a 24 V DC relay logic control, and not a PLC.

The MK7 Elec Levelok cage power pack with its control panel installed to the 3-deck conveyance, is illustrated in Figure 91 [79]:

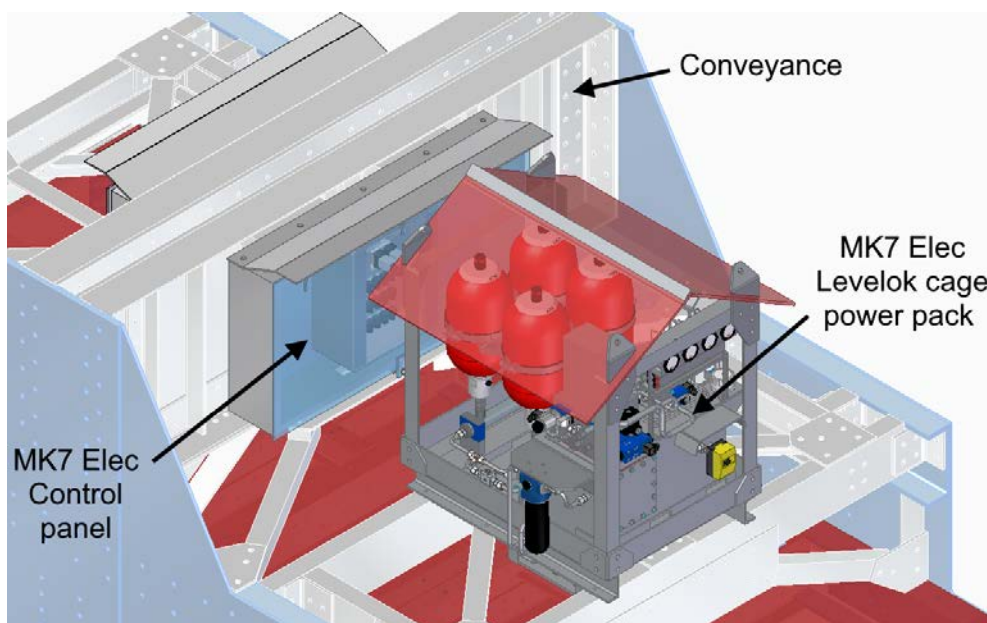


Figure 91: The illustration of the MK7 Elec Levelok cage power pack with its control panel installed to the 3-deck conveyance [79].

8.2 Client requirements and specifications

The same design specifications and system requirements of Mine X's Levelok cage man, material arresting systems, which are listed in Table 6 [43] of Section 3.2, and Table 7 [11] of Section 3.3, respectively, apply to the MK7 Elec Levelok man, material cage system. Thus, all required signals required for indication purposes (indication on the winder driver display and lights on the conveyance), and signals required by the interlock system have stayed unchanged.

The only client requirements that have been added are for the Levelok cage power pack to be operated with a DC current and not pneumatics.

The initial step to assure all specifications and requirements of the hydraulic power pack and system are met is to construct the hydraulic system circuit diagram of the complete system MK7 Elec Levelok system.

8.3 Hydraulic circuit diagram

The hydraulic system circuit diagram of the MK7 Elec Levelok system has the same basic elements as that of the Levelok skip system's hydraulic system circuit. These basic elements, together with their sequence operational procedures, were discussed in Section 2.3.2, Chapter 2.

The hydraulic system circuit of the MK7 Elec Levelok system includes only one electric motor hydraulic gear pump assembly which supplies high-pressure fluid to four 10 liter hydraulic fluid accumulators. The hydraulic circuit also consists of only 1 decompression arrangement assembly that controls the clamping and unclamping sequences of four 4.5 Ton Levelok cage clamps.

The Levelok system 4 clamp layout at Mine X and its corresponding MK7 hydraulic system circuit diagram are illustrated in Figure 92 and Figure 93 [80], respectively:

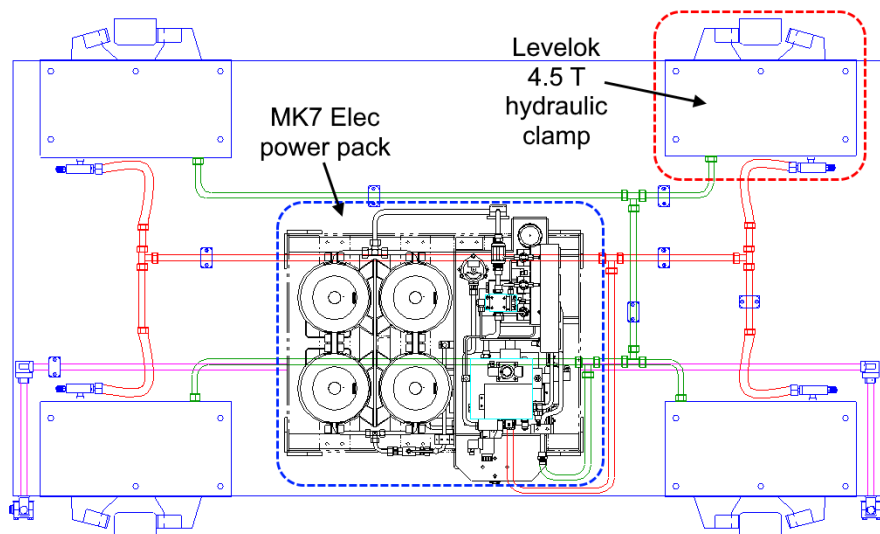


Figure 92: The 4 clamp Levelok system layout of the Mine X installed systems [80].

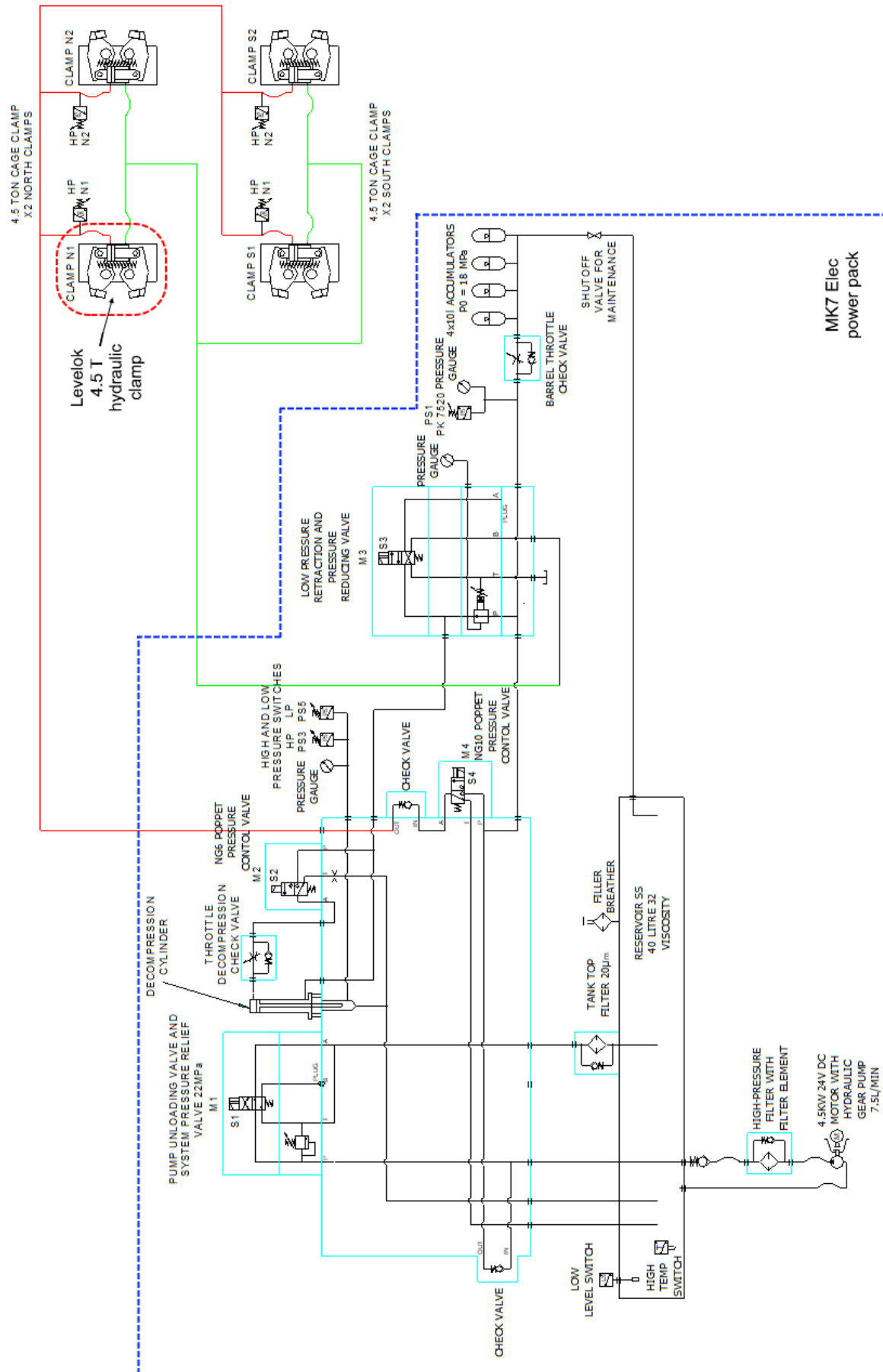


Figure 93: The MK7 Elec hydraulic system circuit diagram [80].

To simplify the four clamp Levelok system layout and corresponding MK7 Elec hydraulic system circuit diagram illustrated in Figure 92 and Figure 93 [80], all high-pressure hydraulic fluid lines are coloured red, the low-pressure hydraulic fluid lines assisting with the retraction of the Levelok clamps are coloured in green. The magenta-coloured piping is the representation of a steel conduit containing the electrical wires coming from the clamp and unclamp buttons, situated on each deck of the conveyance. On both diagrams the Levelok hydraulic clamp unit is circled in red, the MK7 Elec Levelok cage power pack unit in blue, and the manifold blocks fitted to the power pack are represented with the aqua lining. All other components and piping are installed separately onto the cage conveyance.

8.4 Components and 3D model design

The hydraulic system circuit diagram in Figure 93 [80], is used for assistance in selecting the required components to construct the 3D models of the main components of the MK7 Elec Levelok man, material cage arresting system. These 3D models are then used to draft machining details of the different sub-components for fabrication and machining.

8.4.1 4.5 Ton Levelok hydraulic clamp

The 4.5 Ton Levelok hydraulic clamp's technical design specifications and system requirements, remained unchanged for the use in the MK7 Elec Levelok system and have been discussed in Chapter 3 of this dissertation. The components used in these Levelok clamps and the 3D modeling thereof were constructed in Section 7.4.1 (See Figure 79 [75]). The same programmable pressure switches are used to send the clamp and unclamp signals to the JT conveyance communication system for further distribution and usage.

The only alteration that was made to the 4.5 Ton Levelok clamps, was that of the hydraulic seals used in the clamp cylinders. The pneumatically controlled clamp retracting side of the double-acting cylinder would be controlled with 60 Bar of hydraulic fluid pressure, using the MK7 Elec Levelok cage power pack. Thus, the specifications on the hydraulic seals were revised and the hydraulic seals changed accordingly, and the area in question is displayed in Figure 94 [82].

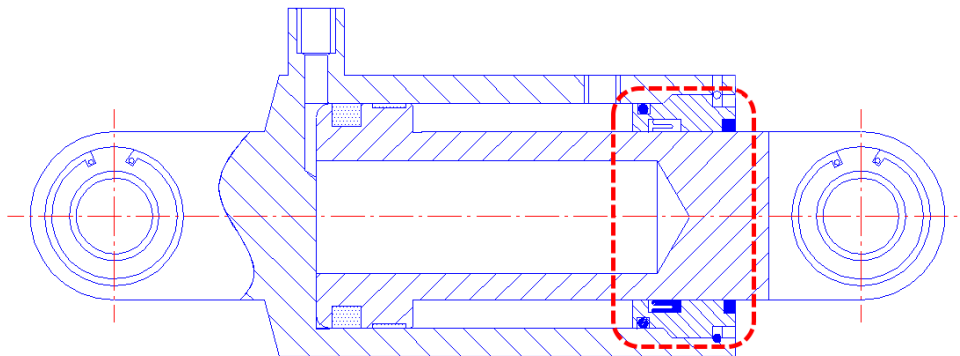


Figure 94: Illustration of the hydraulic seals which were altered for the use in the MK7 Elec Levelok system [82].

8.4.2 MK7 Elec Levelok cage power pack

The 3D model design of the MK7 Elec Levelok cage power pack was completed by using the hydraulic system circuit diagram illustrated in Figure 93 [80]. This was done to assure the MK7 Elec Levelok system satisfies the required design specifications and system requirements, as stipulated in Section 8.2.

These factors included the number of hydraulic accumulators required in the system, the size of the hydraulic fluid reservoir, and the power output of the electric motor fitted with a hydraulic gear pump. To calculate the accumulator storage needed, the minimum and maximum allowable pressures had to be defined. The minimum allowable pressure was identified to be the interlock main pressure value set at 180 Bar (P_2). The Levelok system's hydraulic pressure cannot deviate under this critical pressure point during the clamp arresting of the cage conveyance. If the system pressure deviates under this required interlock pressure, the interlock circuits could be deactivated during clamping operation and cause a dangerous situation for mining personnel. The maximum pressure can be defined as the system pressure of 210 Bar (P_3), as stipulated in Table 6 [43], Section 3.2.

If it is assumed that the precharge nitrogen gas in the hydraulic bladder accumulators is compressed isothermally from the precharge pressure to the system pressure P_3 , Boyle's gas laws can be used to calculate the nitrogen gas and hydraulic fluid volumes in the accumulators.

Hence Equations 23 & 24:

$$\therefore P_3 \times V_3 = P_1 \times V_1 \quad (23)$$

$$V_3 = \frac{P_1}{P_3} \times V_1$$

$$V_3 = 0.7714V_1 \quad (24)$$

Where

P_3 = System pressure [Pa]

V_3 = Volume of hydraulic fluid [m^3]

P_1 = Precharge, $0.9P_2$ [Pa]

V_1 = Required accumulator volume [m^3]

P_2 = Main pressure [Pa]

It is also assumed, with the initiation of the clamping sequence, that the hydraulic bladder accumulators would discharge adiabatically to the minimum allowable system pressure P_2 .

Hence Equations 25 & 26:

$$\therefore (P_3 \times V_3)^{1.4} = (P_2 \times V_2)^{1.4} \quad (25)$$

$$\text{Where } V_3 = 0.7714V_1$$

$$V_2 = 0.9572V_1 \quad (26)$$

Where

$$P_3 = \text{System pressure [Pa]}$$

$$V_3 = \text{Volume of hydraulic fluid [m}^3\text{]}$$

$$P_1 = \text{Precharge, } 0.9P_2 \text{ [Pa]}$$

$$V_1 = \text{Required accumulator volume [m}^3\text{]}$$

$$P_2 = \text{Main pressure [Pa]}$$

$$V_2 = \text{Volume of hydraulic fluid after discharge [m}^3\text{]}$$

During the commissioning of the MK7 Elec Levelok system, both the high-pressure and low-pressure lines will be bled to extract all air out of the system. With this procedure completed, it can be considered that during the clamping and unclamping procedures, only the volume displacement regarding the cylinder strokes would need to be considered in the volume calculations. These volume displacements are considered on the high- and low-pressure sides of the double-acting cylinders as both sources are supplied by the hydraulic accumulators. Thus, the total displacement volume of the four Levelok clamp double-acting cylinders is calculated to be 3.77 liters per clamping and unclamping sequence.

The other factor that needs to be considered, is that of the number of clamping and unclamping sequences the MK7 Elec Levelok power pack can accomplish before its installed hydraulic accumulators need to be recharged. There are four station levels where the Levelok system is required to clamp at least once on each level, with one recharge between station levels 95 and 100. Thus, the total displacement volume of the two clamping and unclamping sequences is calculated to be 7.54 liter.

Thus, with the total displacement volume of two clamping and unclamping sequences calculated, the total accumulator storage needed can be calculated, utilizing Equation 27.

$$\text{Volume of hydraulic fluid displaced} = \text{Required accumulator volume} \quad (27)$$

$$0.00754 = V_2 - V_3$$

$$0.00754 = 0.9572V_1 - 0.7714V_1$$

$$0.00754 = 0.185812V_1$$

$$V_1 = 0.040578 \text{ m}^3$$

The four 10 liter hydraulic bladder accumulators are sufficient to achieve this clamping and unclamping sequence objective. (Note: The calculated value for V_1 can be lower because the main pressure of 180 Bar was considered for both pressure sides of the double-acting cylinders. The actual total time the system would clamp with one accumulator charge, will be confirmed with the validation tests completed in Chapter 9.) The hydraulic fluid reservoir is designed to have a volume limit of 54 liters. The hydraulic bladder accumulators will be charged and the reservoir refilled to the 40-liter range limit, this is efficient enough as the accumulators will only discharge 7.54 liter after each recharge. Due to the needed weight reduction on the Levelok power pack, the hydraulic fluid reservoir cannot be designed to hold more hydraulic fluid than the 40-liter limit.

The minimum kilowatt rating on the electrical motor needed to drive the hydraulic gear pump (That is specified with a flow rating of 7.57 l/m), to recharge the hydraulic bladder accumulators is calculated with Equation 28 (Note: 1.2 factor is added to account for the inefficiency of the hydraulic system & motor with hydraulic gear pump):

$$\begin{aligned} \text{Power of electrical motor} &= \frac{P_3 \times \text{Gear pump flow rate} \times 1.2}{60} \quad (28) \\ &= \frac{21 \text{ MPa} \times 7.57 \times 1.2}{60} \\ &= 3.18 \text{ kW} \end{aligned}$$

The 24 V DC 4.5 kW electrical motor was selected. This electric motor will be working at 70 % of its power capacity, retracting 132.5 A of current, and will run for 1 minute to charge the hydraulic accumulators to maximum system pressure. This is an allowable time, as it is shorter than the time it takes to travel between station levels. The Illustration in Figure 95 [79] [80], shows the 3D model of the hydraulic bladder accumulators, hydraulic fluid reservoir, electric motor with gear pump, and all extra accessories of the MK7 Elec Levelok cage power pack, referenced to its corresponding hydraulic circuit diagram segment.

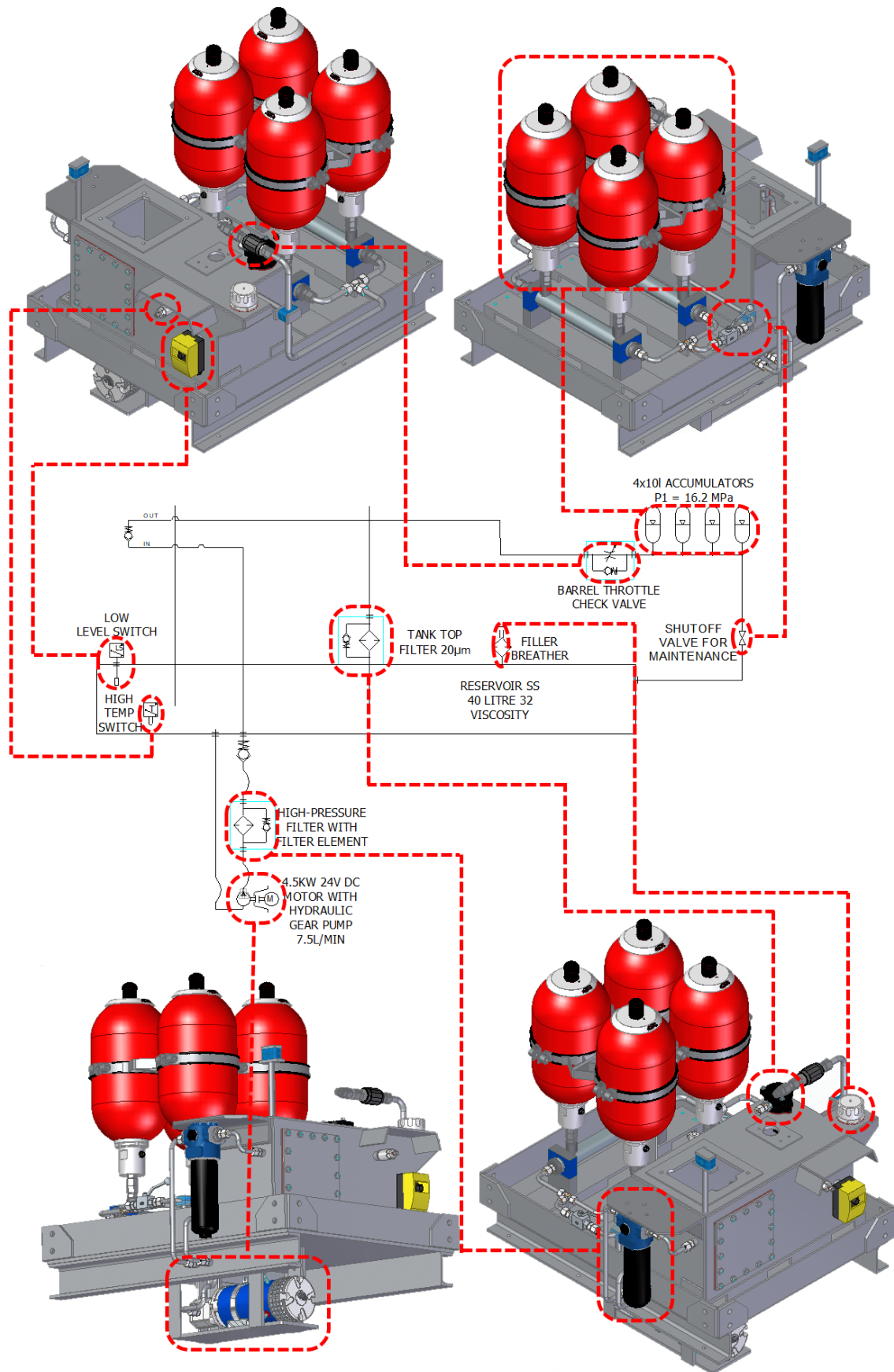


Figure 95: Illustration of the 3D model of the hydraulic bladder accumulators, hydraulic fluid reservoir, 24 V DC electric motor with gear pump, and all extra accessories, referenced to the corresponding MK7 Elec hydraulic circuit diagram [79] [80].

The 24 V DC directional control valves, together with the MK7 Elec decompression cycle arrangement assembly, are installed in two manifold blocks designed according to the MK7 Elec hydraulic circuit diagram of Figure 93 [80]. The ports in the manifold blocks are specifically designed to connect all the control elements and are machined on a five axes milling machine. The illustration in Figure 96 [79] [80], illustrates the locations of the machined manifold blocks and displays the positions of the 24 V DC directional control valves. The sequencing of the 24 V DC directional control valves is similar to that of the Levelok skip system explained in Section 2.3.2, Chapter 2.

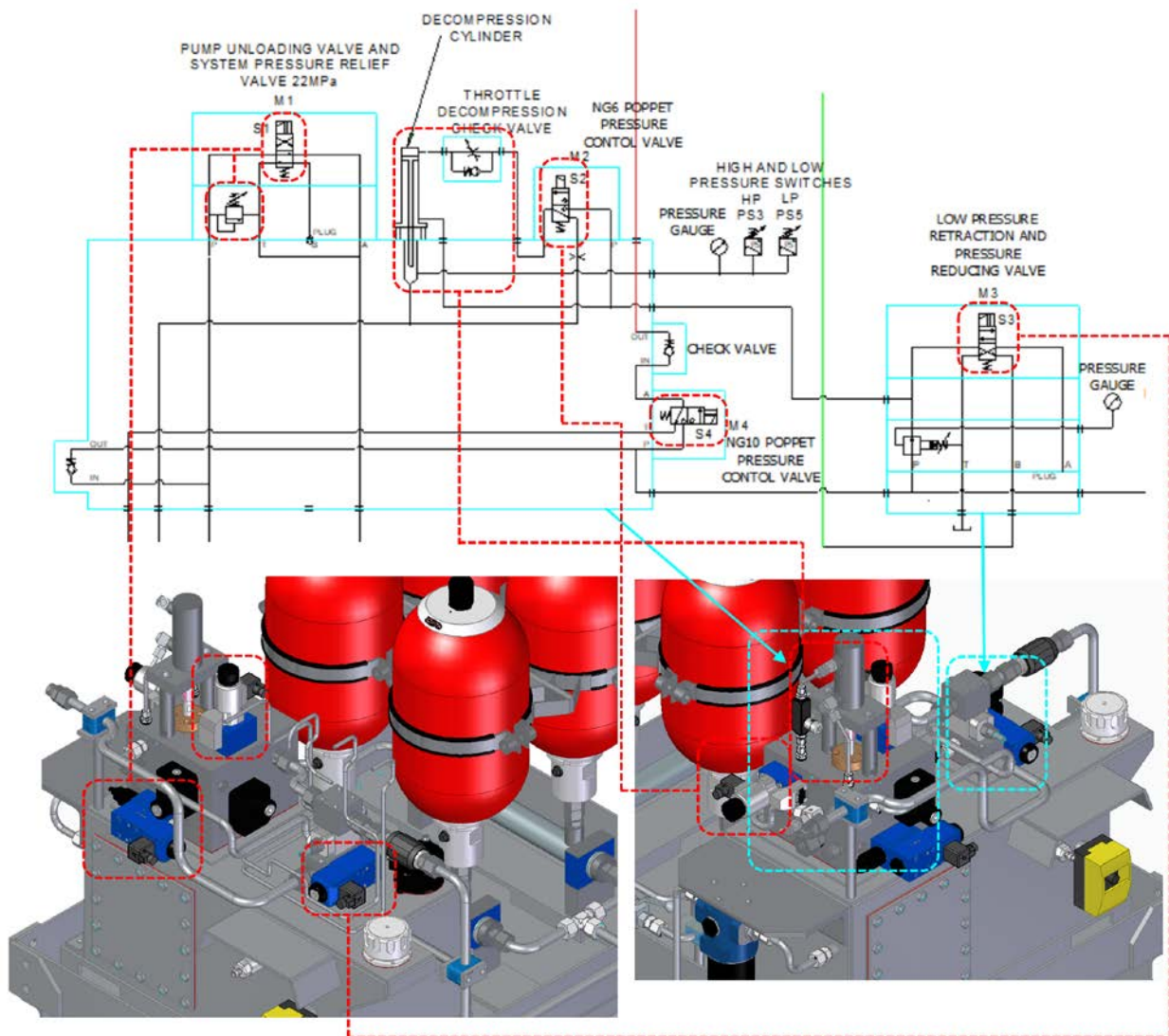


Figure 96: Machining drafts of the main manifold block & the manifolds and control valves positions [79] [80]

The MK7 Elec Levelok cage power pack's MK7 Elec decompression cycle arrangement assembly is illustrated in Figure 97 [79]. This decompression cycle arrangement assembly was designed with the same knowledge obtained from the decompression tests conducted in Chapter 5 and the analysis completed in Chapter 6. The same basic principles in the MK7s decompression cycle arrangement are implemented in this MK7 Elec design. The spindle and seat geometries are the same as the MK7s decompression cycle arrangement spindle and seat, with the correct required narrow annulus size. The O-rings used are all specified to be made of a rubber material with a specified 90 A-shore hardness specification. The seat also screws into the spindle body to allow for proper alignment between the spindle and seat, assuring these two components are always concentric to one another. The main difference separating this decompression cycle arrangement design from that of the other MK7 range of power pack's design is that the decompression cylinder and piston are electrical-hydraulically controlled, other than pneumatic-hydraulically.

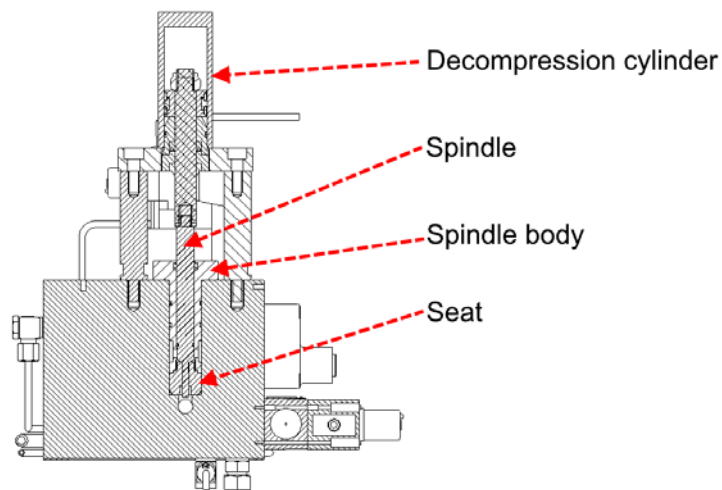


Figure 97: The MK7 Elec decompression cycle arrangement schematic [79].

The MK7 Elec Levelok cage power pack is controlled by 3 separate pressure switches connected to the 24 V DC relay logic control. To understand how the system works and to assist with problem finding during routine maintenance, the important pressures are displayed on high-pressure pressure gauges. This pressure equipment is displayed in Figure 98 [79].

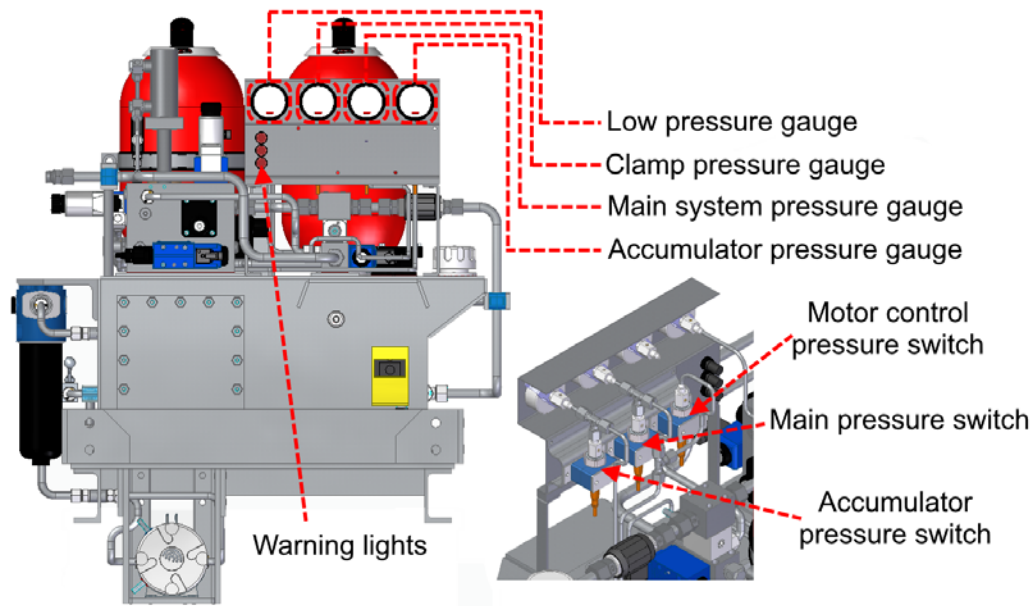


Figure 98: Illustration of the pressure gauges & switches installed to the MK7 Elec Levelok cage power pack [79].

The illustration in Figure 91 [79] shows where the MK7 Elec Levelok cage power pack is to be installed on the cage conveyance. The Levelok power pack unit is open to all falling objects in the shaft, including different rock sizes and a lot of dust. Thus, the MK7 Elec Levelok cage power pack was fitted with a protective roof constructed from 700 Hardox robust steel to protect the unit against these falling objects. The MK7 Elec decompression cylinder and open spindle part are also covered to protect it from dust particles. This protective Hardox roof and protective cover box are both illustrated in Figure 99 [79].

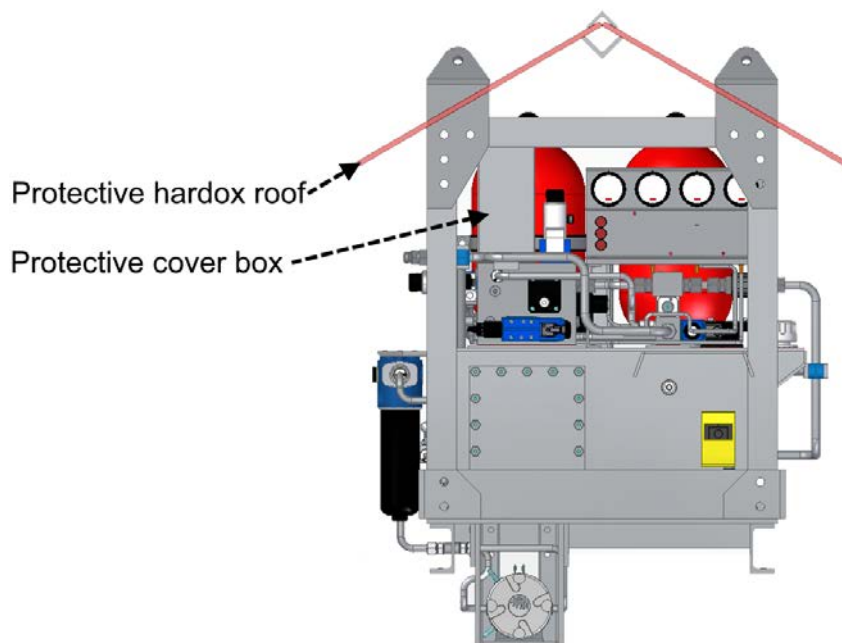


Figure 99: This protective hardox roof and protective cover box [79].

8.5 Control design & interlock circuit signals

The MK7 Elec Levelok cage power pack is a unit controlled by a relay logic control panel. This relay logic control unit is designed according to specific sequenced procedures and required internal functions. The method that was followed to construct the electrical circuit diagram of this complex system, was to construct the different relay logic diagrams to describe the sequencing of the different electrical equipment and the signals needed to perform certain functions. These relay logic diagrams were then combined to interact with each other to form the basis of the MK7 Elec Levelok electrical circuit diagram.

8.5.1 MK7 Elec Levelok cage power pack main pressure control

The MK7 Elec Levelok cage power pack is required to control the hydraulic fluid pressure in the hydraulic bladder accumulators automatically. This is normally done with a pressure switch, set to the required pressure, and connected to the high-pressure line of the hydraulic bladder accumulator, sending signals to the pressure control valve. The typical signal wave that would be established by this connected pressure switch, is illustrated as the blue curve in Figure 100 [50]. This signal wave will turn the pressure control valve and the electrical motor on and off constantly, and cause the shortened life span of this electrical equipment.

The desired signal wave from the pressure switch, to protect the electrical equipment, is represented by the green curve in Figure 100 [50]. This signal wave allows a time delay between the change of state of the electrical equipment, because of the lower switching frequency rate. This signal wave is obtained by using a pressure switch with two normally open set points (an upper and lower pressure limit), together with the constructed relay logic diagram in Figure 101 [50].

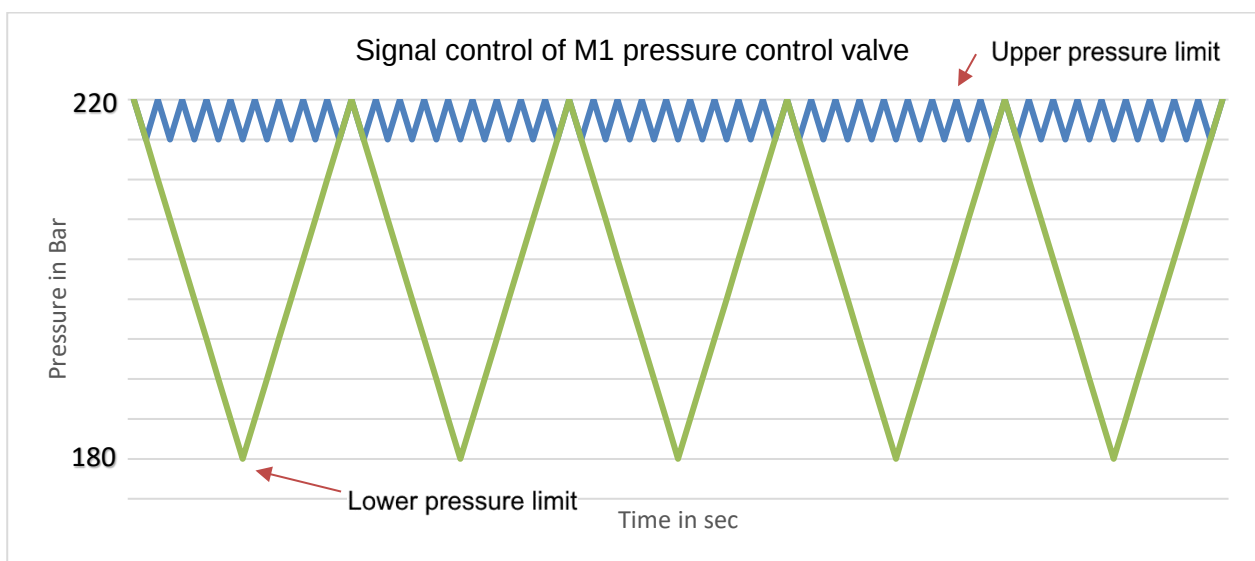


Figure 100: Illustration of the signal wave controlling the M1 directional control valve [50].

POWER PACK MAIN PRESSURE CONTROL

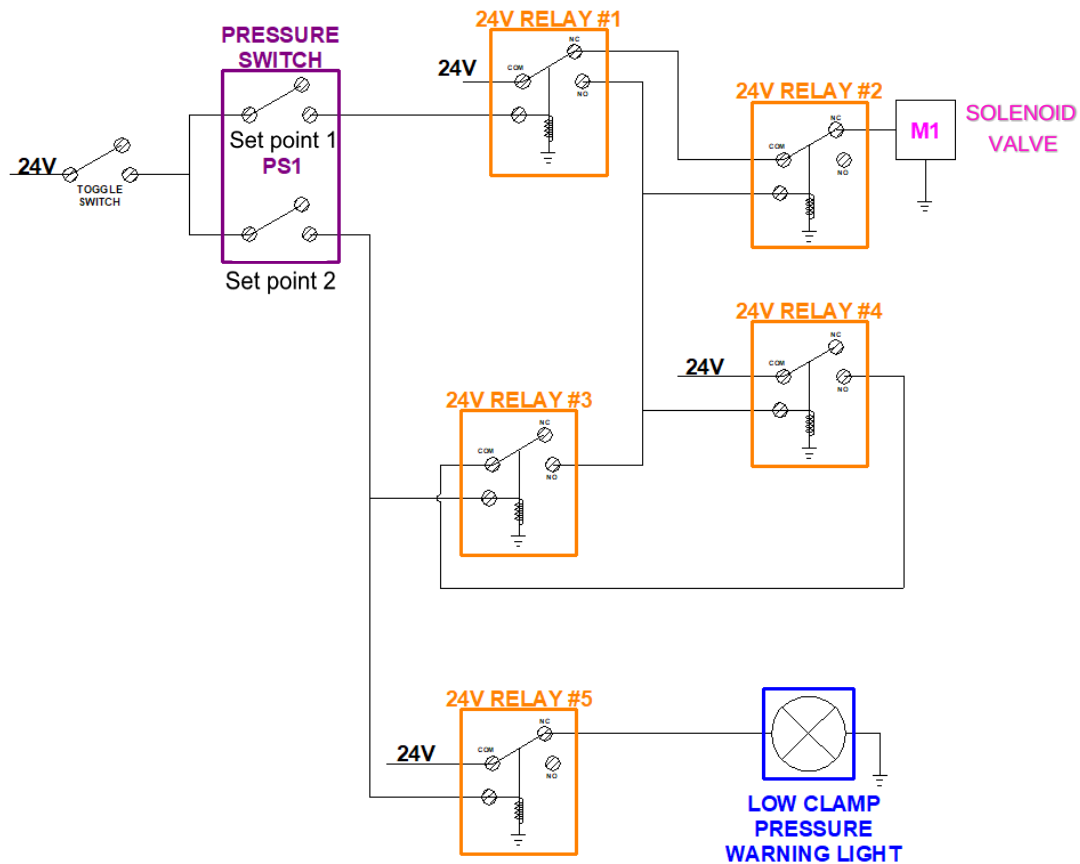


Figure 101: MK7 Elec Levelok cage power pack main pressure control relay logic diagram [50].

The relay logic diagram illustrated in Figure 101 [50], makes use of 4 types of 24 V DC electrical instruments. The hydraulic pressure switch with two set points, Setpoint 1 at 210 Bar & Setpoint 2 at 180 Bar, are coloured in purple. The 40 A 5-pin relays are represented in orange, the solenoid valve in magenta, and the low-pressure LED light in Blue.

The relay logic diagram is constructed to regulate the hydraulic pressure in the bladder accumulator between two limits, set by the main pressure switch. When the power pack is switched on and the toggle switch is closed, the pressure switch connections stay open, relay 2 is energized and the M1 solenoid receives power. This allows the M1 control valve to pressurize the power pack, and the low clamp pressure warning light illuminates. As soon as the pressure rises above 180 Bar, setpoint 2 on the pressure switch changes state, and relays 3 and 5 are energized, de-illuminating the low clamp pressure warning light. As soon as the pressure rises above 210 Bar, setpoint 1 on the pressure switch also changes state, energizing relays 1, 2, and 4, and the M1 solenoid loses power and the M1 control valve stops pressurizing the power pack.

When the Levelok system is used, the system pressure will start to decay under the 210 Bar set point and de-energize relay 1. Relay 2 will still be energized due to the loop formed between relays 3 and 4. Thus, the hydraulic pressure will still decay without signaling the M1 control valve to pressurize the system. Only when the hydraulic pressure drops under the 180 Bar set point, the loop formed between relays 3 and 4 will be broken, and the M1 solenoid would receive power, allowing the M1 control valve to energize the Levelok power pack again, and the sequence repeats itself.

A similar relay loop is used in the MK7 Elec Levelok cage power pack clamp & unclamp sequence control relay logic diagram, represented in Figure 102 [50]. A time delay unit is added to this relay logic diagram and is represented in red.

Figure 102: MK7 Elec Levelok cage power pack clamp & unclamp sequence control relay logic diagram [50].

To activate the clamping sequence of the MK7 Elec Levelok system, the green clamp push button needs to be pushed. Relay 7 will be energized and will stay in this state, energizing itself, even when the green clamp button is released. Simultaneously, relays 8 and 9 will be energized with relay 10 energized 1 second later. Thus, the control valves M2, M3, and M4 are switched to powered and the Levelok system starts to clamp.

The one second delay on the activation of the M4 control valve can be explained by referring to the hydraulic system circuit diagram of the MK7 Elec Levelok system, represented in Figure 93 [80]. The M2 and M3 directional valves control the decompression cylinder of the decompression cycle arrangement. The one-sec delay allows these two control valves to properly seat the spindle in the seat, before the high-pressure control valve M4 is opened, preventing premature hydraulic pressure leakage.

To activate the unclamping sequence of the MK7 Elec Levelok system, the red unclamp push button needs to be pushed. Relay 6 will be energized, breaking the relay 7 self-energizing loop, allowing the relays 8, 9, and 10 to be de-energized, and the M2, M3, and M4 control valves to be deactivated. The decompression cycle of the system is activated and the clamps start to release.

8.5.3 MK7 Elec Levelok cage power pack hot temperature warning

The hydraulic fluid hot temperature switch, as illustrated in Figure 95 [79] [80], is used to send a warning signal when the hydraulic fluid reaches a temperature higher than 50 ° C in the hydraulic fluid reservoir. The relay logic diagram in Figure 103 [50], illustrates that the hot temperature warning light will illuminate when the hydraulic fluid hot temperature switch changes state and energizing relay 11.

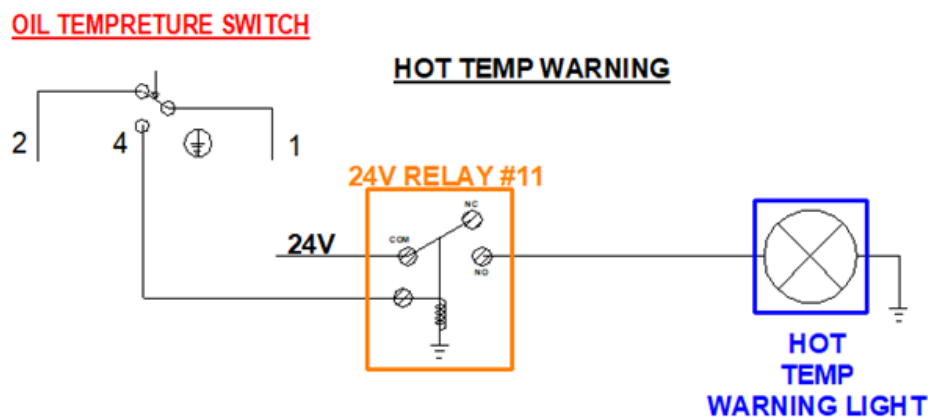


Figure 103: MK7 Elec Levelok cage power pack hot temperature warning relay logic diagram [50].

8.5.4 MK7 Elec Levelok cage power pack low hydraulic fluid warning

The low-level switch, as illustrated in Figure 95 [79] [80], is used to send a warning signal when the hydraulic fluid level in the hydraulic fluid reservoir deviates under the required 40-liter hydraulic fluid level. The relay logic diagram in Figure 104 [50], illustrates that the Low oil level warning light will illuminate when the hydraulic fluid low-level switch changes state and energizing relay 12.

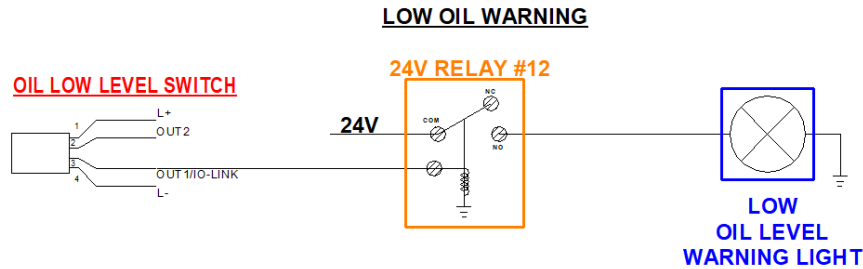


Figure 104: MK7 Elec Levelok cage power pack low hydraulic fluid warning relay logic diagram [50].

8.5.5 MK7 Elec Levelok cage power pack motor on control

The discussion in Section 8.5.1, mentioned that the electrical motor would be turned off, for protection, when not needed between the upper and lower system pressure setpoints of the main pressure automatic control. It is important that the electric motor idles first before it is used for pressurizing the system, if not the electric current will be much higher, draining the conveyance's batteries faster. This is the reason for the two pressure switches used in the relay logic design represented in Figure 105 [50], an upper and lower motor idle limit.

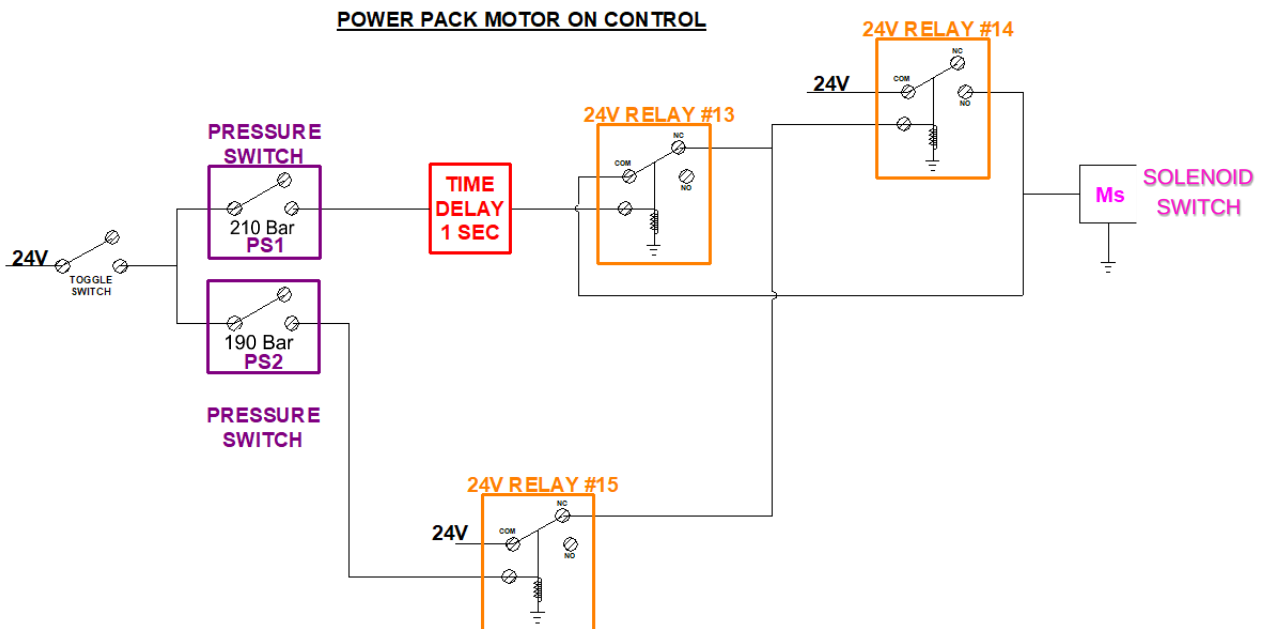


Figure 105: MK7 Elec Levelok cage power pack motor on control, relay logic diagram [50].

As soon as the MK7 Elec Levelok cage power pack is connected to a 24 V DC electrical supply, relay 14 will be energized. The electric motor solenoid switch, Ms, will be activated and the electric motor started to start energizing the Levelok power pack. As the pressure in the Levelok power pack's hydraulic bladder accumulators rise and reach a pressure higher than 190 Bar, pressure switch 2 (PS2) changes state, and relay 15 is energized. At this point, relay 14 is still energized due to its self-sustaining loop. As the pressure rises higher than 210 Bar, pressure switch 1 (PS1) changes state, and with a one-second time delay relay 13 is energized, breaking the self-sustaining loop of relay 14. The electric motor solenoid switch, Ms, is deactivated and the electric motor is turned off.

When the Levelok system is used, the system pressure will start to decay under the 210 Bar set point of pressure switch 1 (PS1) and de-energize relay 13. Only when the hydraulic pressure drops under the 190 Bar set point of pressure switch 2 (PS2), that relay 15 would be de-energized and relay 14 energized again, allowing the electric motor to start idling. As soon as the hydraulic pressure drops under the 180 Bar set point of pressure switch 1 (PS1, Setpoint 2), the M1 solenoid would receive power, allowing the M1 control valve to engage the electric motor to energize the Levelok power pack again, and the sequence repeats itself.

8.5.6 MK7 Elec Levelok system signals sent to JT system

The design specifications and system requirements of Mine X's Levelok cage man, material arresting systems, which are listed in Table 6 [43] of Section 3.2, and Table 7 [11] of Section 3.3, require five signals from the MK7 Elec Levelok system. The five signals are required for the use in the interlock circuit of the system and for indication purposes on the winder driver display and on the cage conveyance itself. These required interlock safety signals are listed in the relay logic diagram in Figure 106 [50]. The same clamping numbering is used as that of the MK7s Levelok system.

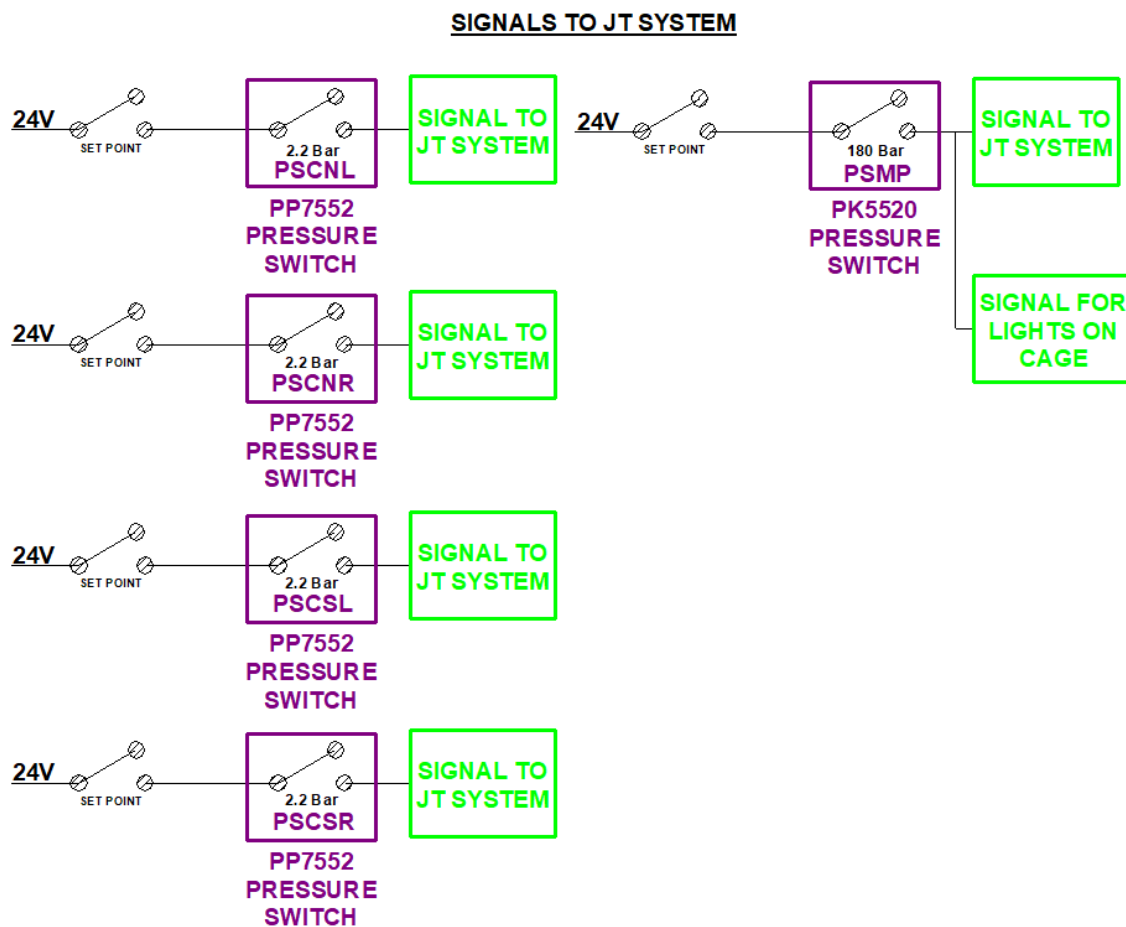


Figure 106: MK7 Elec Levelok system signals sent to the JT system relay logic diagram [50].

8.5.7 MK7 Elec Levelok cage power pack pressure & motor control relay logic diagram integration

The relay logic diagram designs represented in Figure 101 and Figure 105 [50], make use of the same PS 1 pressure switch set point. Thus, these two relay control diagrams were combined to obtain the relay logic diagram represented in Figure 107 [50].

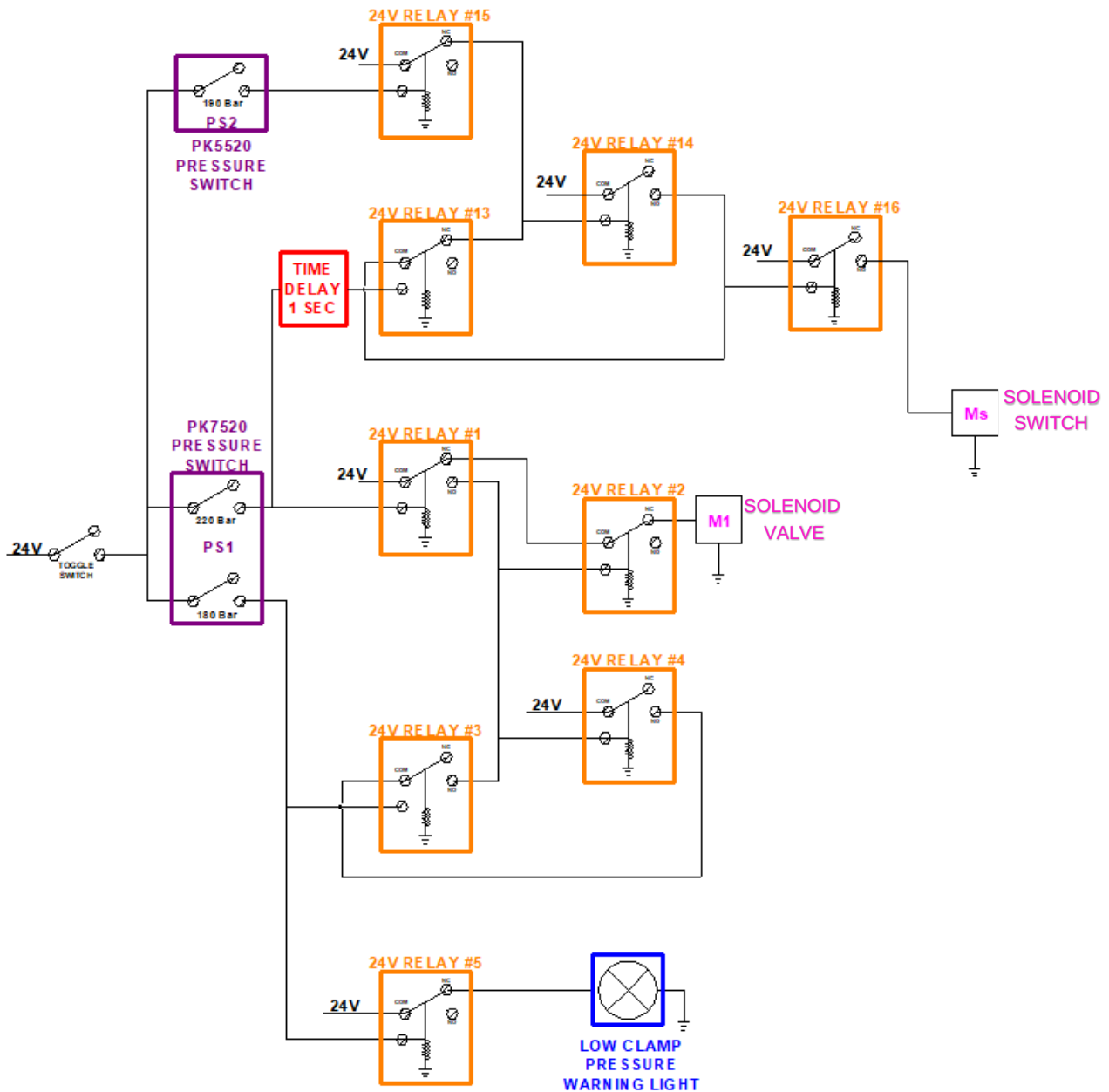


Figure 107: MK7 Elec Levelok cage power pack pressure & motor control logic diagram integration relay logic diagram [50].

8.5.8 MK7 Elec Levelok man, material cage system electric circuit diagram

The logic diagrams in Figure 101 to 107 [50], were used to assist with the design of the MK7 Elec Levelok man, material cage system electric circuit diagram, which is illustrated in Annexure I [81]. This is a 24 V DC system, all red and blue coloured lines represent the positive and negative wire connections, respectively, supplying all instruments with electrical current. The black and green coloured lines represent all signal connections.

This electric circuit diagram was used to design the control panel of the MK7 Elec Levelok man, material cage system, and to construct and wire it, as illustrated in Figure 108 [47] [79].

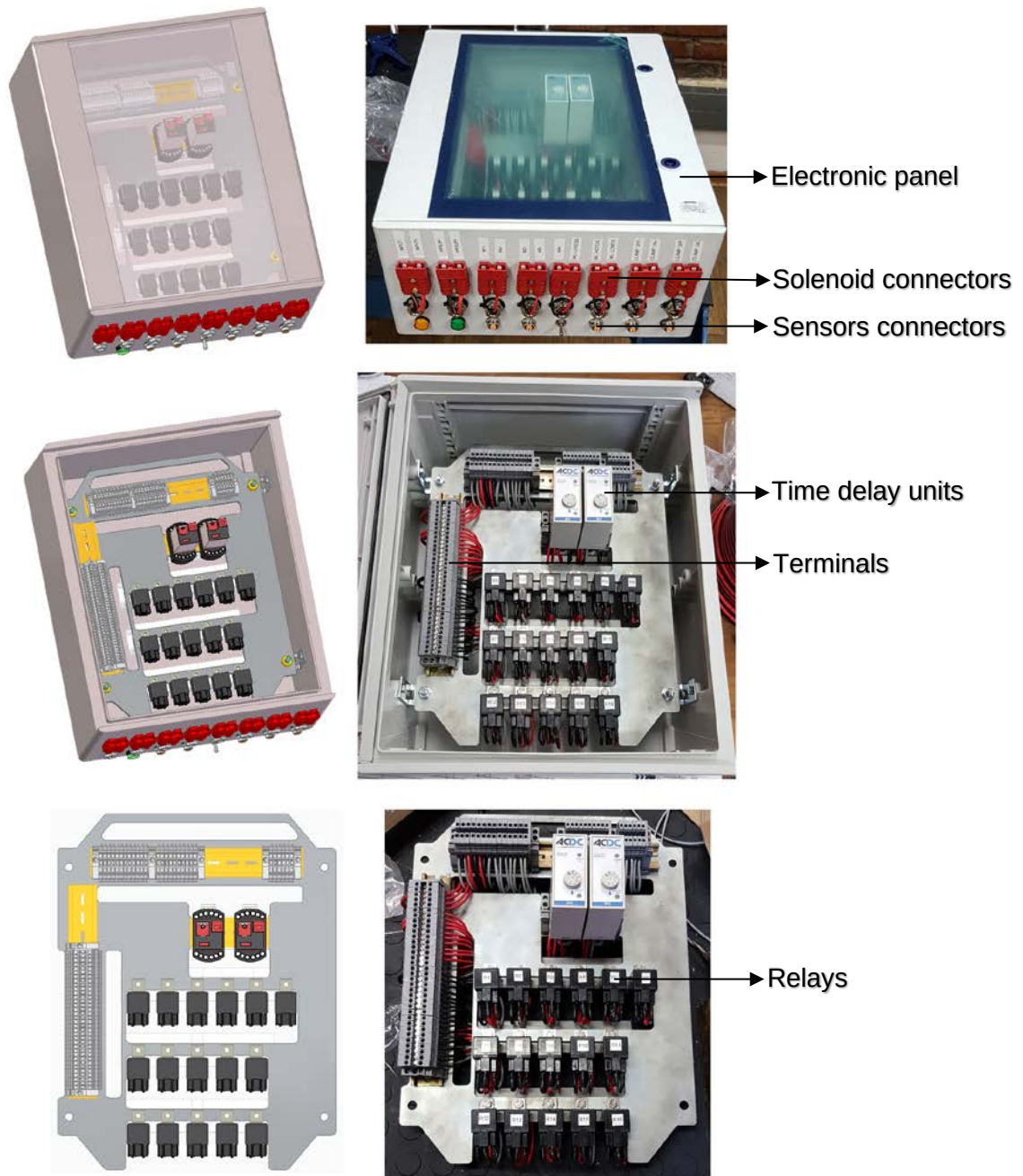


Figure 108: 3D Model and image illustrations of the MK7 Elec Levelok man, material cage system control [47] [79].

CHAPTER 9

VERIFICATION AND VALIDATION

9.1 Overview

The MK7s and MK7 Elec man, material cage system developments and designs were a direct result of the research study conducted on the Levelok man, material cage systems installed at Mine X. This objective of developing a documented design methodology for the MK7 range of Levelok man, material cage systems, could only have been achieved by analysing the results of the different decompression tests conducted in Chapter 5.

The main objective of this chapter is to determine the validity of the simulated displacement results of the conveyance displacement mathematical prediction model. The verification of the accuracy of this mathematical instrument, would in turn validate the considerations and recommendations made with relation to the new MK7 range of design methodologies. The conveyance displacement mathematical prediction model could potentially be employed as a reliable verification and validation instrument for future power pack designs.

During this study, this verified mathematical instrument was used to satisfy the objective of validating the functionality and control philosophies of the new MK7 range of Levelok cage power pack designs. Thus, multiple MK7s and MK7 Elec Levelok power pack units were manufactured, to conduct the same range of decompression tests as completed on the old MK4 and MK5 Levelok cage power packs in Chapter 5, and analyse the results using the conveyance displacement mathematical prediction model.

9.2 Conveyance displacement mathematical prediction model accuracy verification

The accuracy of the conveyance displacement mathematical prediction model was verified by completing numerous varieties of tests on the Levelok man, material cage system, installed on Mine X's 2-deck cage conveyance. These tests included the decompression tests done on bank-level and the conveyance "slide" tests conducted on Level 95, 2740 m beneath the surface level.

The objective was to use the decompression cycle data obtained from the decompression tests at the bank level, to simulate the conveyance displacement using the conveyance displacement mathematical prediction model. These simulated conveyance displacement results would then be compared with the actual conveyance displacement results, obtained from the conveyance "slide" tests conducted on Level 95.

9.2.1 Accuracy verification tests, test setup, and procedures

The MK7s Levelok man, material cage system was used to conduct the required decompression and 'slide' tests. The illustrations in Figure 109 and Figure 110 [47] illustrate the setup of this system, installed on the roof deck of the 2-deck cage conveyance, together with references to the different Levelok components discussed in Chapter 7.

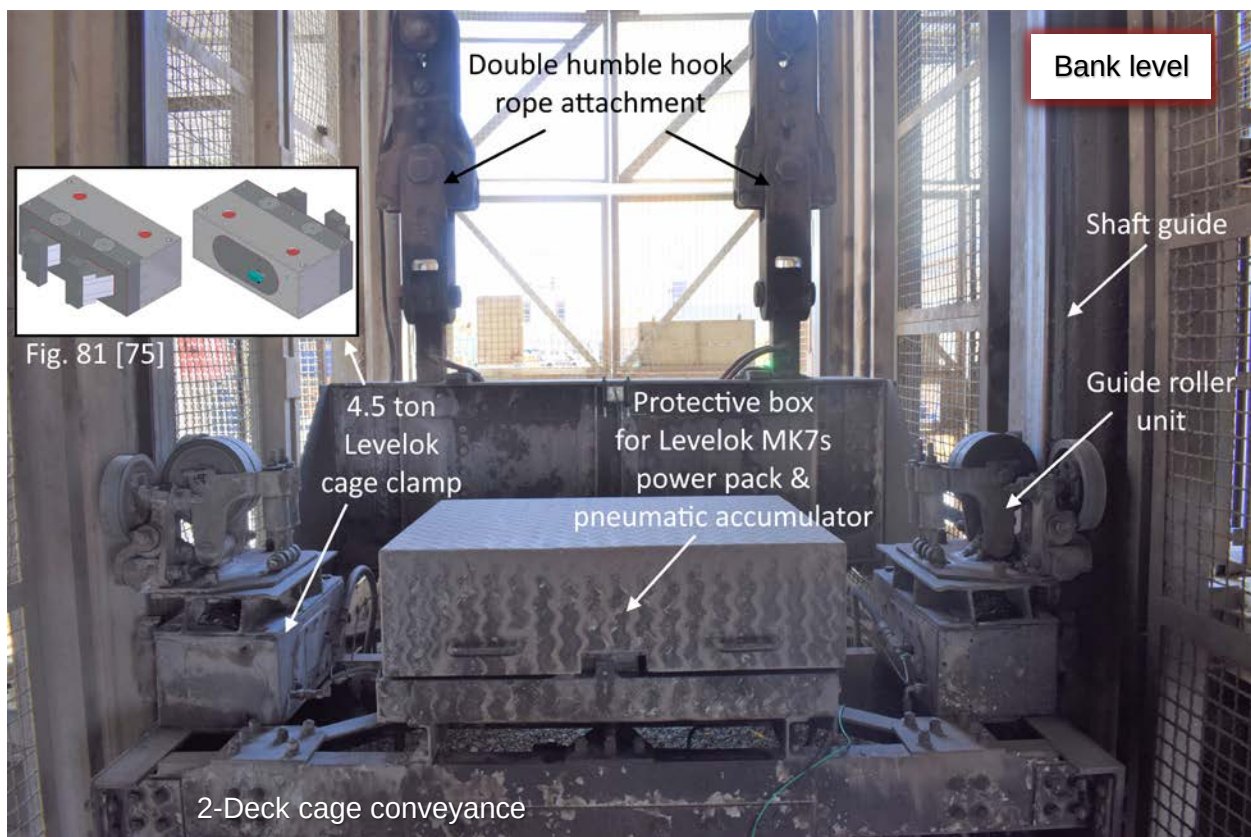
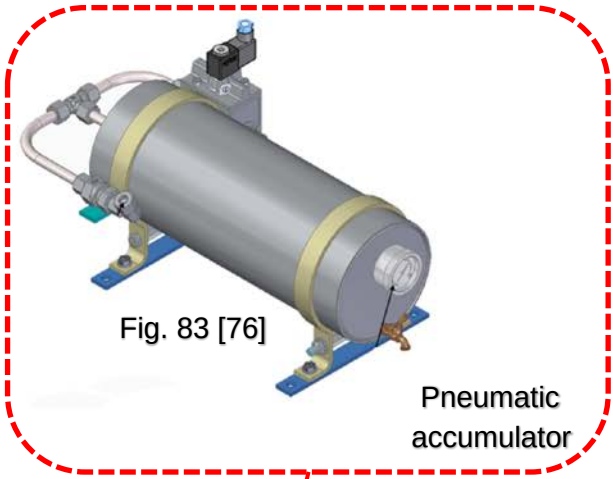


Figure 109: The MK7s Levelok man, material cage system installed on the roof deck of the 2-deck cage conveyance [47].

Inside the protective box for the Levelok MK7s power pack & pneumatic accumulator



Junction box 1
Fig. 92 [78]

4.5 Ton
Levelok
clamp
pressure
sensor

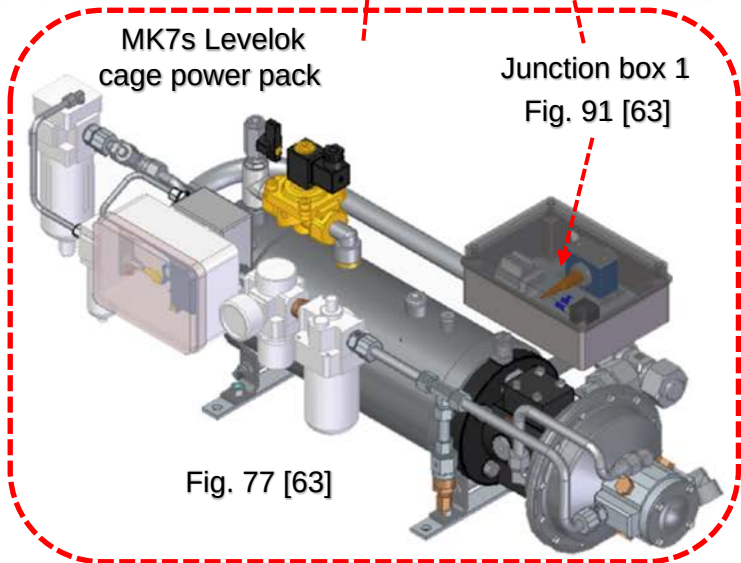
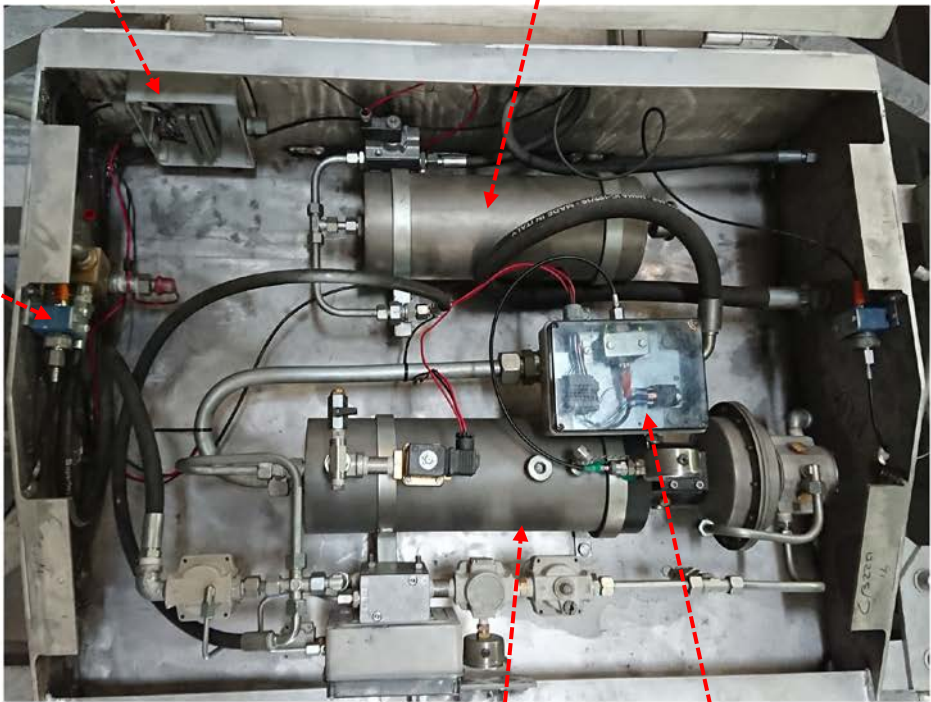


Figure 110: The MK7s Levelok cage power pack, pneumatic accumulator & electronic junction boxes inside the protective box [47].

The decompression tests were completed on the bank Level, using an Ahlbron Almemo precision measuring instrument [61], together with the recommended pressure sensor, to data log the decompression cycle pressure data. The onsite audit decompression testing procedure is discussed in Annexure F [6]. The testing equipment was connected to the MK7s Levelok cage power pack's "Minitest" testing point, as illustrated in Figure 111 [47].

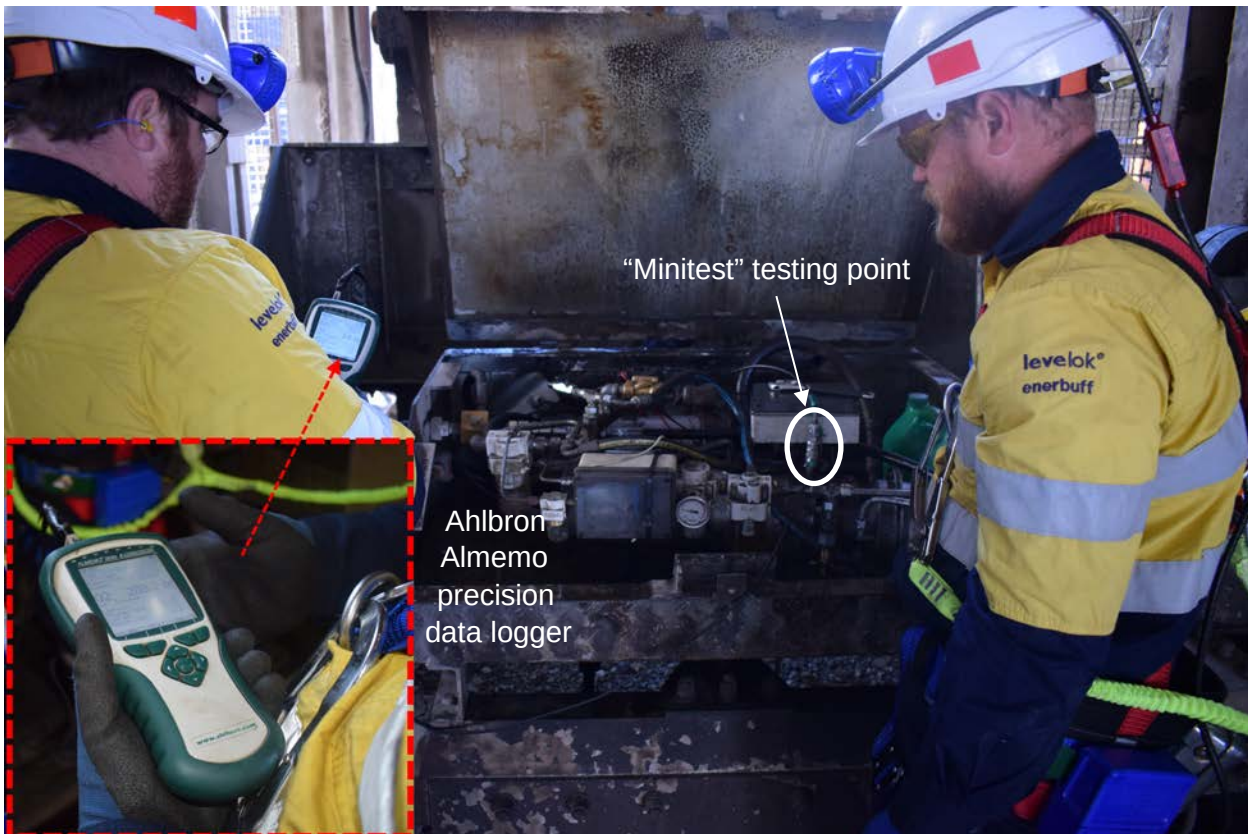


Figure 111: Ahlbron Almemo precision data logger setup [47].

The pressure data was downloaded from the datalogger onto a Laptop, and the decompression cycle curve was graphed for visual observation. The data pressure values were also entered in the conveyance displacement mathematical prediction model, to assure the desired output was obtained and the settings of the MK7s Levelok cage power pack were set as required. The graphed decompression curve, and the outputs of the conveyance displacement mathematical prediction model acquired from this completed decompression test (MK7s Levelok cage power pack SN: 219-09-18), are represented in Annexure H [62] and will be discussed further in Section 9.2.2.

The actual conveyance displacement data were obtained by completing numerous conveyance “slide” tests at 95 station Level, 2740 m beneath the bank level. A 6-Ton Levelok testing trolley load, illustrated in Figure 112 [47], was used to induce rope stretch on the hoisting winding rope of the conveyance. Using Equation 8, in Section 3.2, Chapter 3, the expected rope stretch of the conveyance’s hoisting winding rope could be calculated. This expected value was calculated to be equal to 908 mm, with a payload of 6 Tons, and a winding rope length of ± 2780 m (Distance from bank-level to sheave wheels included). The actual value, measured on-site during the conducted tests, was 795.5 mm. The 112 mm difference could be due to an inaccurate measurement of the weight value of the Levelok testing trolley load supplied by the mine.

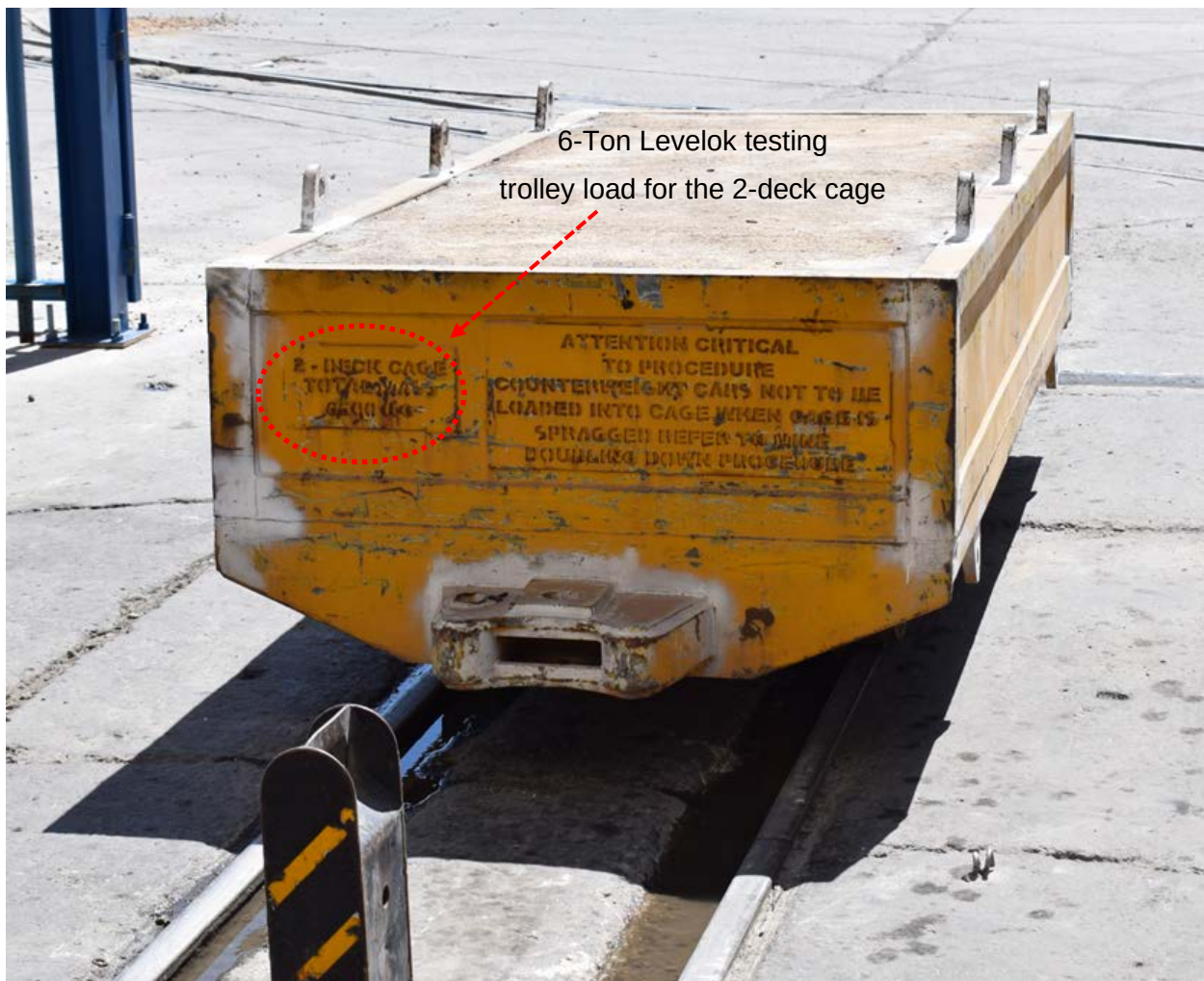


Figure 112: 6-Ton Levelok testing trolley load for the 2-deck cage at Mine X [47].

The illustration in Figure 112 [47], also illustrates how the 6-Ton Levelok testing trolley load was loaded in and out of the 2-deck cage conveyance. This was done to allow the cage conveyance to move up or down in the shaft, due to the induced rope stretch when the 6-Ton Levelok testing trolley load was unloaded from or loaded into it, respectively. This movement of the cage conveyance is referred to as “The Slide”, as discussed in Chapter 2. The step-by-step testing procedure of how the Levelok “slide” test is conducted is discussed in Annexure F [6].

The conveyance “slide” tests conducted for this study were somewhat different. Normally this type of test is completed for the purpose of a system performance check, done during Levelok system commissioning or auditing. For purposes of the conveyance displacement mathematical prediction model’s accuracy verification, the same normal testing procedure was followed but included more testing equipment. The illustration in Figure 113 [47], shows where the eDaq [53] datalogger was placed on the top deck of the cage conveyance.



Figure 113: Illustration of the top deck where the eDaq [53] equipment was placed for data logging during the “slide” tests [47].

The eDAQ was used to data log the synchronized pressure and acceleration values of the decompression cycle, and the conveyance's movement, during the "slide" tests. The Pressure sensor of the eDAQ was connected to the same "Minitest" pressure testing point on the MK7s Levelok cage power pack as illustrated in Figure 111 [47]. The connected wire of the pressure sensor was led through the manhole of the roof deck into the eDAQ protective box. The accelerometer measuring the acceleration values was placed in the same protective box as that of the eDAQ data logger.

More accurate displacement result values could have been obtained using displacement lasers. Unfortunately, due to the limited access, and strict regulations, these displacement lasers could not be utilized. Thus, the frame-by-frame video analyses were the best data accumulator for the tests conducted onsite. All tests were conducted 3 times, for repeatability.

The idea behind the synchronized data logged pressure and acceleration values was to determine the pressure value of the actual point of slip. The acceleration data values could also be used to determine the actual displacement of the conveyance, by integrating the values twice. However, this is a very inaccurate way of determining the conveyance's displacement [3]. Thus, a camera was placed on Level 95 to record videos of the cage conveyance's movement, to be analysed frame by frame, using a video editor afterward.

The illustration in Figure 114 [47], illustrates the reference dimension used to determine the actual conveyance displacement. The displacement of the conveyance after Levelok clamp release was measured frame by frame, logged, and then corrected using the reference dimension. The reference dimension was measured between the two 50 mm x 50 mm rail bars, equaling the rail gauge of the rolling stock. The rail gauge was confirmed on the G.A. drawings of the 2-deck cage.

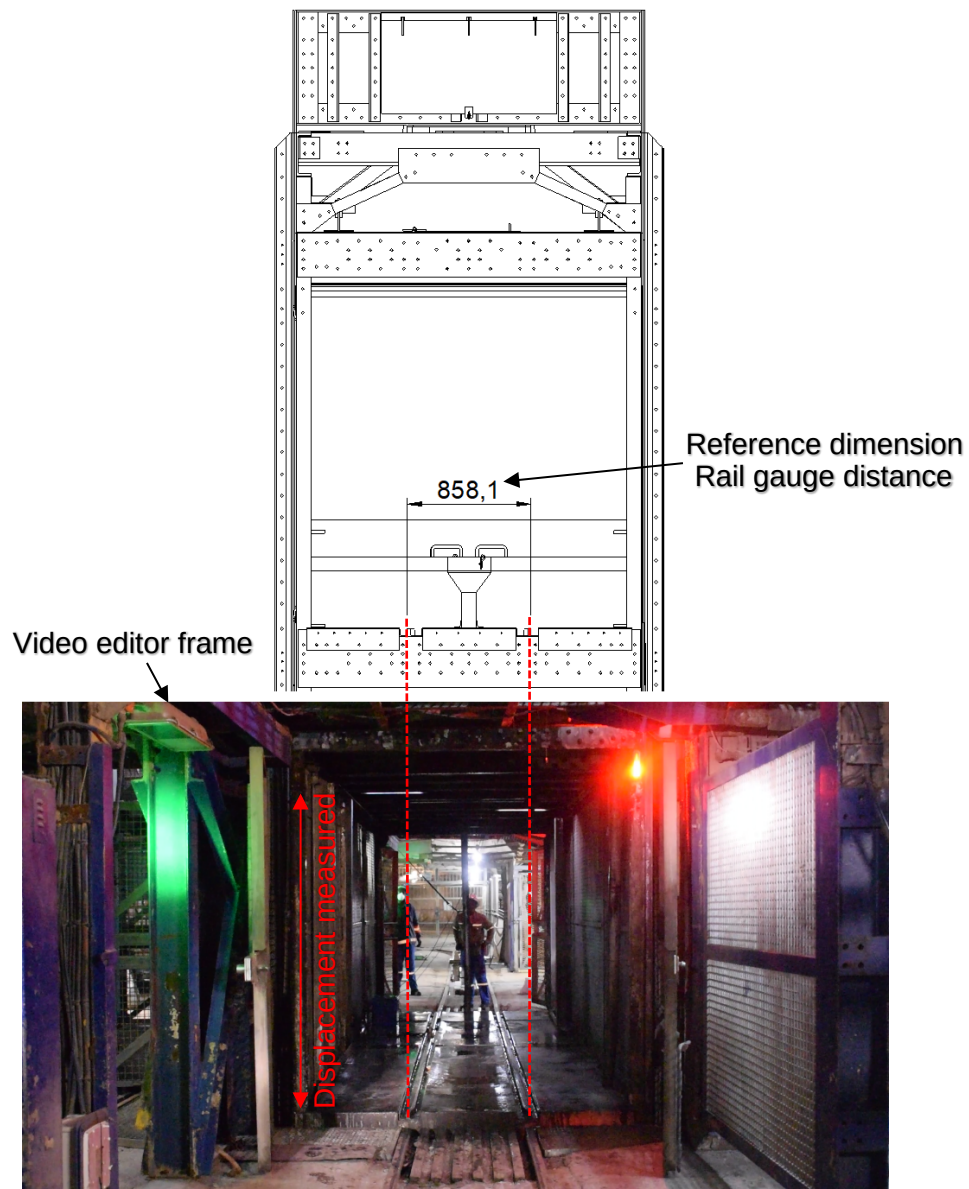


Figure 114: Frame by frame analyses on a video editor with reference dimension [47].

9.2.2 Accuracy verification tests results

The acquired pressure data, from the completed decompression tests conducted at the bank level, generated the decompression cycle curve represented with the blue curve in Figure 115. This curve is also identical to the decompression cycle curve graphed from the accumulated pressure data, recorded with the eDAQ data logger, during the completed conveyance “slide” tests.

Figure 115 also illustrates the corresponding filtered acceleration values in red. The nCode data processing software package [57] was used to filter out all unwanted frequencies in the data. These unwanted frequencies source from the guide wheel clusters fitted to the conveyance. When determining the wheel diameter and speed of the conveyance when moving, this frequency can be calculated. (Note: the filtered frequency showed minimal effect)

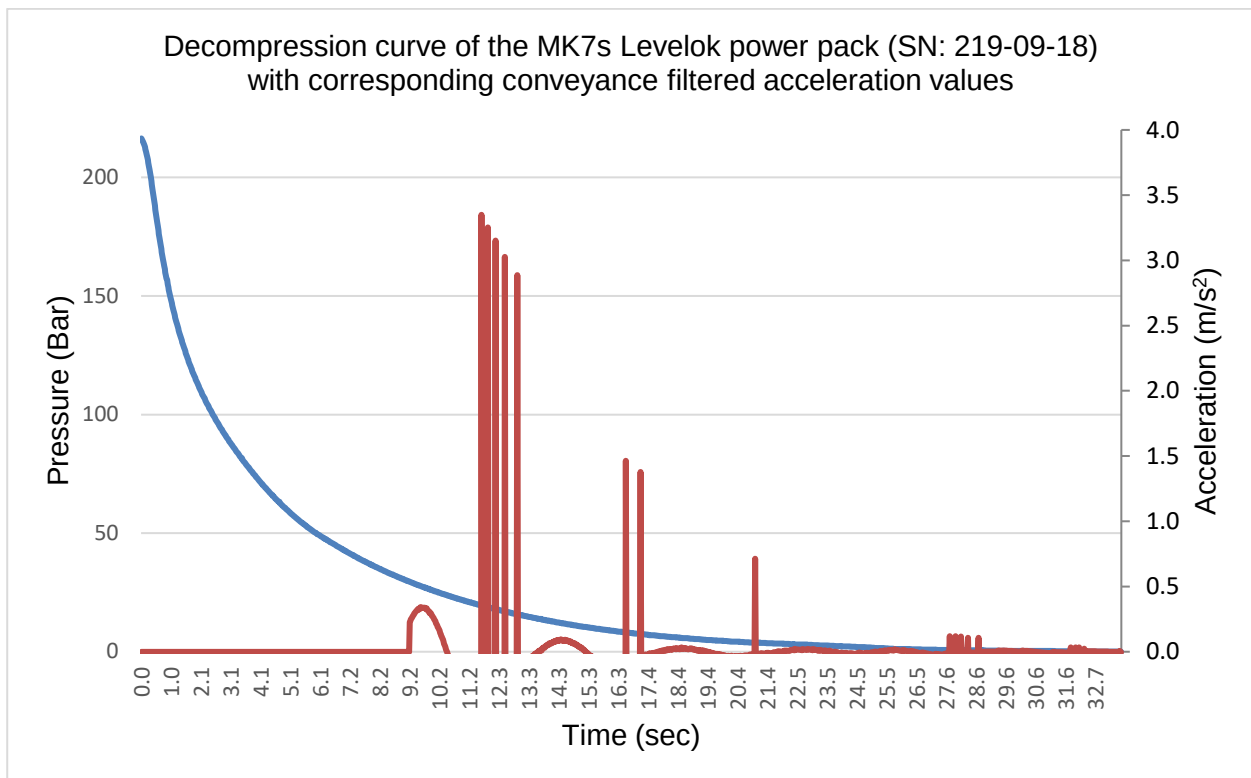


Figure 115: Decompression curve of the MK7s Levelok power pack (SN: 219-09-18) with its corresponding filtered conveyance acceleration values.

The conveyance displacement mathematical prediction model calculated the pressure slip point to be located at 29 Bar. The actual slip pressure value of 26 Bar was calculated from the data represented in Figure 115. The difference in this slip pressure value can be due to several factors.

These factors include the accuracy of the weight measurement of the 2-deck 6-Ton Levelok testing trolley load. These loads were calculated from the CAD models generated for manufacturing purposes. In an ideal world, the calculated load value would be the same as the actual load value, but this is not the case due to the tolerances in the manufacturing of the final product as well as the tolerances incorporated in the manufacturing of the steel sections supplied.

The inaccuracy of the static friction value used in the prediction model due to the unknown shoe and shaft guides conditions is another factor that needs to be considered. The static friction coefficient is the most important value which will define the slip point. A very wet shaft will have a very low static friction coefficient and thus a lower slip pressure, whereas with a dryer shaft it is the opposite.

The loads and the static friction properties are both big role players when the slip pressure is to be determined as described by Equation 8, in Section 3.2. A small adjustment in these values has a big change in the determined slip pressure, it is, therefore, for this dissertation and test purposes, the predicted values and actual measurements however fall within an acceptable margin of error of 10%. This is acceptable because all this implies is that the conveyance will only start to move half a second sooner as calculated, but will not have any effect on the final response of the system.

The blue and green curves illustrated in Figure 116, represent the same measured acceleration curve and generated decompression cycle curve as illustrated in Figure 115. This curve's decompression pressure values were used in the conveyance displacement mathematical prediction model, to predict the displacement of the 2-deck cage conveyance. The simulated result is represented with the red curve in Figure 116. The red circle indicates the point of slip where the conveyance starts to move, notice how close the measured acceleration data is to this point. This is an illustration that supports the statement where the 10% error between the calculated and actual slip pressures is negligible.

The actual conveyance displacement results obtained from the frame-by-frame measurement video analyses were plotted on the same graph as that of the predicted displacement curve of Figure 116, for comparison. This comparison of the two curves is represented in Figure 117.

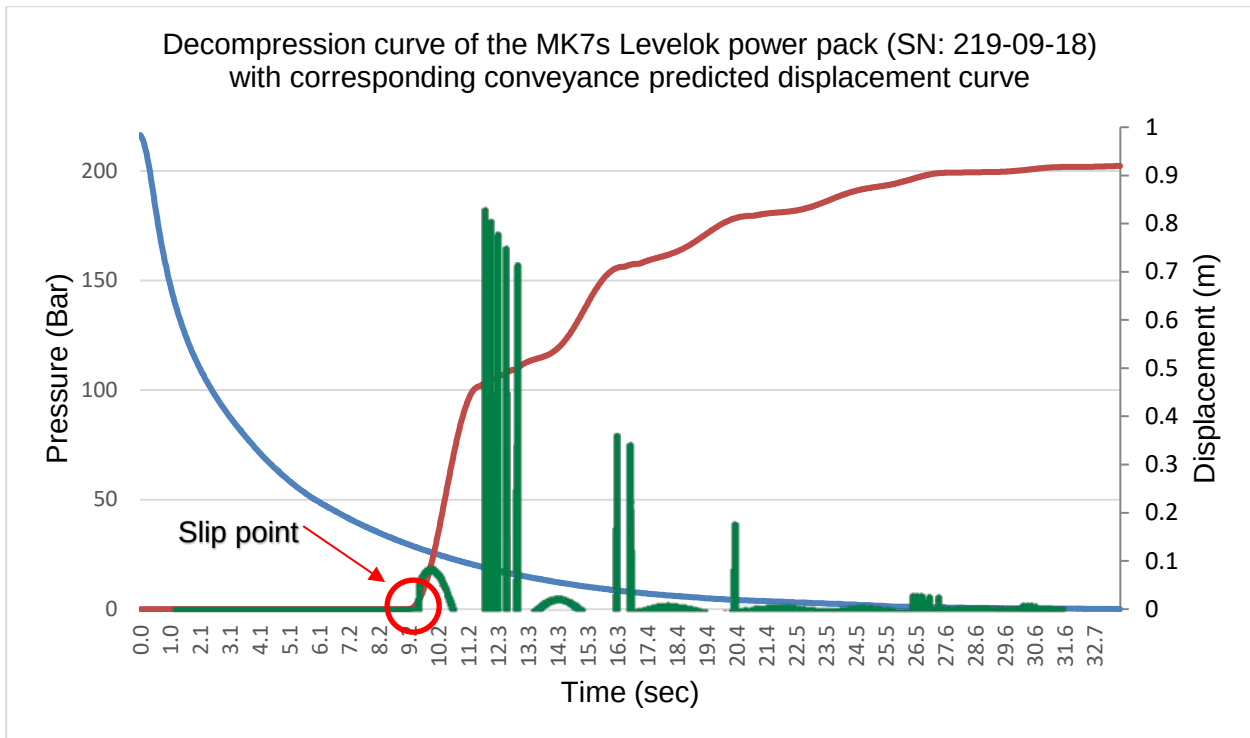


Figure 116: Decompression curve of the MK7s Levelok power pack (SN: 219-09-18) with its corresponding conveyance predicted displacement curve.

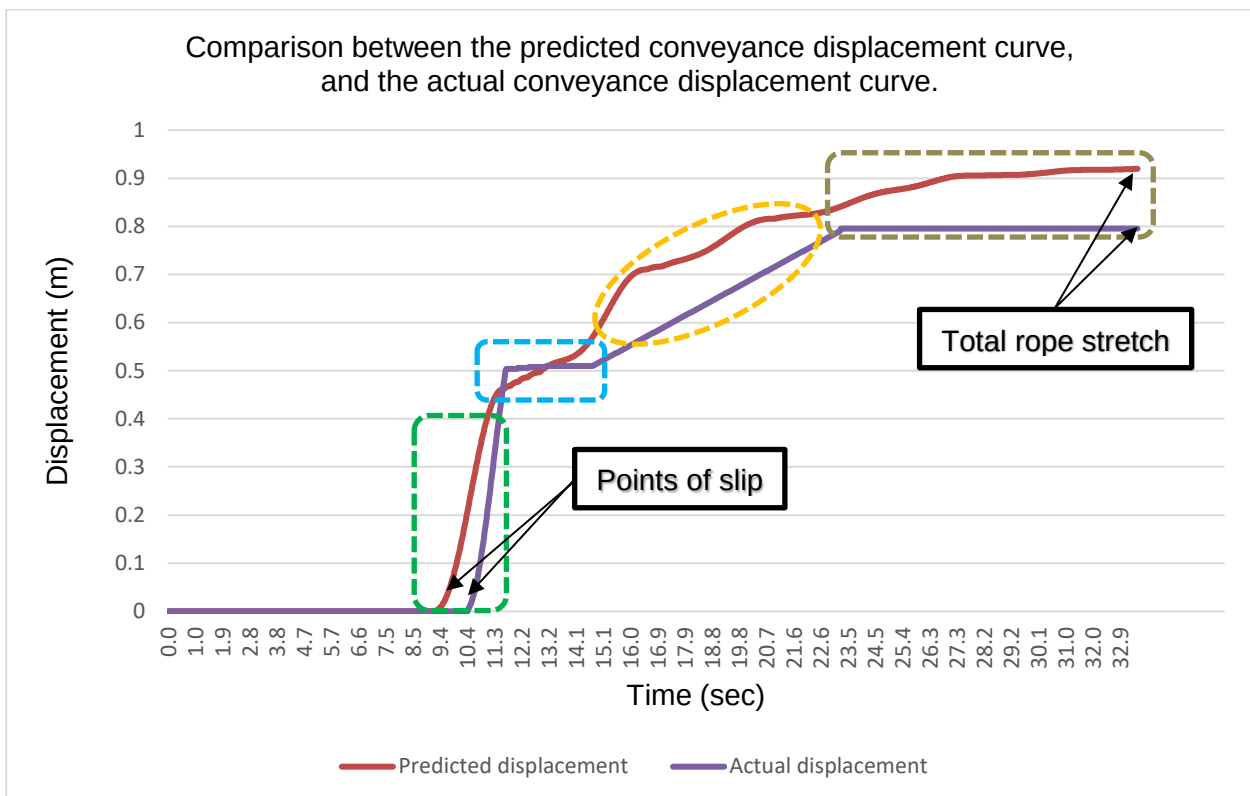


Figure 117: Illustration of the comparison between the predicted conveyance displacement curve, and the actual conveyance displacement curve.

The actual and predicted conveyance displacement curves, compared in Figure 117, have a few technical differences, such as the point of slip and the total rope stretch. Despite these differences, there is a good agreement between the characteristic trends present in both sets of results. These similarities are indicated with the green, blue, yellow, and gold outlines, shown in Figure 117.

After the point of slip, indicated inside the green outlined box, the gradient of the two curves is close to the same value. The conveyance “slide” rapidly for approximately 2 seconds before the movement is halted. At this point, represented with the blue outlined box, both curves’ gradient values tend toward zero. After 14.5 sec, the start point of the area represented with the yellow outlined box, the static friction coefficient is overcome and the conveyance starts to “slide” again at a constant speed until the total rope stretch is taken up. Both the curve gradients in this gradual “slide” are similar. The gold outlined box, show the area of the graph where both curves settle after 23 seconds, indicating the end of the conveyance movement in the shaft.

These similarities, together with the small margin of error on the slip pressure and the rope stretch values, verify that the conveyance displacement mathematical prediction model could be employed as a potentially reliable verification and validation instrument for future power pack designs.

9.3 MK7 & MK7s Levelok cage power packs validation

The conveyance displacement mathematical prediction model was used to analyse the recorded pressure data obtained from the decompression tests completed on the old MK4 & MK5 Levelok systems, documented in Chapter 5. The results of these mathematical simulations assisted in raising certain technical considerations and recommendations for the new MK7 range of design methodologies.

The MK7s Levelok cage power pack, and the new MK7 decompression cycle arrangement assembly thereof, were the direct results of the application of these considerations and recommendations. There were four MK7s Levelok cage power packs manufactured for the Levelok man, material cage systems installed at Mine X. These power packs were used to conduct validation tests on the Levelok cage testing workbench, using the experimental setup as illustrated in Figure 37 [50], Section 4.3.

These validation tests included the same decompression analysis, repeatability check, and decompression cycle vs conveyance displacement prediction tests, as conducted on the old MK4 and MK5 Levelok cage power packs. The average decompression curve of the four power packs to be tested was used in the conducted validation tests. This was done to assure that all encountered system faults, which were identified in Chapters 5 and 6, were addressed and resolved.

9.3.1 Control philosophy check test

The results obtained in Section 5.3, presented some complications regarding the effects certain components of the MK5 Levelok man, material cage system had on the decompression cycle, and effectively on a conveyance's predicted displacement. These components included the pneumatic assisted 12 V solenoid release valve, which caused a resistance against the pneumatic flow when the Levelok man, material cage system was released. With the pneumatic accumulator's pneumatically operated release valve that actuated too early, it amplified the detrimental effects of other components on the decompression cycle curve.

The comparison between the faulty MK5 system's decompression curve, in red, with the new MK7s system's decompression curve, in blue, illustrated in the graph of Figure 118, proves that these complications were addressed and the decompression curve was rectified using the MK7s Levelok cage's redesigned power pack.

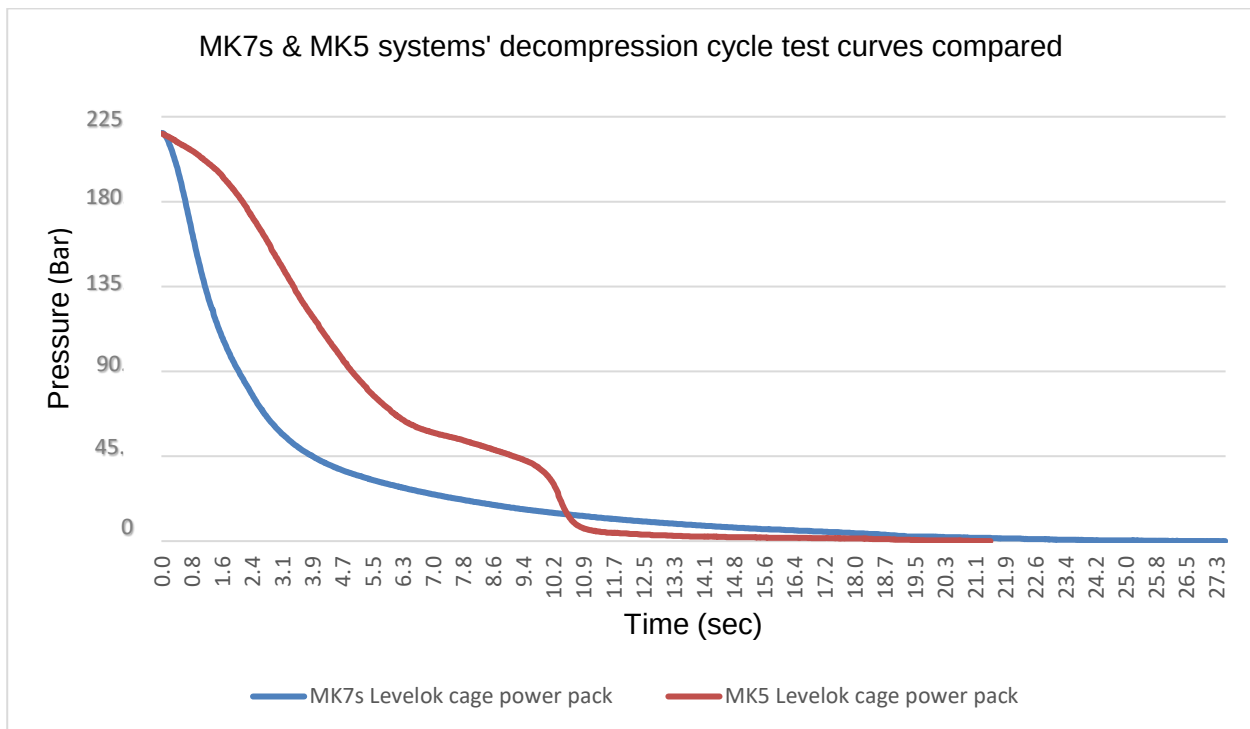


Figure 118: MK7s & MK5 systems' decompression cycle test curves compared.

9.3.2 Repeatability check tests

The system audit tests conducted, together with the discussions with different shaft engineers of Levelok operational mine shafts, revealed that the MK5 Levelok cage system's release of an arrested conveyance did not work with sufficient repeatability and consistency. The decompression tests conducted on an MK5 Levelok cage power pack in Section 5.5, confirmed this inconsistency and raised cause for concern. The decompression cycle analysis completed in Chapter 6, revealed that this inconsistency could be caused by the misalignment of important components of the decompression cycle arrangement assembly, during the decompression cycle sequence. This misalignment was one of the factors addressed in the new MK7 decompression cycle arrangement assembly design.

To validate the new MK7 decompression cycle arrangement assembly's consistency, decompression cycle repeatability tests were conducted on an MK7s Levelok cage power pack fitted with this new assembly. These repeatability tests were conducted with a similar procedure as that of the repeatability tests conducted on the MK5 Levelok cage power pack, as documented in Section 5.5. The decompression cycle results of this tested MK7s Levelok cage power pack are plotted in Figure 119. The comparison of these results with the MK5 Levelok cage power pack test results, represented in Figure 511, Section 5.5, Chapter 5, and also represented in the cyan area of Figure 119, prove that the new MK7 decompression cycle arrangement assembly addressed the problem of an inconsistent decompression cycle. The illustration shows that the new MK7 data are grouped more tightly than that of the MK5 powerpack.

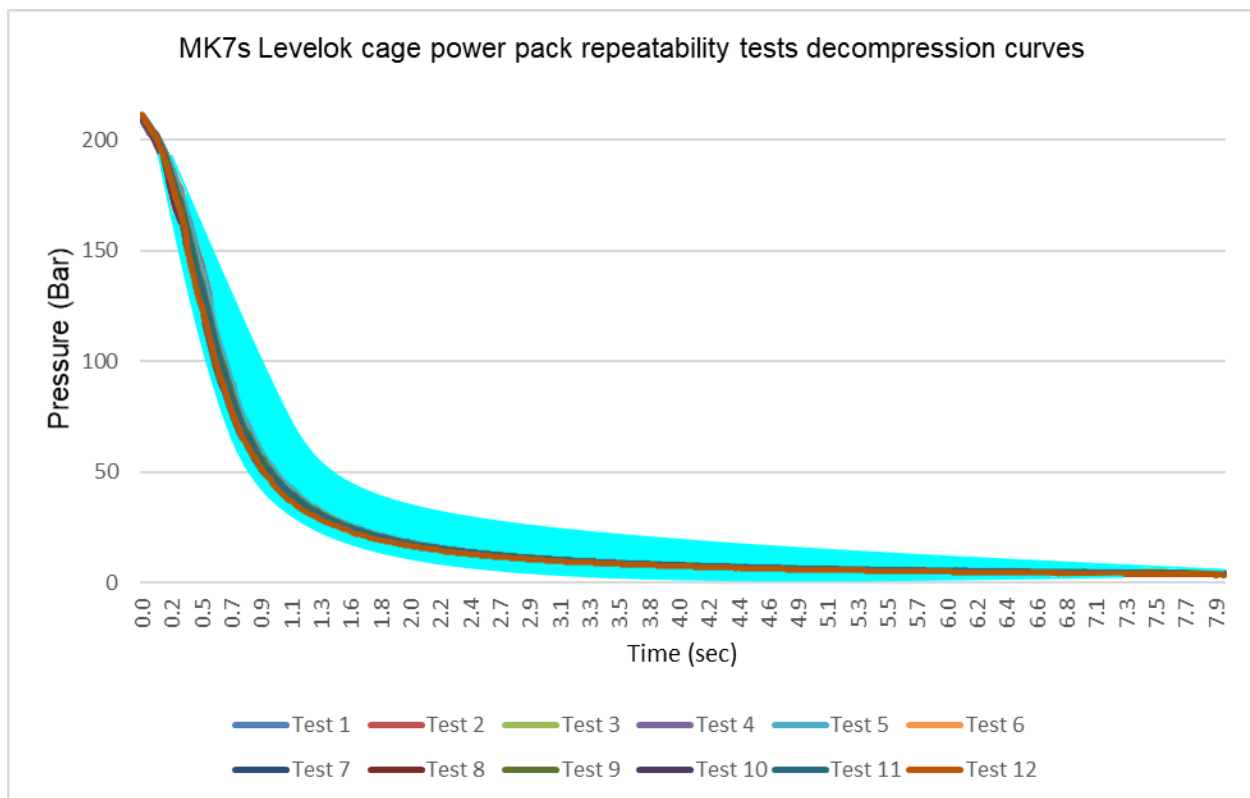


Figure 119: MK7s Levelok cage power pack repeatability tests decompression curves.

9.3.3 Decompression cycle vs conveyance displacement prediction tests

The verification tests conducted on the MK7s Levelok cage power pack (SN: 219-09-18) in Section 9.2, verified that the conveyance displacement mathematical prediction model could be employed as a potentially reliable verification and validation instrument for future Levelok power pack designs.

The decompression cycle test results obtained from these tests, attained the predicted conveyance displacement curve illustrated in Figure 116, which showed similarities to the actual conveyance displacement curve, plotted on the same graph. Thus, this same decompression test data was used to verify if this MK7s Levelok power pack will still attain the desired conveyance displacement output, with a maximum payload weight of 18 Tons operated at the deepest station level.

The decompression cycle curve, together with this corresponding predicted conveyance displacement curve (full payload operated at 2986 m beneath the surface level), is illustrated in Figure 120.

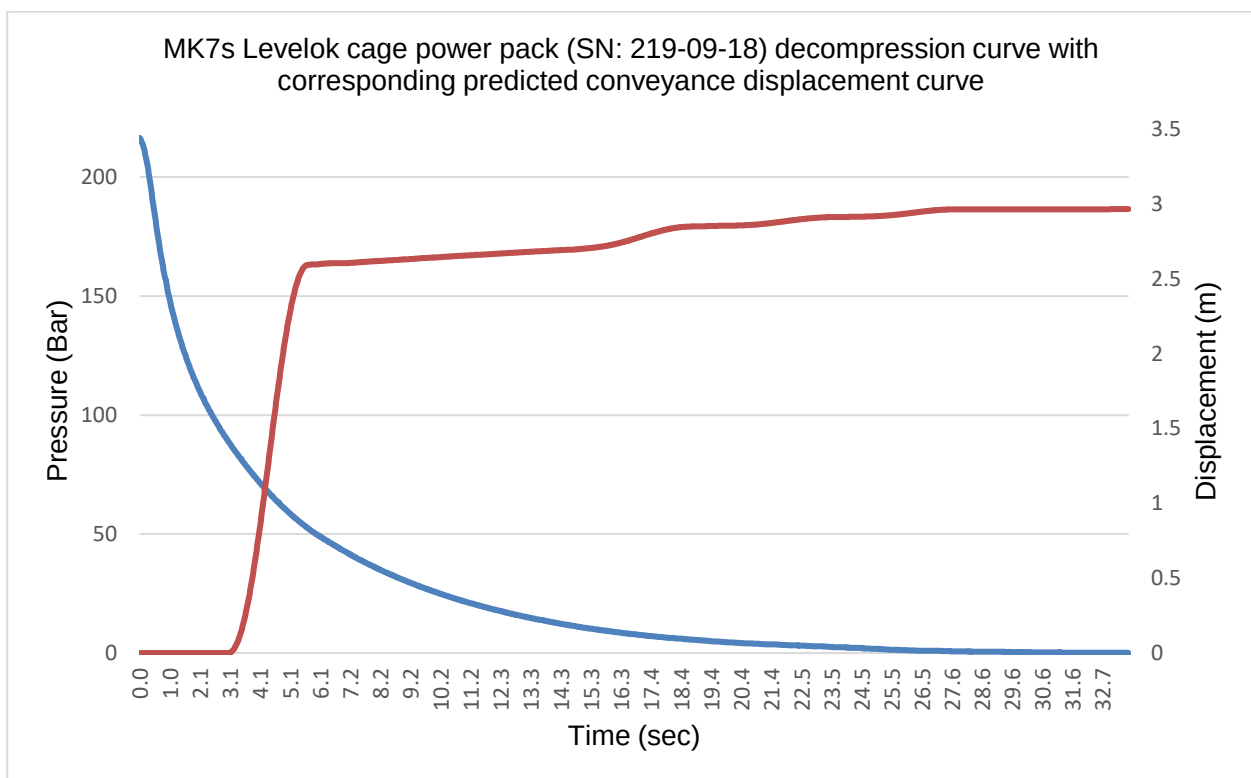


Figure 120: MK7s Levelok cage power pack (SN: 219-09-18) decompression curve with the corresponding predicted conveyance displacement curve.

The predicted conveyance displacement results illustrated in Figure 120, predict that the MK7s Levelok cage power pack (SN: 219-09-18), will still attain the desired conveyance displacement output, with a maximum payload weight of 18 Tons operated at the deepest station level. Final validation tests on the operational conveyance to obtain the actual displacement data for the 18 Ton cage, could unfortunately not be conducted due to restrictions on mining operations. However, the engineering management of Mine X has informally confirmed during later communications, that from their visual observations, the new MK7s Levelok man, material cage system, operates and functions reliably consistently, even with a fully loaded conveyance at the deepest station level.

9.4 MK7 Elec Levelok cage power pack validation

The problem of supplying clean, water-free pneumatic pressure to all Levelok operated shaft levels, forced the MK7 Elec Levelok cage power pack to be designed. This 24 V DC electrical design has not as of yet been implemented on an operational mining conveyance, but validation tests have been completed using the Levelok workshop experimental setup illustrated in Figure 121 [47]. With the control unit, illustrated in Figure 108 [47], connected to the electrical cage power pack, the hydraulic clamps could be operated and the decompression release cycle tested and recorded. The 24 V DC electrical motor was connected to a 220 V AC to 24 V DC output transformer. This was done, due to the high amperage demand of this electric motor, to ensure the hydraulic fluid pressure supply of 210 Bar in the bladder accumulators.

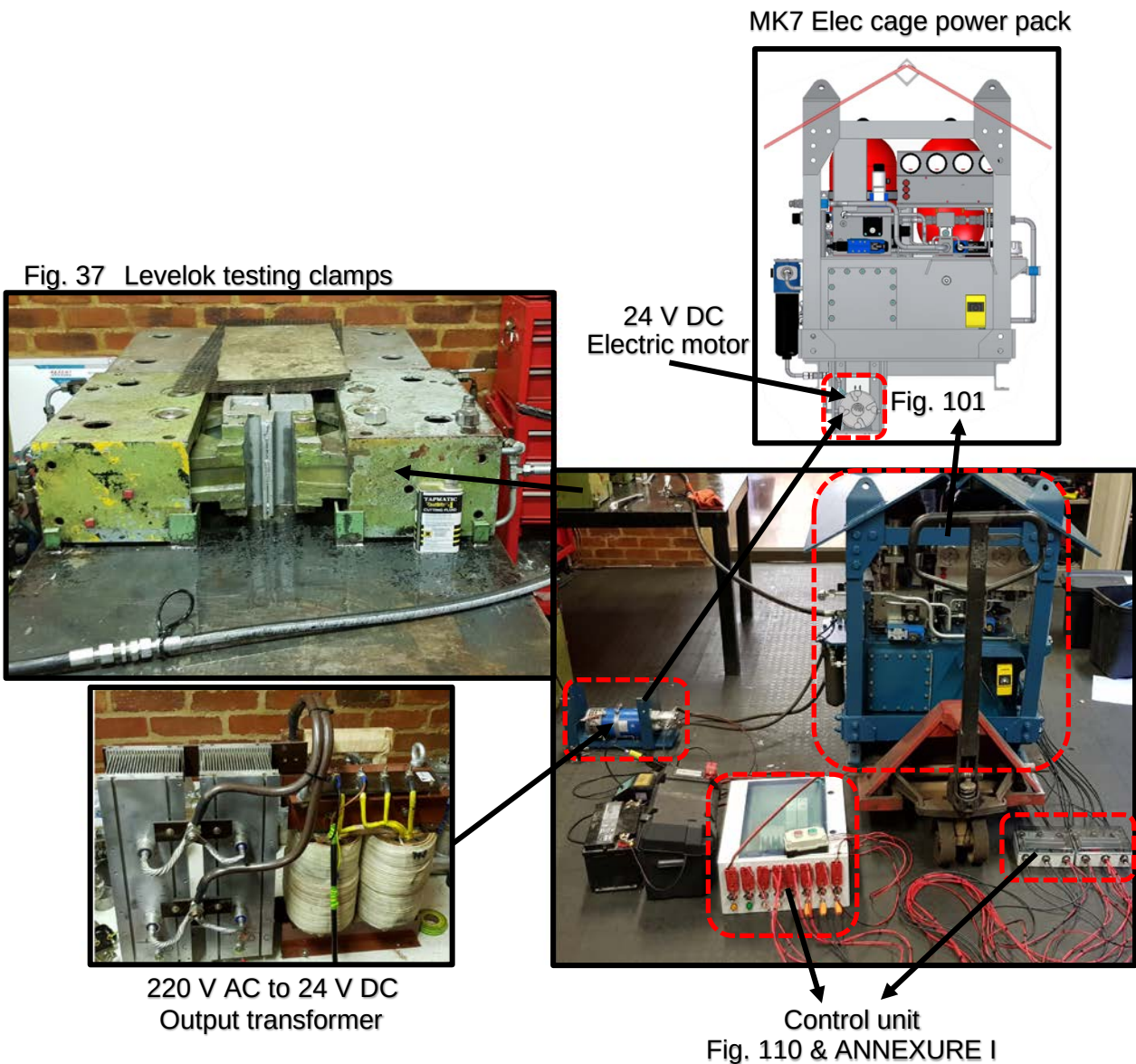


Figure 121: Experimental setup of the MK7 Elec Levelok cage power pack's validation tests [47].

9.4.1 Levelok cage power pack validation tests

The pressure data recorded during the completed tests were plotted and analysed. The advantage of using an electrical system is its ability to save time during operation. The blue and red curves, in Figure 122, represent the time it takes for an MK7 Elec and MK7s Levelok cage power packs to clamp, and reach system pressure, respectively. The data was captured with both power packs actuated at the same time.

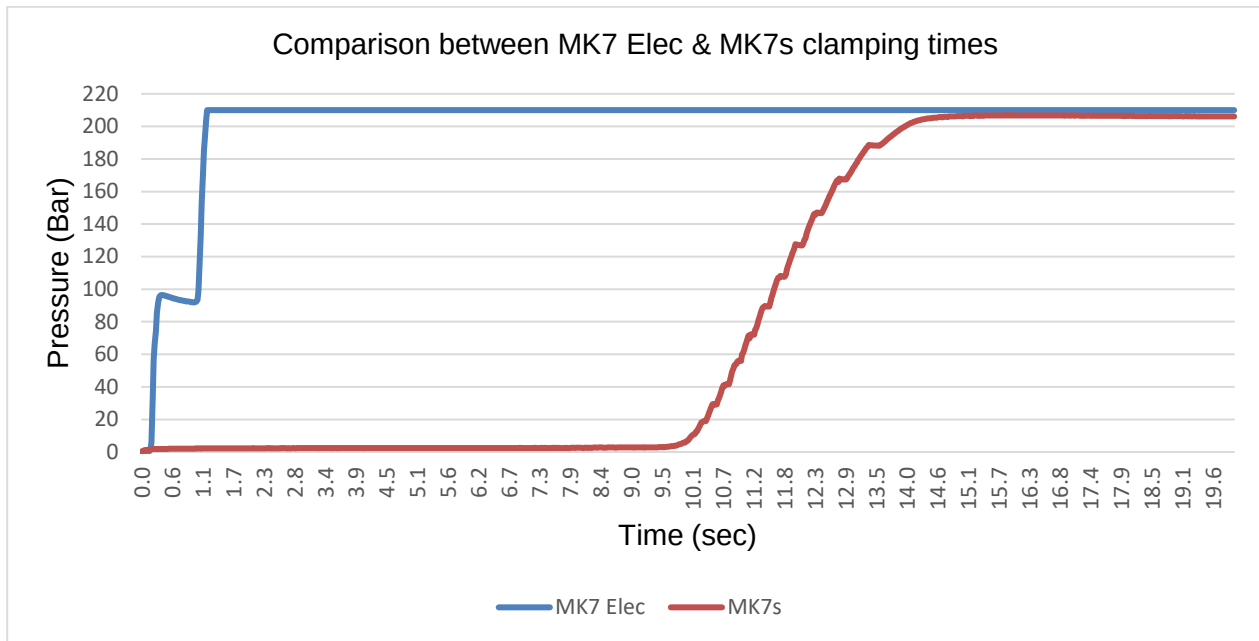


Figure 122: Comparison between MK7 Elec & MK7s clamping times.

This data representation shown in this figure illustrates that the electric operated power pack unit allows the Levelok cage system to clamp and reach system pressure 15 seconds faster than the pneumatic operated unit. This gives the MK7 Elec power pack the potential to save time during the loading and unloading procedures of normal daily mining operations.

The reason for this 15-second time delay of the MK7s power pack is since the MK7 Elec Levelok power pack has four pre-charged hydraulic bladder accumulators which could supply the needed hydraulic pressure instantly, assisting the electric motor with a hydraulic gear pump. The MK7s Levelok power pack does not have this precharged energy at its disposal.

The decompression cycle, on the other hand, is expected to be somewhat similar to that of the MK7s Levelok cage power pack, because of the unchanged rope and shaft characteristics. The average decompression data accumulated during the different decompression tests completed on the MK7 Elec power pack is represented by the curve plotted in Figure 1223.

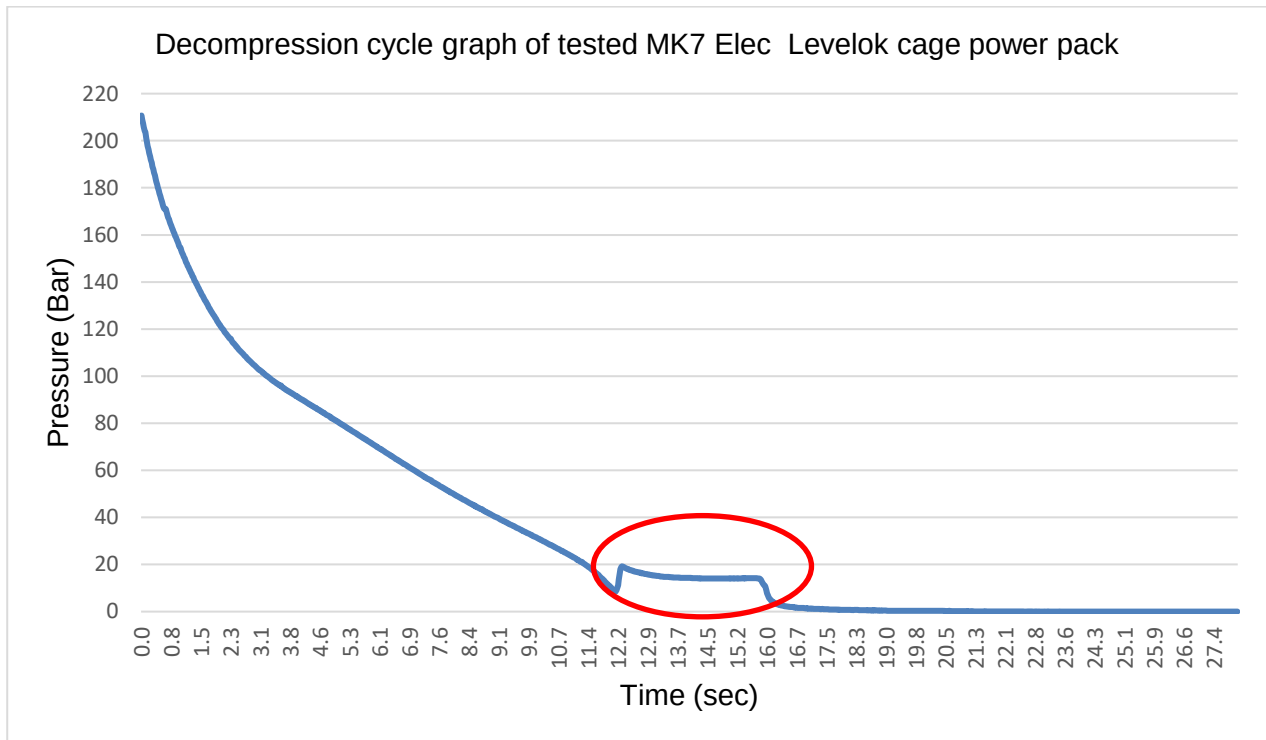


Figure 123:Decompression cycle graph of tested MK7 Elec Levelok cage power pack.

The red circle indicates the one difference of this MK7 Elec decompression cycle curve, compared to the MK7s decompression curve illustrated by the blue curve in Figure 120. This “bump” in the decompression curve, is caused by the 60 Bar low-pressure line forcing the clamps to open. When the Levelok system is released the decompression cycle pressure de-energizes as expected, but as soon as it reaches a pressure under the rated pressure of the low-pressure line, back pressure from the Levelok clamp cylinders tends to occur.

To see if this phenomenon would affect the displacement of the conveyance after the Levelok system is released and it slides into its new position in the vertical mine shaft, the decompression pressure data was used to predict the conveyance displacement, utilizing the mathematical conveyance prediction model. The displacement results that were obtained, are illustrated in Figure 124.

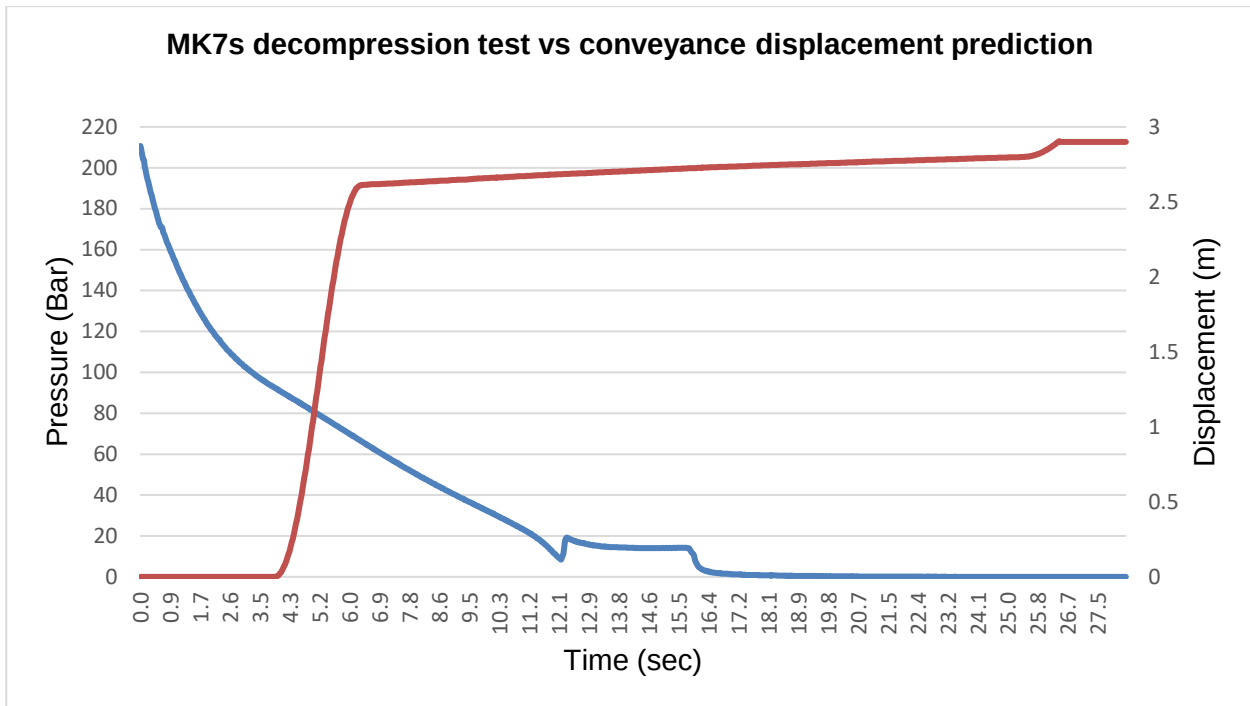


Figure 124: MK7s decompression test vs conveyance displacement prediction.

From this illustration, it was clear that the backpressure occurring in the Levelok clamp cylinders did not affect the displacement of the conveyance after a system release. The numerical model's prediction gave a positive result, and the Levelok power pack was validated to operate according to the design requirements and system specifications, as set out in Chapter 3, but some recommendations could be made for further development of this electrical Levelok cage power pack unit.

These recommendations include the use of a PLC to control the Levelok power pack unit. A PLC programed control system could delay the low-pressure line supply, to assure that the backpressure from the clamp cylinders does not occur, thus assuring a smoother decompression cycle output.

CHAPTER 10

CONCLUSION

The purpose and main objective of this research study were to develop a design and evaluation methodology for the Levelok conveyance arresting system, a safety system used for conveyance arresting in the mining industry. The concept behind the Levelok system offers numerous potential advantages, but unfortunately, did not yet fully deliver on the promises of these advantages in practical situations. The system proved in practice not to be reliable and consistent according to the consumer's system specifications and requirements. Therefore, the necessity for the establishment of a potentially reliable design and evaluation methodology presented itself.

This project aimed to first investigate and understand the different Levelok systems, their different components, and how their diverse control philosophies caused the interaction of critical assemblies to obtain the desired conveyance “slide” output. Thus, the bulk of the research focused on analysing the Levelok system itself.

With the knowledge obtained, the critical and controlling unit of the Levelok system was identified and studied. This breakthrough technology of the decompression cycle arrangement, grants the Levelok conveyance arresting system the ability to control the gradual pressure release in the hydraulic clamps, causing a conveyance to gradually slide in a controlled manner into its new position in the shaft after hoisting wire rope stretch was induced, due to loading or unloading of men, material or equipment to or from the conveyance.

Defining the consumer's system specifications and requirements, by conducting numerous on-site system audits, examining multiple Levelok system operational manuals, together with the late Peter Horne's preserved notes, assisted with the identification of the main system shortcomings. The most important of these deficiencies being the situation where the Levelok system did not release correctly, causing the load of the conveyance to be rapidly transferred to the winder hoisting rope, causing the conveyance to oscillate up and down in the shaft. This proved that the decompression cycle output, caused by the hydraulic fluid flow through the narrow annulus formed between the spindle and seat, was not yet fully understood under operational conditions.

Numerous decompression tests were conducted to address this unknown factor and understand how the different components of the Levelok system, affect the decompression cycle output. Unfortunately, there was no documented methodology, for the quality testing against specific consumer requirements, taking shaft and winder rope characteristics into account.

The development of the mathematical model for assessment of the Levelok decompression cycle output was devised from basic principles. This mathematical instrument provides the ability to predict a conveyance's displacement, when its Levelok conveyance arresting system is released, after loading or unloading of the conveyance has been completed. This conveyance displacement mathematical prediction model was validated by comparing the results of the predicted displacement with actual measured data. This validation enabled the mathematical instrument to be employed as a potentially reliable verification and validation instrument for future Levelok power pack designs. This conveyance displacement mathematical prediction model was used to analyse the results obtained from the numerous decompression tests.

The results of these decompression tests, together with their corresponding conveyance predicted displacement results, not only assisted with the determining of the required annulus size between the spindle and seat but also identified other concerns affecting the desired decompression cycle output. These concerns were investigated, by analysing the decompression cycle arrangement assembly. Several technical and practical deficiencies were identified and assisted in raising certain technical considerations and recommendations for the new MK7 range of design methodologies.

The new MK7 decompression arrangement was one of the products created with the knowledge obtained during this research study. The concept behind this new invention formed the base of the new MK7 Levelok cage power pack range. The objective of developing a documented design methodology for the Levelok conveyance arresting system was done for both pneumatic and 24 V DC-operated Levelok system solutions. These Levelok power packs were then manufactured and tested on the appropriate testing workbenches, with the objective to verify and validate the designs. The experimental measurements were again analysed with the conveyance displacement mathematical prediction model, taking specific consumer requirements, shaft, and winder rope characteristics into account, and were considered successful.

This research study did not address the system drawbacks such as that presented by Lamprecht (2015) [8], stating that the Levelok system does not align the conveyance in the mine shaft. The recommendation can be made to implement a more intensive research study focusing on the Levelok hydraulic clamps and the accessories thereof, to better investigate how this system shortcoming could be addressed.

This research study is however considered a success, in that all main objectives were satisfied and the research purpose fulfilled.

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ANNEXURE A

THE CLAMPING AND UNCLAMPING PROCEDURES OF THE DIFFERENT LEVELOK SYSTEMS IN OPERATION [11].

1. Introduction

All Levelok systems consist of at least one Levelok hydraulic power pack and numerous hydraulic clamps that hold a conveyance steady during the transfer of loads. The clamps then release their grip at a controlled rate to allow the rope stretch to be taken up gradually. These different Levelok systems have different clamping and unclamping procedures. In this chapter, the different step-by-step clamping and unclamping procedures are stipulated.

2. List of definitions

Levelok On:	The Levelok Hydraulic clamps have clamped and confirmation has been received, that safe clamping pressure has been reached and it is safe for the operator to continue with the loading or unloading procedure.
Levelok Off:	The Indication that the clamps have retracted completely, and that it is safe to hoist the conveyance.
Fly Hose:	The flexible hydraulic hose to connect pneumatic pressure to the conveyance, equipped with quick couplers and a check valve. The Fly Hose is parked onto a Park Panel at the King post and should be used for both the overlay and underlay conveyances.
Levelok in Use:	When the Fly hose is disconnected from the Park panel this is the indicator light that illuminates on the winder driver display.
Park Panel:	The Park Panel is a junction box supplied with pressure & position limit switches. The goal of this panel is to park the Fly Hose when it is not used. This is a safety precaution to assure the winder driver that the Fly Hose is not connected to the conveyance when the conveyance is to be hoisted.
Levelok Release:	The decompression procedure is initiated. The release of the hydraulic pressure in the system from the main pressure to no pressure take less than 35 sec.

Main Clamping Pressure:	The design pressure of the system that controls the “Levelok on” indication.
Winder Driver Display:	This display is normally a digital display in the winder driver’s cabin. It displays the SCADA from the PLC, assisting the winder driver in the conveyance hoisting dynamics.
Levelok OUT of USE:	This display is the opposite of Levelok in use.
Bell panel:	The communication panel situated at each level station, used to communicate with the winder driver.

3. List of Levelok system procedures

The following Levelok system clamping and unclamping procedures are covered:

- MK4 Levelok Man, Material cage system
- MK5 Levelok Man, Material cage system
- MK6 Levelok Man, Material cage system
- Mk7 Levelok Man, Material cage system
- Mk7s Levelok Man, Material cage system
- Mk7Elec Levelok Man, Material cage system
- Levelok Skip arresting system

4. Clamping & Un-clamping procedure for the MK4 & Mk7 Levelok systems

The clamping & un-clamping procedures for the MK4 & Mk7 Levelok man, material cage systems are similar. The sequential operating procedure is as follow:

- The conveyance approaches the desired vertical mine shaft level station. Shaft magnetic switches or the Onsetter on the level feed a signal through to the winder control system that the cage is in position.
- The Winder driver applies the brakes of the hoisting winder machine.
- The Onsetter opens the shaft gates.
- The Onsetter, who is the only authorized person, removes the “**Fly Hose**” from the “**Park Panel**” that will, in turn, lock the hoisting winder machine brakes and indicate a signal “**Levelok in Use**” to the winder driver.
- A quick coupler is used to connect the “**Fly Hose**” to the conveyance.
- For the first 4 seconds, pneumatic line pressure will close the clamp arms onto the guides. After 4 seconds the intensifier in the power pack will start and raise the hydraulic pressure to safe clamping pressure.

- The magnetic/pressure switches in the clamps will change state and the green "**Levelok Off**" light in the "**Winder Driver Display**" will de-illuminated.
- The green LED Go/No-Go light on the front of the conveyance will illuminate as the pressure switch on the hydraulic power pack indicates "**Main clamping pressure**" has been reached. The same pressure switch will cause the "**Levelok On**" to illuminate in the hoist control system.
- Loading and unloading can now take place as long as the green LED Go/No-Go light is on.
- After loading/unloading is completed. Cage doors are closed. (Some mines interlock the cage doors as well).
- The "**Fly Hose**" is removed from the conveyance and parked onto the "**Park Panel**" and the "**Levelok OUT of USE**" indication light switches on the "**Winder Driver Display**".
- On removal of the "**Fly Hose**", the "**Levelok Release**" sequence is activated and the clamps start to release due to pressure decay in the system.
- After about 2 seconds the pressure in the system will decay enough to change the state of the main pressure switch on the hydraulic power pack which in turn will cause the "**Levelok On**" light to de- illuminate on the "**Winder Driver Display**".
- After about 4 seconds the cage will start to move and slide in a controlled manner to its new position in the shaft.
- The magnetic/pressure switches in the clamps will cause the "**Levelok Off**" to illuminate on the "**Winder Driver Display**" and winder brakes can now be deactivated and the conveyance hoisted.

5. Clamping & Un-clamping procedure for the MK5, MK6 & Mk7s Levelok systems

The clamping & un-clamping procedures for the MK5, MK6 & Mk7s Levelok man, material cage systems are similar. The sequential operating procedure is as follow:

- The conveyance approaches the desired vertical mine shaft level station. Shaft magnetic switches or the Onsetter on the level feed a signal through to the winder control system that the cage is in position.
- The Winder driver applies the brakes of the hoisting winder machine.
- The Onsetter opens the shaft gates.
- The Onsetter, who is the only authorized person, removes the "**Fly Hose**" from the "**Park Panel**" that will, in turn, lock the hoisting winder machine brakes and indicate a signal "**Levelok in Use**" to the winder driver.
- A quick coupler is used to connect the "**Fly Hose**" to the conveyance.

- For the first 4 seconds, pneumatic line pressure will close the clamp arms onto the guides. After 4 seconds the intensifier in the power pack will start and raise the hydraulic pressure to safe clamping pressure.
- The magnetic/pressure switches in the clamps will change state and the green "**Levelok Off**" light in the "**Winder Driver Display**" will de-illuminated.
- The green LED Go/No-Go light on the front of the conveyance will illuminate as the pressure switch on the hydraulic power pack indicates "**Main clamping pressure**" has been reached. The same pressure switch will cause the "**Levelok On**" to illuminate in the hoist control system.
- Loading and unloading can now take place as long as the green LED Go/No-Go light is on.
- After loading/unloading is completed. Cage doors are closed. (Some mines interlock the cage doors as well).
- The "**Fly Hose**" is removed from the conveyance and parked onto the "**Park Panel**" and the "**Levelok OUT of USE**" indication light switches on the "**Winder Driver Display**".
- The Onsetter places the key into the "**Bell panel**" and pushes the deactivation button on the "**Bell panel**". A signal is sent into the winder controller, then onto the cage communications controller, and the 12 V solenoid valve on the Levelok hydraulic power pack will be energized and maintained for 40 seconds.
- After about 2 seconds the pressure in the system will decay enough to change the state of the main pressure switch on the hydraulic power pack which in turn will cause the "**Levelok On**" light to de- illuminate on the "**Winder Driver Display**".
- After about 4 seconds the cage will start to move and slide in a controlled manner to its new position in the shaft.
- The magnetic/pressure switches in the clamps will cause the "**Levelok Off**" to illuminate on the "**Winder Driver Display**" and winder brakes can now be deactivated and the conveyance hoisted.

6. Clamping & Un-clamping procedure for the Mk7Elec Levelok system

The clamping & un-clamping procedure of Mk7Elec Levelok man, material cage system is not only a much faster procedure but is also a quicker response system. The sequential operating procedure is as follow:

- The conveyance approaches the desired vertical mine shaft level station. Shaft magnetic switches or the Onsetter on the level feed a signal through to the winder control system that the cage is in position.
- The Winder driver applies the brakes of the hoisting winder machine.
- The Onsetter opens the shaft gates.
- The Onsetter pushes the green push button, located on the cage next to the cage door.
- This button activates the clamping sequence of the system. It takes 3 seconds for the system to reach "**Main Clamping Pressure**".
- The pressure switches in the clamps will change state and the green "**Levelok Off**" light in the "**Winder Driver Display**" will de-illuminated.
- The green LED Go/No-Go light on the front of the conveyance will illuminate as the pressure switch on the hydraulic power pack indicates "**Main clamping pressure**" has been reached. The same pressure switch will cause the "**Levelok On**" to illuminate in the hoist control system.
- Loading and unloading can now take place as long as the green LED Go/No-Go light is on.
- After loading/unloading is completed. Cage doors are closed. (Some mines interlock the cage doors as well).
- The Onsetter pushes the red push button, located on the cage next to the cage door.
- This button activates the un-clamping sequence of the system.
- The Onsetter moves away from the cage and closes the shaft gates.
- After about 2 seconds the pressure in the system will decay enough to change the state of the main pressure switch on the hydraulic power pack which in turn will cause the "**Levelok On**" light to de- illuminate on the "**Winder Driver Display**".
- After about 4 seconds the cage will start to move and slide in a controlled manner to its new position in the shaft.
- The pressure switches in the clamps will cause the "**Levelok Off**" to illuminate on the "**Winder Driver Display**" and winder brakes can now be deactivated and the conveyance hoisted.

7. Clamping & Un-clamping procedure for the Levelok skip arresting system

The clamping & un-clamping procedure of the Levelok skip system is fully operated by a PLC. Normally the clamping and un-clamping of a conveyance at the loading station occur every minute depending on the shaft depth and the speed of the conveyance hoisting. With a Levelok skip system to conveyances are operated with one system, as the underlay skip and the overlay skip of the winder are interchanged during hoisting. The sequential operating procedure is as follow:

- When an empty skip approaches the loading station, it passes a level switch that sends a signal to the PLC indicating the skip position in the shaft.
- The skip stops in the loading position under the chute of the flask. The proximity switch or magnetic switch in the shaft together with the **“Brakes On”** signal and **“Flask Full”** sends signals to the Levelok PLC **“Skip in Position”**.
- The Decompression solenoid valve and low-pressure retraction valve and then ½ second later system pressure solenoid valve on the hydraulic power pack is energized.
- The clamps are applied by high-pressure fluid from the accumulators, and line pressure will then build up to operate the **“Main Clamping Pressure”** indication which transmits a signal to the flask controls to open the flask door.
- The rock will then discharge into the skip. A load cell under the flask will signal a complete emptying of the flask and this will then signal the release of the clamps. (An analog signal can be used from the load cell so the weight can be recorded as the flask empties. This displacement in value can assist in optimizing the loading times.)
- After loading the system pressure solenoid valve will be de-energized followed by the time delay of ½ second before decompression solenoid valve.
- Clamp pressure will decay through the decompression arrangement. The hydraulic decompression cylinder and spindle drop the pressure and allows the skip to slide and take up the rope stretch.
- When the decay in pressure in the system reaches the point where the low-pressure switch change state, a signal is sent to the PLC.
- The low-pressure retraction valve will de-energize when the low-pressure signal is activated.
- Low-pressure fluid from the low-pressure retraction valve forces the clamp arms of the skip and at the same time, the driver will receive the signal to hoist the skip.

ANNEXURE B

HYDRAULIC OIL SPECIFICATIONS OF HYDRAULIC OILS ISO 32, 46, 68, 100, 150, 220 [34] [37]



SPEC OIL HYDRAULIC OIL ISO 32, 46, 68, 100, 150, 220

DESCRIPTION

High quality anti-wear hydraulic fluid formulated for use in high pressure stationery and mobile hydraulic systems. Incorporates zinc phosphate additive technology.

APPLICATION

Not recommended for systems with silver plated components.

- Wide range of industrial hydraulic equipment.
- Hydraulics on construction and mobile equipment.
- Hydraulic systems with gear, vane or piston pumps.
- Industrial circulating systems.
- Machine tools and enclosed gear systems.
- Plastic injection moulding.

BENEFITS

- Outstanding pump and equipment protection, even in very severe operating conditions.
- Extends oil and equipment service life by avoiding problems such as servo valve sticking.
- Prolongs oil change intervals.
- Reduces yellow metal corrosion by controlling oil stability.
- Prevents downtime by minimising flow restrictions due to clogged filters and extends life equipment
- Suitable for many other industrial applications.

SPECIFICATIONS

- DIN 51524 Part 2 (HLP) & Part 3 (HVLP)
- GM LS2
- ISO 11158 Categories HM and HV
- ASTM D 6158 Type HM and HV
- Afnor NF E 48-603 HM and HV
- US Steel 126 and 127
- Cincinnati P-68, P-69, P-70
- Denison HF-0, HF-1 and HF-2
- Eaton 694 for 35VQ25A (formerly M-2950 and I-286-S)

KEY PROPERTIES

ISO Grade	32	46	68	100	150	220
Air Release @ 50 °C; min	5.0	6.7	8.6	11.0	11.2	11.4
Viscosity @ 40 °C	32	46	68	100	150	220
Viscosity Cst @ 100 °C	5.4	6.7	8.6	11.1	14.8	20.3
Viscosity Index	99	98	97	96	95	95
Flash Point °C (Min)	210	220	226	240	254	262
Pour Point °C (Max)	-33	-30	-24	-22	-21	-18

Product Data



BP Hydraulic Oil Range

Anti-wear hydraulic oil

Description

The BP Hydraulic Oil range are based upon mineral oil enhanced with a stabilised zinc additive system

Application

BP Hydraulic is primarily for use in hydraulic equipment, but is suitable for other duties in which lubricants with good oxidation stability and lubrication performance are required. The quality of its base oils and additives permits the application of the BP Hydraulic range in lightly loaded gears and for use as circulating oil in applications where a rust and oxidation inhibited oil is required.

The BP Hydraulic oils meet the specification requirements of the Vickers vane-pump test, DIN 51524 Part 2 and is classified as DIN 51502 classification – HLP & ISO 6743/4 – Hydraulic Oils Type HM.

The range is fully compatible with elastomer materials commonly used for static and dynamic seals, such as nitrile, silicone and fluorinated (e.g. Viton) polymers.

Advantages

- Good anti-wear performance – prevents wear of internal components reducing downtime
- Resistant to oxidation – extends service life
- Good water separation – reduces downtime and prolongs lubricant life

Typical Characteristics

Test	Method	Units	Hydraulic 32	Hydraulic 46	Hydraulic 68
ISO Viscosity Grade	-	-	32	46	68
Density @ 15°C	ISO 12185	g/ml	0.88	0.88	0.88
K.V. @ 40°C	ISO 3104	mm ² /s	32	46	68
K.V. @ 100°C	ISO 3104	mm ² /s	5.44	6.82	8.77
Viscosity Index	ISO 2909	-	>95	>95	>95
Pour Point	ISO 3016	°C/°F	-30/-22	-27/-17	-24/-11
Flash Point, COC	ISO 2592	°C/°F	210/411	215/419	226/440
Foam Seq I	ISO 6247	mls	10/0	10/0	10/0
Water Separability @ 54°C	ISO 6614	Mins	15	15	15
Air Release Value	ISO 9120	Mins	4	8	8
FZG fail stage (A8.3/90)	DIN 51354	-	11	12	12
Rust Test (24 hrs distilled water)	ASTM D665A	-	Pass	Pass	Pass
Rust Test (24 hrs Synthetic sea water)	ASTM D665B	-	Pass	Pass	Pass

Subject to usual manufacturing tolerances.

ANNEXURE C

LEVELOK CLAMP SPECIFICATION SHEET [40]



WJ Engineering (PTY) LTD.

12 Grobler Street, Potch Industria, Potchefstroom, RSA

☎ +27 (0)18 294 3395

📠 +27 (0)18 294 5472

wjeng@mweb.co.za

www.wjengineering.co.za

4.5 Ton Levelok Clamp Specification Sheet

Customer : Mine X

Settings

Test pressure of the clamp : 25 MPa

Operating pressure of the clamp : 20 MPa

High-pressure oil leaks on the hydraulic cylinder : Nil

Air leaks on the hydraulic cylinder : Nil

Arms retracted fully : Yes 180mm +

Free displacement of shoes : Yes

WJ Engineering (PTY) LTD.

Signed : _____

Date: _____

ANNEXURE D
MINE X WINDING ROPE TEST CERTIFICATE [41]



CSIR Implementation Unit
Rope Testing Laboratory
Private Bag X28 Auckland Park 2006 South Africa
Tel: +27 11 482 1300
Fax: +27 11 726 6418
Internet: <http://engminlabs.csir.co.za>
Delivery Address: Cnr Merton Road & Frost Avenue
Cottesloe 2092 Johannesburg

CERTIFICATE OF TEST CONDUCTED ON WINDING ROPE

CERTIFICATE No : 260445

Rope received : 2018/05/16

Date of test : 2018/06/20

Specimen Supplied By : [REDACTED]

Address : [REDACTED]

INSTALLATION PARTICULARS

Winder permit : [REDACTED]

Date installed : 2016/10/21

Name of shaft : [REDACTED]

Length of wind (m) : 2986

Type of shaft : Vertical

Name of compartment : Underlay Inner

ROPE PARTICULARS

Coil No of rope : 155745001

Wire finish : Drawn Galvanised

Manufacturer : HAGGIE

Type of heart : Fibre

Date of manufacture : 2013/10/24

Tensile grade (MPa) : 1900

Nominal Diameter (mm) : 42.0

Rope mass (kg/m) : 7.44

Rope length (m) : 3200

Type of lay : RHL

Number of strands : 6

Nominal lay length (mm) : 337

Wire diameters (mm) : 3.05 1.84 1.56 1.16

Lubricant : Unknown

No. of wires in strand : 30(12/12/6+3T)

Construction : Compound Triangular Strand 6x30(12/12/6+3T)F

Type of strand core : Platted

SPECIMEN PARTICULARS

Breaking force of new rope (kN) : 1433

Date specimen cut : 2018/04/11

Breaking force at previous test (kN) : 1483

Length of specimen supplied (m) : 5.00

Minimum allowable breaking force (kN) : 1290

RESULTS OF TEST AND EXAMINATION

Breaking force (kN) : 1492.0 $\pm$ 0.64%

Specimen gauge length (m) : 2.75

Diameter without preload (mm) : 42.7

Measured lay length (mm) : 380

Diameter with preload (mm) : 41.5

Least outer wire dimension (mm) : 3.03

Corrosion : Traces against the heart. Traces between the strands. Traces inside the strands. Very slight pitting and corrosion on the outside of the rope.

Lubrication : Fair.

Appearance of wires at fracture : Ductile.

Number of strands broken : Two.

Position of fracture : Centre

Test remarks : First wire failure at 1440kN.

CSIR

Technical Signatory :

Gerit Coertzen

Engineer :

Riaan Bergh

TEST PROCEDURE: COTT-SOP-1

Page: 1 of 2

This Certificate of Test relates only to the specimens or components tested and is issued subject to the conditions of the CSIR. Please see overleaf for Terms and Conditions of Rope Testing.

ANNEXURE E

CALCULATION SHEET OF SYSTEMS INSTALLED AT MINE X [43]



ENGINEERING SOLUTIONS
THROUGH INNOVATION

Calculation sheet

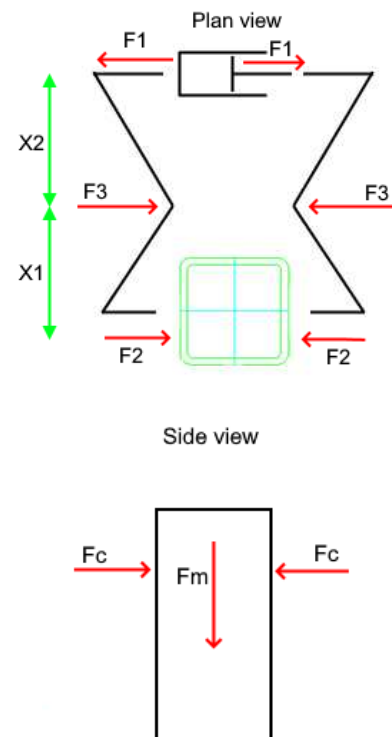
Project: Mine X 3-deck & 2-deck conveyance systems.
Product: 18 Ton Levelok man, material cage arresting system.
Prepared by: Jaundré Taljaard

Clamp inputs

Shoe clearance from the guide
Diameter of cylinder
Cylinder stroke
Arm dimension X1
Arm dimension X2
Friction insert coefficient
System pressure
Point of slip
Cylinder volume required per clamp
F1 Force per clamp
F2 Force per clamp
F3
Fc Total
Fm
Holding mass
Safety factor
Commercial holding mass per clamp

Static

0.029	m
0.1	m
0.06	m
0.154	m
0.18	m
0.27	
210	Bar
88.96	Bar
0.471	l
164.93	kN
192.78	kN
357.71	kN
385.56	kN
104.10	kN
18	Ton
2.36	
5.21	Ton



System design settings

Number of clamps	4	
Clamp shoes maximum opening	210.7	mm
Hydraulic fluid	33 Viscosity	
Spindle diameter	6.22	mm
Spindle undercut	7	mm
Seat undercut	7	mm
System hydraulic pressure	21	MPa
Point of slip with a full payload	8.90	MPa
Power pack pressure switch setting	18	MPa
Timer setting	6	sec
Clamping time	12	sec
Release time	32	sec
Power pack max pressure hold time	1	hr
Accumulator max pressure hold time	1	hr
Minimum decompression elect hold time	25	sec
Clamplock valve setting	0.7	mm
Clamp pressure switch setting	2	Bar
Coil voltage	12	V DC

ANNEXURE F
LEVELOK HYDRAULIC POWER PACK DECOMPRESSION TESTING
PROCEDURE [6]



TESTING PROCEDURE FOR LEVELOK CAGE POWER PACK

Input

- Power pack settings to be set according to the "TEST SETTINGS FOR POWER PACK" sheet of the specific customer.
- This sheet is compiled by the Engineer and the workshop foreman to check settings accordingly.

Procedure

The Levelok power pack has four control settings that are required to ensure that a system operates correctly.

The four settings are:

- 1) The maximum clamping forces.
- 2) The timer setting.
- 3) The minimum clamping times.
- 4) The maximum decompression time for the system.

1. Location of setting the setting

The Levelok decompression control valve is situated under the oil filler plug on the power pack reservoir. The timer setting is inside the perspex box on the pneumatic supply service line and the regulator setting is next to the perspex box in the pneumatic supply service line.

2. Setting the system pressure

- To set the system pressure, deregulate the regulator completely. With a clamp connected to the power pack, apply the pneumatic supply to the pneumatic supply service line and then wait for the pneumatic supply/oil pump to activate.
- With a "Minitest" lead and 0 to 25 MPa gauge connected to the "Minitest" connector on the power pack, regulate the regulator until the desired design hydraulic pressure is achieved.
- The power pack will stall at the set pressure. To reduce the pressure, the pneumatic supply must be disconnected and the regulator deregulated and then the procedure repeated for the correct setting.

The clamping time of a Levelok system is a function of two activities, namely the incoming pneumatic supply system pressure and the timer setting of the Levelok power pack. We are only able to control the timer setting.

3. Setting the Timer

- Open the perspex box in the pneumatic supply line to reveal the timer unit.
- Turn the adjustment screw anti-clockwise to reduce the timer setting and clockwise to increase the timer setting.
- The purpose of the timer setting is to allow the clamps to close onto the guide's face under the pneumatic supply pressure of a minimum of 4 to 6 bar.
- The time setting is usually 4 seconds and for 4 or more clamps 6 seconds, unless otherwise specified.
- Always lock the adjustment screw.

4. Setting the Decompression time

The Levelok decompression control valve is situated under the oil filler plug on the Power pack reservoir.

- Connect the gauge and "Minitest" hose connection to the "Minitest" quick connector fitting on the Levelok power pack.
- Apply pneumatic supply to the quick coupler on the supply line to the power pack.
- Allow the power pack to stall and ensure the hydraulic pressure is set to the specified clamping pressure setting.
- Disconnect the pneumatic supply pressure from the quick coupler.
- The gauge needle must drop to 10 MPa within 3 seconds and to 0 MPa within a further 9 seconds. (Decompression time specified on the "TEST SETTINGS FOR POWER PACK" sheet.)

- The adjustments are done without any pneumatic supply pressure on the system.
- Too slow or lengthen the decompression, turn the adjustment in clockwise 1/8 of a turn per test. Larger adjustments can be made if the setting is far out.
- The oil filler cap must be replaced after every adjustment.
- Repeat the adjustment until the required rate is achieved.

Conducting workbench tests

After the control settings setting procedure of the Levelok power pack is set, according to the supplied "TEST SETTINGS FOR POWER PACK" sheet, the power pack is ready for the decompression cycle test to be completed. The experimental setup being used is illustrated in Figure 37:

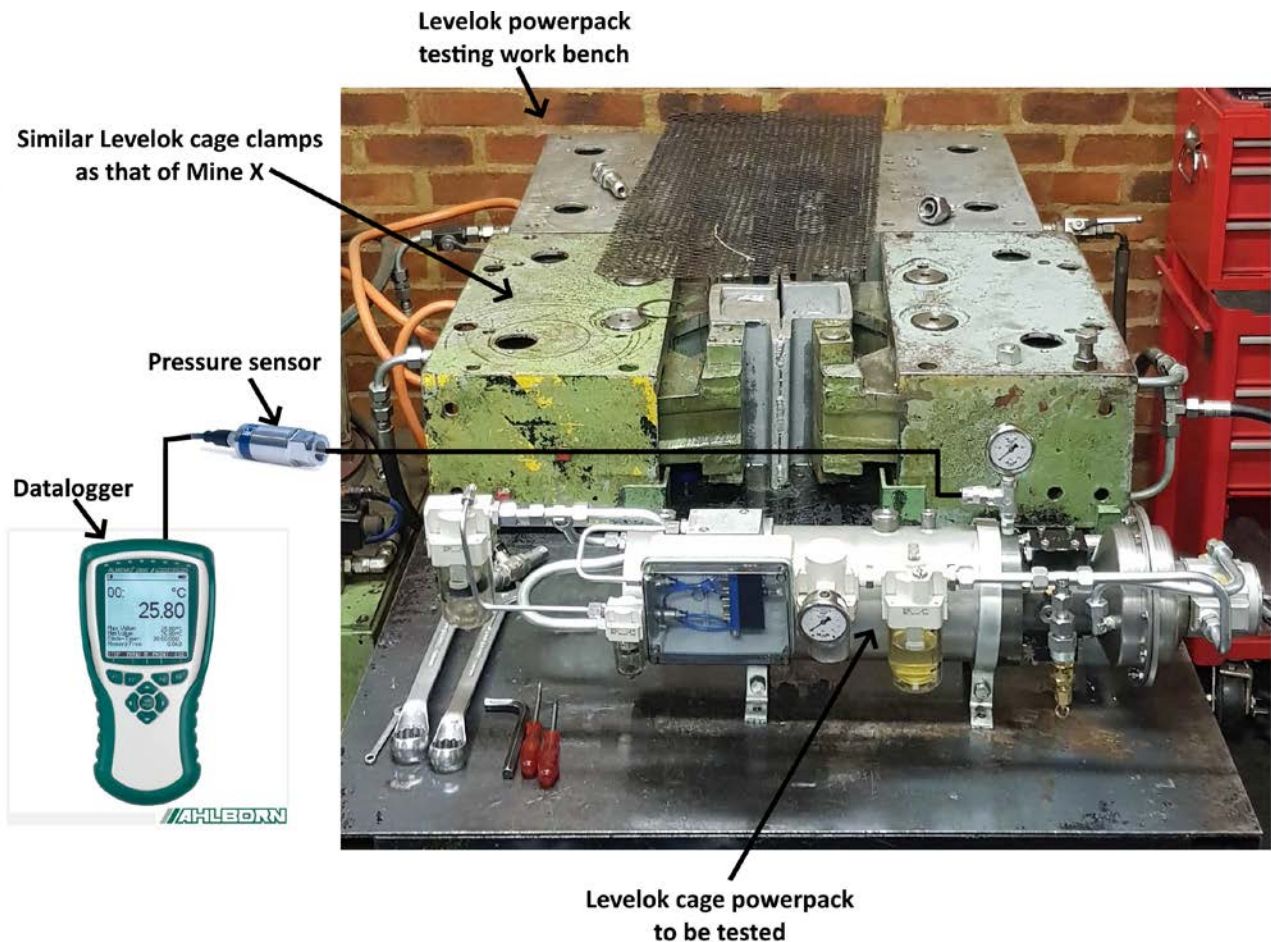


Figure 37: Experimental setup for the test of Levelok cage power packs [50].

The testing procedure is carried out as follow:

- Connect the datalogger and "Minitest" hose connection to the "Minitest" quick connector fitting on the "Levelok" power pack.
- Apply pneumatic supply to the quick coupler on the supply line to the power pack.
- Allow the power pack to stall and ensure the hydraulic pressure is set to the specified clamping pressure setting.
- Press the start button on the datalogger to start the recording of the pressure data.
- Disconnect the air supply pressure from the quick coupler.
- Release the Levelok system and keep on recording the data until the pressure indicator reaches 0.
- Stop the data logging on the data logger.
- Download data from the data logger onto a personal computer and analyse the data.

Conducting on-site audit tests

The Levelok decompression on-site audit tests and sliding tests follow the same control settings setting procedure as laid out from points 1 to 4.

The procedure would be as follow:

- The WJ Engineering audit team position themselves on top of the conveyance to check Levelok parameters and fix testing equipment to the Levelok hydraulic power pack.
- The same testing procedure is then followed as explained in the testing procedure of "Conducting workbench tests".
- After the decompression tests are completed, the audit team would be taken down to the deepest Levelok operational level in the shaft for slide testing.
- The mine personnel loads the testing weights in the conveyances at the bank level. These testing weights are normally 50% of the payload weight.
- 3 Slide tests on each conveyance are conducted. Videos and observations are taken.

A slide test is conducted by the following procedure:

- Conveyance is stopped at the testing level.
- The Levelok system is clamped and the testing weight is removed from the conveyance.
- The Levelok system is then released and the "slide" of the conveyance will occur and be recorded.
- The conveyance is re-positioned in the shaft, clamped and the testing weight is loaded.
- The Levelok system is then released again and the "slide" of the conveyance will occur and be recorded.

Notes:

When the power pack has stalled the following checks need to be carried out:

No air leaks are accepted on the air system.

No Hydraulic oil leaks are accepted on the system.

The air exhaust valve may not leak excessively.

The hydraulic pressure may not vary while the pump has stalled.

ANNEXURE G
REPORT ON THE CALCULATION OF THE STATIC AND KINETIC
COEFFICIENTS OF FRICTION FOR DIFFERENT TYPES OF LEVELOK
CLAMP SHOE INSERTS [48]



Report on the experimental findings on the static & kinetic coefficients of friction
for different Levelok hydraulic clamp shoe inserts

1 Purpose & objectives

The static and kinetic coefficients of friction for the Levelok clamp shoe inserts are an unknown entity. These values are essential for the completion of a mathematical model which predicts the displacement of a conveyance after it is released from a Levelok conveyance arresting system.

The objective of the experiments documented in this report is to define these values for 5 different types of Levelok hydraulic clamp shoe inserts. These inserts consist of different materials and different clamp contact area sizes and the coefficients of friction calculated from basic principles.

2 Theory & formulas

From basic principles, the static and kinetic coefficients of friction can be defined as the ratio of friction forces to the normal force of a mass. Hence Equations 19b & 19c:

$$f_s = \mu_s \times F_N \quad (19b)$$

$$f_k = \mu_k \times F_N \quad (19c)$$

Where f_s = Friction force of shoe on guide surface [N]
 f_k = Friction force of shoe on guide surface [N]
 μ_s = Static friction coefficient [Unitless]
 μ_k = Kinetic friction coefficient [Unitless]
 F_N = Normal force [N]

Considering the case where a Levelok clamp clamps against a guide, T-bar or any other steel framework as illustrated in Figure 125 [50] [52], these equations of friction can be adjusted for the calculation of the friction coefficients of the different clamp shoe inserts during the clamping operations:

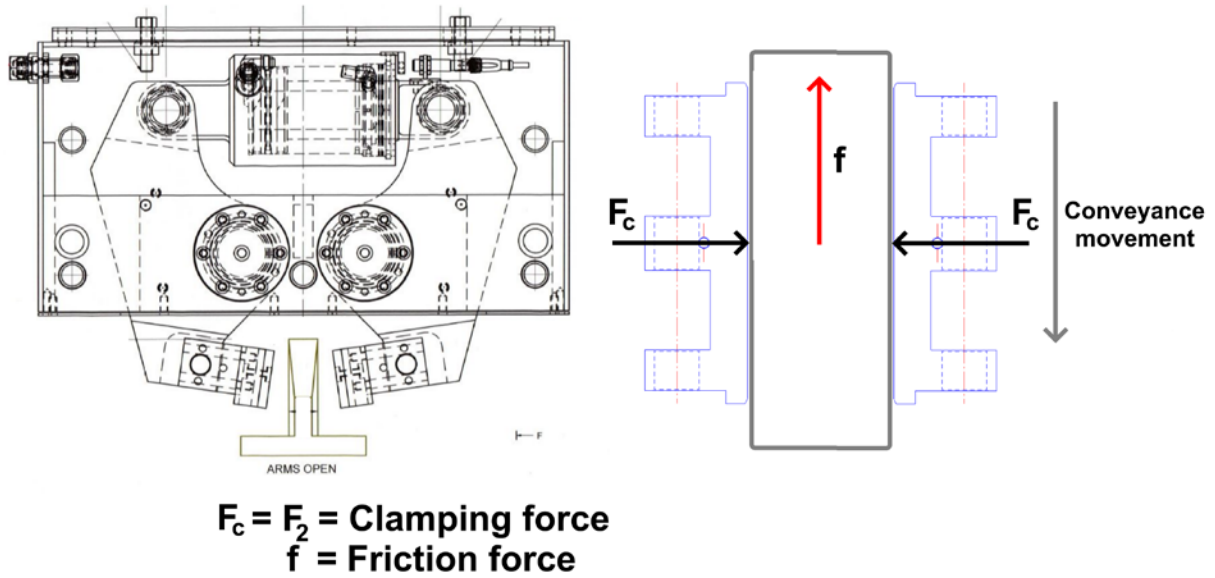


Figure 125: Levelok clamp clamped against a guide, T-bar, or any other steel framework [50] [52].

Hence Equations 19d & 19e:

$$f_s = \mu_s \times 2 \times F_c \quad (19d)$$

$$f_k = \mu_k \times 2 \times F_c \quad (19e)$$

Where $F_c = \text{Clamping force [N]}$

The other factor that can be considered during these experiments to calculate the coefficients of friction is illustrated in Figure 126 [50] [52]:

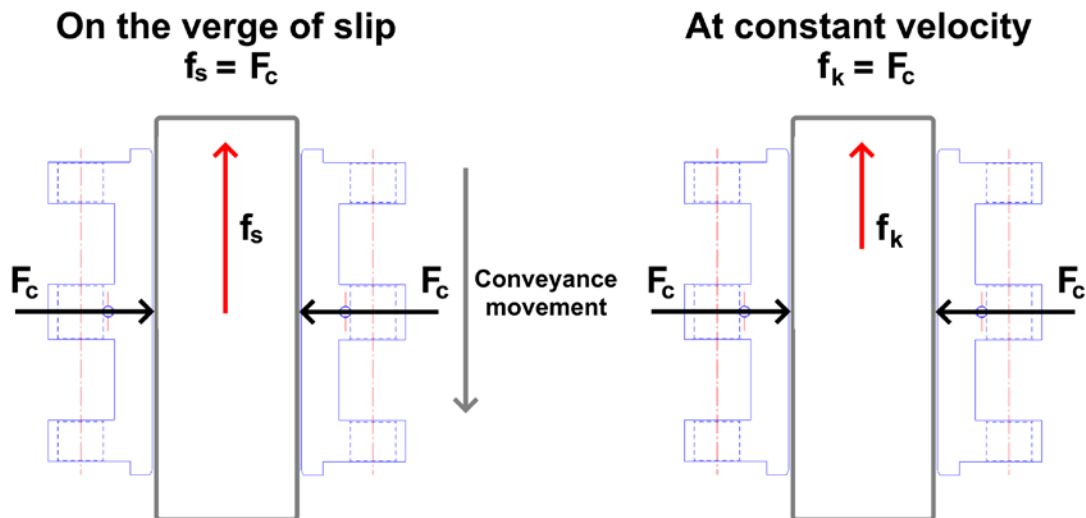


Figure 126: Demonstration of the two cases of friction forces [50] [52].

Figure 126 [50] [52] Illustrates important aspects, one being the force of friction always acts against the direction of the conveyances' motion. The relationship between the different friction forces can be defined as $f_s > f_k$ and consequently, $\mu_s > \mu_k$. The force due to the conveyance mass is equal to the static friction force only at the point of slip and is equal to the kinetic friction force when the conveyance slides at a constant velocity.

To calculate the static coefficient of friction the formula for the pressure at slip point (measured in Bar) can be used:

$$\text{Slip press.} = \frac{m_p \times g}{\mu_s \times \Delta X_2 / \Delta X_1 \times n_c \times \left(\frac{\phi_p}{2}\right)^2 \times \pi \times 2 \times 10^5} \quad (8)$$

$$\therefore \mu_s = \frac{m_p \times g}{\text{Slip press.} \times \Delta X_2 / \Delta X_1 \times n_c \times \left(\frac{\phi_p}{2}\right)^2 \times \pi \times 2 \times 10^5}$$

Where

- Slip press.* = Measured in Bar.
- m_p = Payload mass [kg]
- g = Gravitational acceleration [m/s^2]
- μ_s = Coefficient of static friction [unitless]
- ΔX_1 = Moment lever arm from bearing to shoe on guide [m]
- ΔX_2 = Moment lever arm from bearing to hydraulic cylinder [m]
- n_c = Number of clamps [unitless]
- ϕ_p = Piston diameter [m]

This equation can be used for the calculation of both static and kinetic coefficients of friction. With the measured pressure at the point of slip, the static coefficient of friction can be calculated. With the measured pressure value just after the point of slip, at the moment in time where the conveyance starts to move at a constant velocity, the kinetic coefficient of friction can be calculated (Keep in mind that the payload weight value is also adjusted for this calculation, as the kinetic snatch rope is taking up some percentage of the force as the weight slides down). Figure 127 [50] illustrates these two pressure points graphically for better visualization.

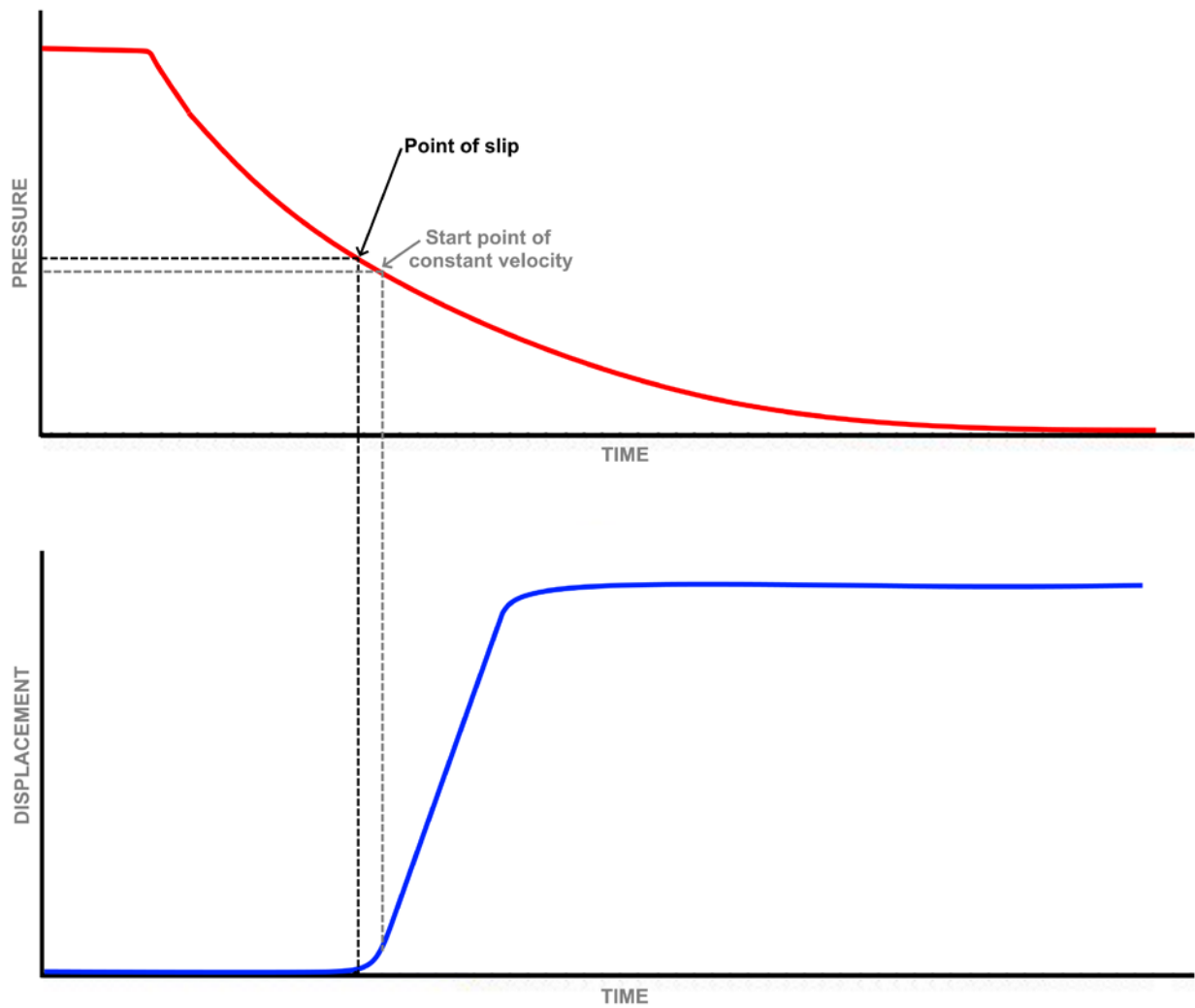


Figure 127: Graphical illustration of the "Point of slip" & "Start point of constant velocity" pressure points [50].

To obtain the pressure values needed to identify the pressure points as illustrated in Figure 127, it is required to measure the pressure in the hydraulic power pack synchronously with the displacement of the moving mass.

3 Workbench setup & testing equipment

The equipment that was used to obtain the results resembling the graphs in Figure 127 consists of:

- Levelok hydraulic skip power pack x1 (A)

The Levelok skip power pack, illustrated in Figure 128 [4], is the hydraulic power pack that is used to control the Levelok skip clamps of the testing setup. Formed part of the main controlling valves manifold, there are “Minitest” testing points to connect hydraulic pressure sensors to measure the hydraulic pressures during the clamping and unclamping procedures.



Figure 128: Levelok skip power pack for Levelok testing work [4].

- Levelok hydraulic skip clamps

x2 (B)

The testing setup is equipped with 2 off Levelok skip hydraulic clamps. These hydraulic clamps are double regulated for better control and are also equipped with “Minitest” testing points to connect hydraulic pressure sensors to measure the hydraulic pressures at the clamp cylinder. The geometry configuration of the clamps was designed to clamp onto a 30mm thick T-bar steel section as shown in Figure 129 [4] [52]:

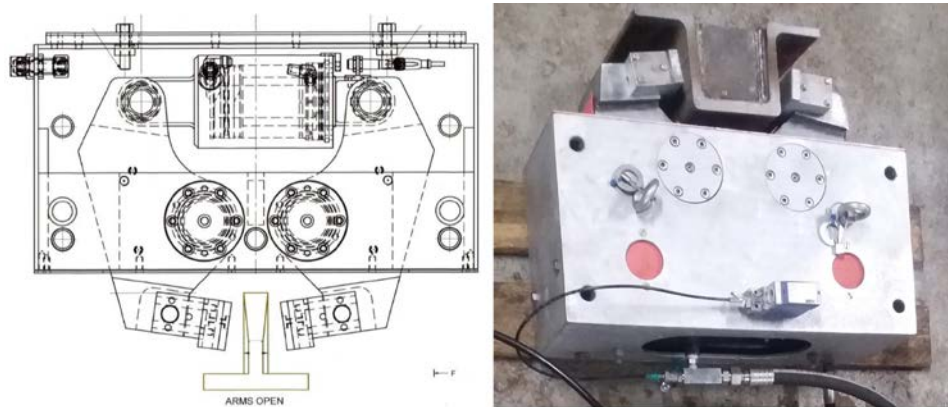


Figure 129: Levelok skip hydraulic clamps for Levelok testing work [4] [52].

- Required system hydraulic piping

x1 (C)

The hydraulic piping, illustrated in Figure 130 [49], connects the Levelok skip power pack to the double regulated Levelok skip clamps.



Figure 130: Levelok testing rig hydraulic piping setup [49].

- Manual PLC control unit x1 (D)

To control the controlling valves and the operation of the Levelok skip power pack, a manually operated testing unit was needed. Normally this type of hydraulic power packs is controlled with a loading station loading control PLC unit. The author designed and built the manual control unit according to the same control philosophy of the loading station PLC. Each valve on the Levelok skip power pack can be controlled separately from this control unit and feedbacks for safe clamping pressure and safe unclamping pressure is also displayed. This unit and the wiring thereof is illustrated in Figure 131 [49]:

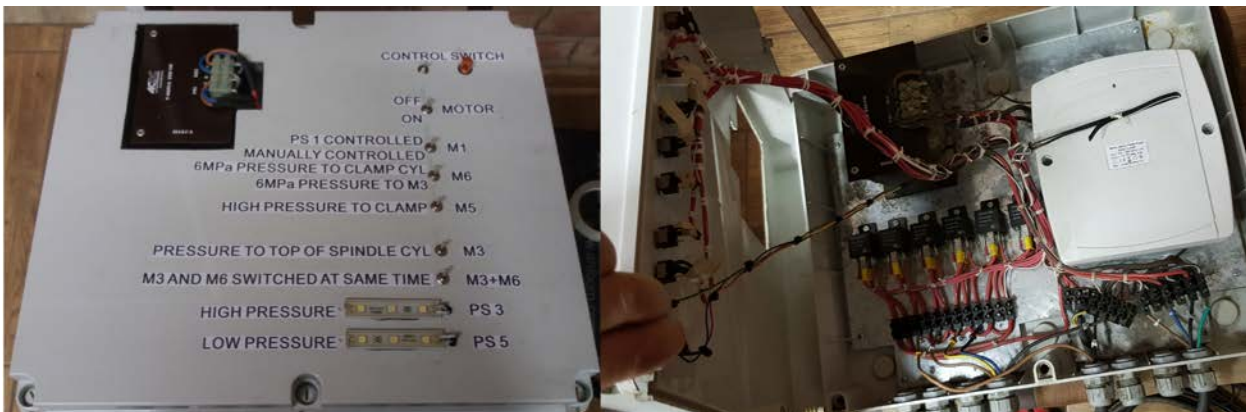


Figure 131: Levelok skip power pack manual PLC control [49].

- Pit with supporting steelwork frames x1 (E)

To complete the tests a steel framework was needed to be strong enough to assist a 13.2-ton weight. Figure 132 [50] illustrates the designed framework where the Levelok clamps are to be installed. This steel framework was placed in one of the WJ Engineering's conveyances inspecting pits, to obtain a higher overhead crane headroom for easier control of the 13.2-ton weight when moved, for testing.

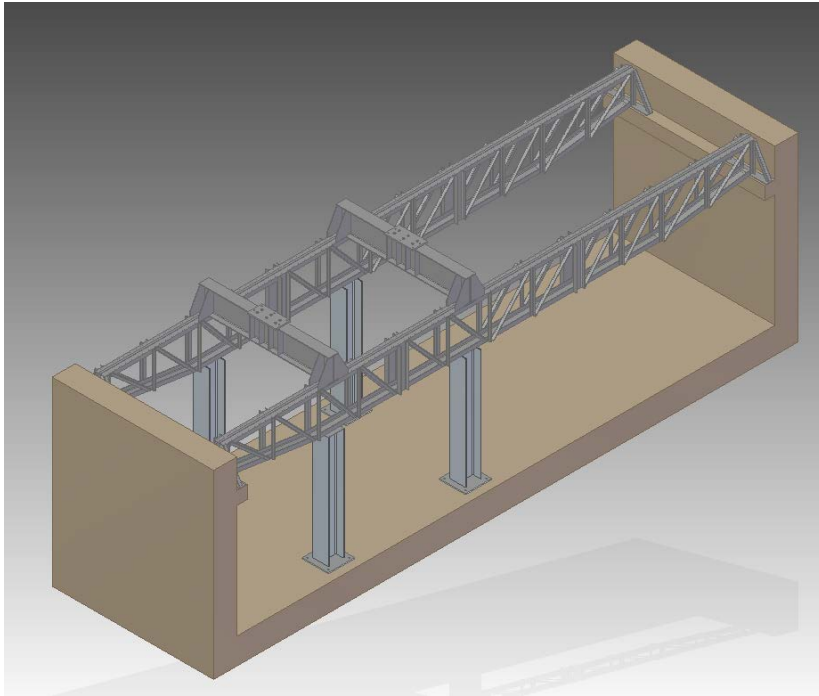


Figure 132: Pit with supporting steelwork frames [50].

- 13.2 Ton kibble

x1 (F)

The testing setup requires a testing weight to clamp and release for obtaining results. The 13.2 Ton kibble, illustrated in Figure 133 [49], was designed and constructed to have the same weight as the payload of a fully-loaded skip conveyance with a similar guide gauge as well. The testing framework holding the clamps obtain the same guide gauge.



Figure 133: 13.2 Ton kibble [49].

- eDAQ datalogger with required pressure sensor & displacement lasers x1 (G)

To datalog all results, the author utilized similar testing units as shown in Figure 134 [53]. The eDAQ is a microprocessor-based data acquisition system designed for portable data collection in a variety of test environments. The hydraulic pressure sensor is connected to one of the “Minitest” testing points on the main control valve manifold of the Levelok skip power pack to record pressure data. The displacement lasers are used to measure the displacement of the weight after it is released.



Figure 134: Edaq datalogger with pressure sensor and displacement lasers [53].

- Kinetic snatch rope x2` (H)

To simulate the rope stretch of the winding rope, two kinetic snatch ropes were used. This is the same rope used as with 4x4 offroading. This rope was chosen for its elasticity properties.

- Hoisting pulleys x2 (I)

To move the weight around and ensure the kinetic ropes move freely as it stretches, two hoisting pulleys were utilized. Due to the two pulleys, the configuration of the two kinetic ropes could be adjusted that the load of the weight was divided into six, as illustrated in Figure 135 [49]. This enabled the kinetic rope to carry the load longer for multiple tests but limited the rope stretch length.



Figure 135: Hoisting pulleys with kinetic rope configuration illustration [49].

- Hoisting equipment x1 (J)

Other hoisting equipment was needed to fix the 13.2 Ton kibble to the hoisting pulleys and the complete setup to the overhead crane.

- 25-Ton overhead crane x1 (K)

The 25-Ton overhead crane was used to move the 13.2 Ton weight around during testing.

The experimental setup for the experiments conducted to calculate the static & kinetic coefficients of friction for different Levelok hydraulic clamp shoe inserts is illustrated in Figure 136 [49]:

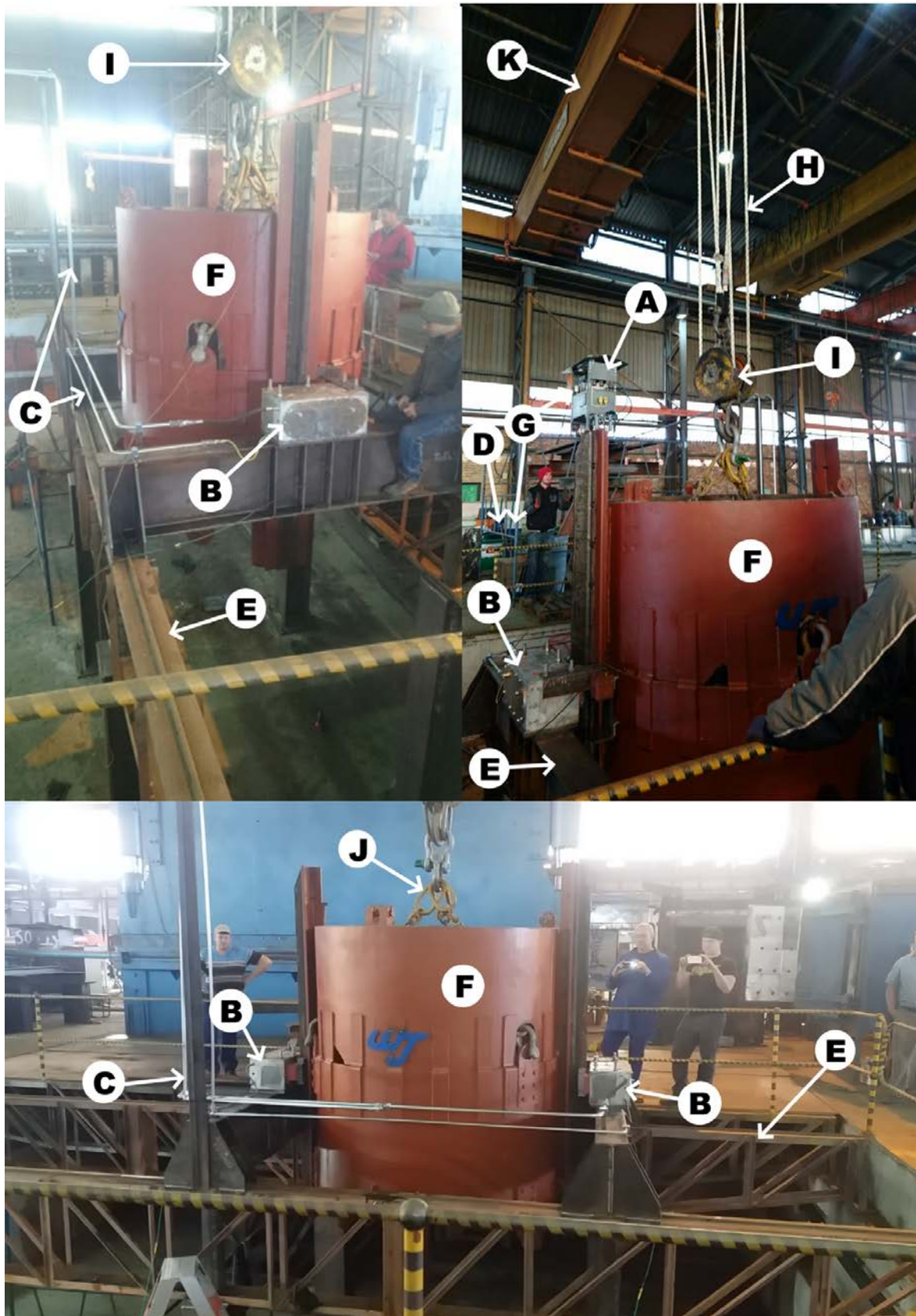


Figure 136: The static & kinetic coefficients of friction for different Levelok hydraulic clamp shoe inserts experimental setup [49].

The Levelok hydraulic skip power pack (A) is connected to the double regulated Levelok hydraulic skip clamps (B), with the required hydraulic piping (C) installed for full operation. The Levelok hydraulic skip clamps (B) and the high & low-pressure hydraulic piping (C) are installed and fixed to the supporting steelwork frame (E) inside the conveyance inspecting pit (E).

The manual PLC control unit (D) is the controlling unit of all the valves of the Levelok hydraulic skip power pack (A). The clamping and unclamping of the Levelok hydraulic skip clamps (B) are controlled with this unit. The manual PLC control unit (D) and the eDaq datalogger (G) are situated on a working table close to the Levelok hydraulic skip power pack (A). The hydraulic high-pressure pressure sensor (G) is connected to the Levelok hydraulic skip power pack (A) main control valve manifold to record the rise and drop of hydraulic fluid pressure in the high-pressure hydraulic line. These recordings are logged in the eDaq system's memory, together with the laser sensor (G) displacement data, and are time stamped. The recording frequency is set at 2000 Hz.

The two laser sensors (G) are fixed to the two Levelok hydraulic skip clamps (B), as illustrated in Figure 137. The sensors are held stationary while it is measuring the displacement of steel plates that are fixed to the 13.2 Ton kibble (F).

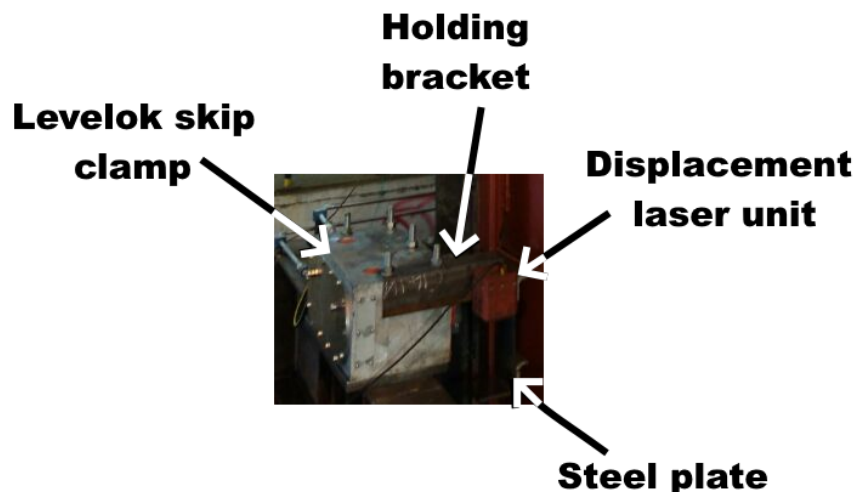


Figure 137: Displacement laser setup [49].

The 13.2 Ton kibble (F) is connected to the 25-Ton overhead crane (K) with the necessary hoisting equipment (J), hoisting pullies (I), and kinetic snatch ropes (H). The kinetic snatch ropes (H) are used to simulate the rope stretch so the displacement of the 13.2 Ton weight is natural, and absorbs unwanted shock loads to protect the 25-Ton overhead crane (K) and other equipment.

4 Test models

The friction shoe inserts test models to be tested differ in type and are made of different friction materials. There are two main types of friction shoe inserts, these include:

- The common flat face friction shoe insert, illustrated in Figure 138 [54]:

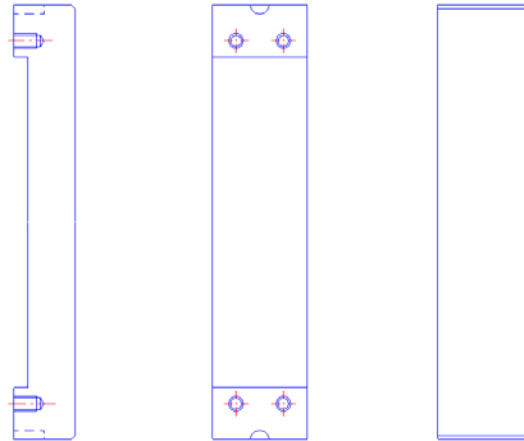


Figure 138: The common flat face friction shoe insert [54].

- The industrial lining friction shoe insert, illustrated in Figure 139 [55]:

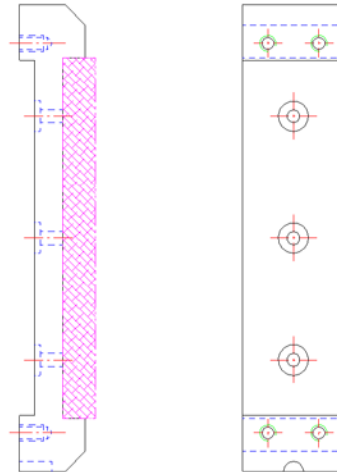


Figure 139: The industrial lining friction shoe insert [55].

The different friction materials used are:

- Hardox 900
- Mild steel (Normal 355 MPa yield)
- ZA Gold
- D9010 industrial grade

Table 11 defines the 5 different test specimens to be tested:

Table 11: Friction shoe inserts test models classification.

Test model nr.	Friction shoe insert type		Material			
	Flat-faced	Indus. Lining	Hardox	Mild steel	ZA Gold	D9010
1	X		X			
2		X	X			
3		X		X		
4		X			X	
5		X				X

The two Levelok hydraulic clamps are each fitted with two friction shoe inserts. The friction shoe inserts are bolted onto separate clamp arm shoes with four bolts. This assembly is illustrated in the assembly drawing in Figure 140 [56]:

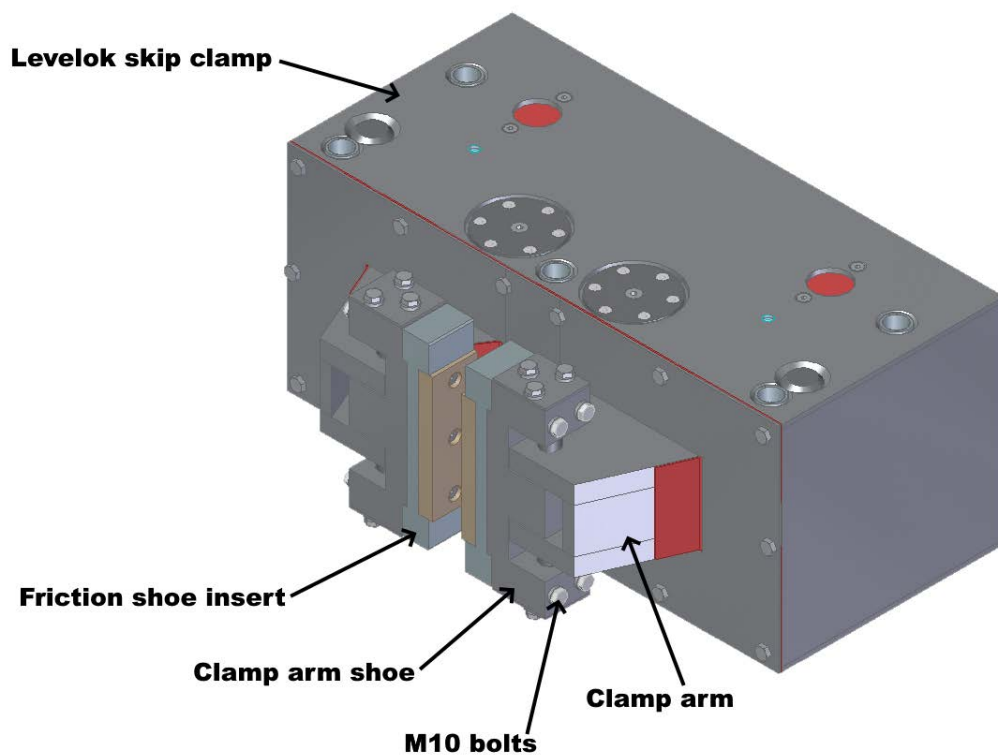


Figure 140: Levelok skip clamp shoe inserts assembly model [56].

5 Method & procedure

For the testing procedure the following steps were followed:

1. The friction test model set was assembled to the Levelok skip clamps and fastened bolts were checked.
2. Hoisting equipment, pulleys & kinetic ropes were attached to the 13.2 Ton kibble and 25 Ton overhead crane. All connections were checked.
3. 13.2 Ton kibble was hoisted and placed in position between the clamps ready to be clamped. All personnel was ordered to stay clear from the hoisted weight.
4. Using a laptop with the TCE program, the eDaq measurements can be zeroed and data recording can be started. (All laser and pressure equipment were also checked)
5. The manual PLC control unit was used to initiate the clamping process. The following valve actuating sequence was used to clamp the system:
 - Turn control switch on (Main power indicator light will turn on).
 - Switch motor of power pack on (Will here motor start turning).
 - Switch the M1 button (M1 valve will open and pressurize the hydraulic accumulators on the power pack. On the indication panel, the accumulator gauge will indicate when accumulator pressure is reached and pressure switch 1 will shut off the M1 valve automatically.)
 - Switch M6 switch, M3 switch.
 - Switch M3+M6 and then M5 one sec later.
 - The Levelok skip clamps will clamp the hoisted weight. Pressure switch 5 will switch the low-pressure indication light off and after about 10 sec the pressure switch 3 will switch the high-pressure indication light on, indicating safe clamping pressure.
6. When the 13.2 Ton weight is clamped in position and then the 25 Ton overhead crane can be used to relieve the tension in the kinetic ropes. The hoisting pulley can be signaled to move down about 800 mm.
7. The manual PLC control unit was then used to initiate the unclamping process to release the 13.2 Ton weight to allow it to slide downwards. The following valve actuating sequence was used to unclamp the system:
 - Switch M5 switch off.
 - Switch M3+M6 off.
 - After the weight has slid to its new position switch all the other M switches off.
8. With the unclamping of the system, the 13.2 Ton weight slides until it stops. The gradual release of the clamps causes the tension to be applied to the kinetic ropes slowly.
9. Stop recording of data, and download data from eDaq.
10. This procedure was repeated 3 times for each friction test model set.

6 Observations & results

The Five friction test model sets with their corresponding observations, photos, data graphs, and calculated static and kinetic friction coefficients are listed. The recorded data were analysed using the nCode software from HBM [57]. With the software, the author was able to calculate the average value between the three tests conducted on each test model set.

Friction test model set 1: Flat-faced friction shoe inserts made of Hardox 900 steel.



Figure 141: Friction test model set 1, Flat-faced friction shoe inserts made of Hardox 900 steel [58].

Figure 141 [58] illustrates photos of the friction test model set 1. The observation that can be made from these images is that there is little to no damage to the friction inserts after the tests were conducted. This can be due to the hardness and high yield value of the material.

Figure 142 [57] [58] illustrates the 3 graphs of the recorded data during the tests of this test set. The red graph illustrates the pressure rise and pressure drop of the hydraulic pressure in the high-pressure hydraulic line from the power pack to the hydraulic double regulated clamps. The blue and green graphs represent the displacement values of the displacement of the 13-Ton kibble, measured on both sides of the kibble at the positions of the clamps.

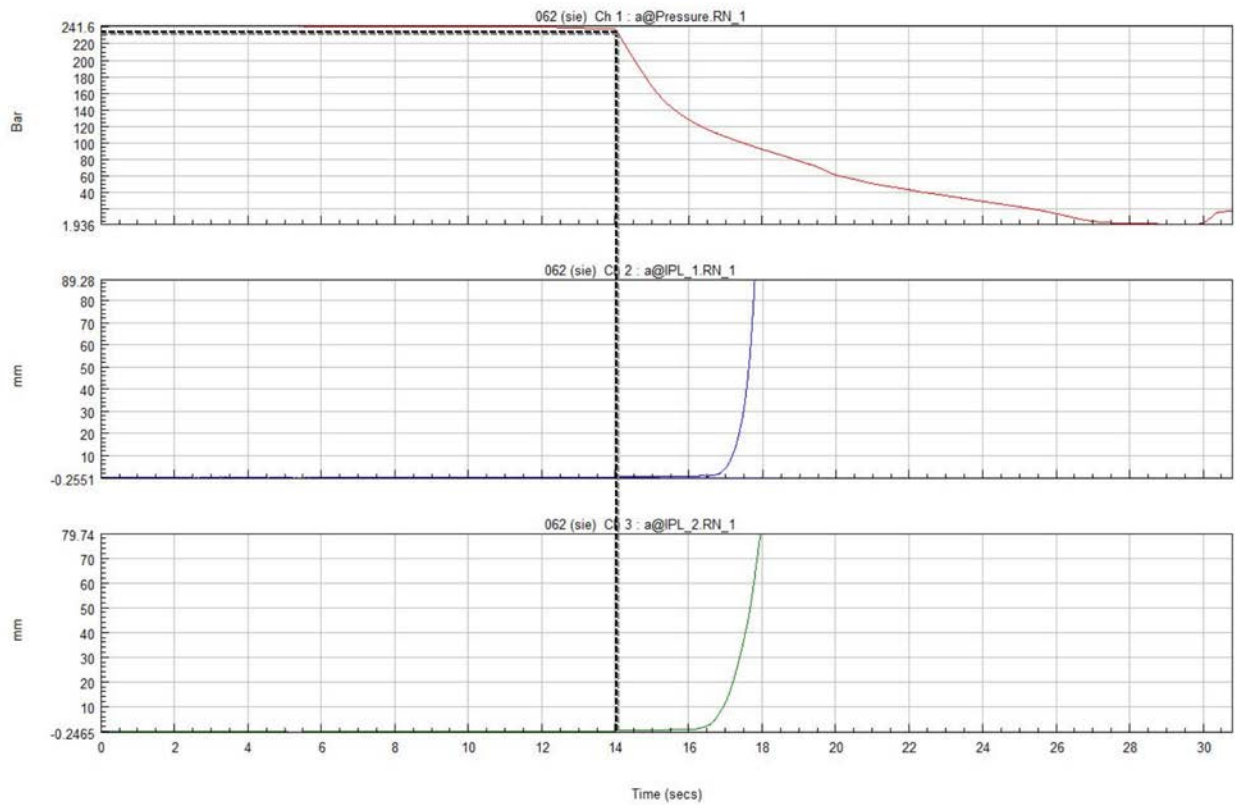


Figure 142: Friction test model set 1, Flat-faced friction shoe inserts made of Hardox 900 steel results [57] [58].

Figure 142 [57] [58] illustrates the two required pressure values clearly. With these pressure values and the equation of slip pressure, the static and kinetic coefficient values can be calculated.

Test set 1	
μ_s	0.25
μ_k	0.23

Friction test model set 2: Industrial lining friction shoe insert with Hardox 900 friction insert.



Figure 143: Friction test model set 2, Industrial lining friction shoe inserts with Hardox 900 friction insert [58].

Figure 143 [58] illustrates photos of the friction test model set 2. The observation that can be made from these images is that there is more damage to the friction inserts than that of the test model set 2. The test set 1 and test set 2 are made of the same Hardox material. The different percentage of damage between the two test sets can be due to the differences in the working area. The smaller working area of test set 2 undergoes more wear.

Figure 144 [57] [58] illustrates the 3 graphs of the recorded data during the tests of this test set. The red graph illustrates the pressure rise and pressure drop of the hydraulic pressure in the high-pressure hydraulic line from the power pack to the hydraulic double regulated clamps. The blue and green graphs represent the displacement values of the displacement of the 13-Ton kibble, measured on both sides of the kibble at the positions of the clamps.

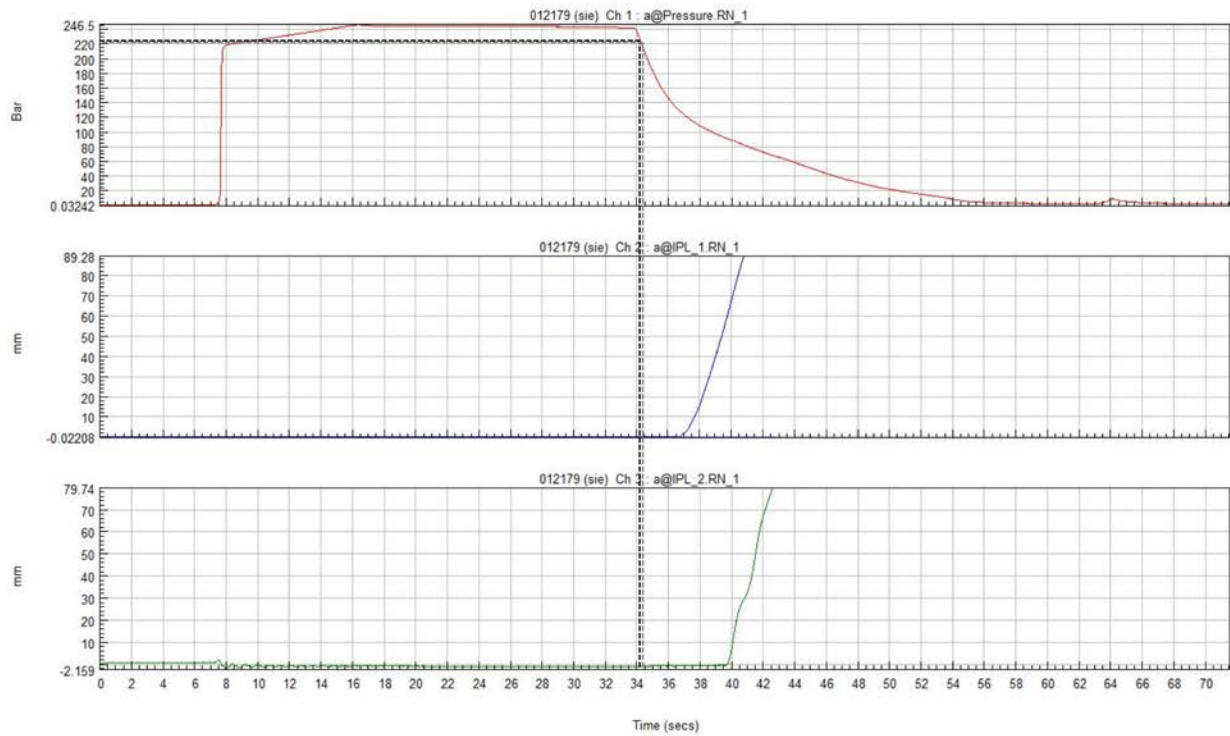


Figure 144: Friction test model set 2, Industrial lining friction shoe inserts with Hardox 900 friction inserts results [57] [58].

Figure 144 [57] [58] illustrates the two required pressure values clearly. With these pressure values and the equation of slip pressure, the static and kinetic coefficient values can be calculated.

Test set 2	
μ_s	0.25
μ_k	0.23

Friction test model set 3: Industrial lining friction shoe insert with mild steel 355J friction insert.



Figure 145: Friction test model set 3, Industrial lining friction shoe inserts with mild steel 355J friction insert [58].

Figure 145 [58] illustrates photos of the friction test model set 3. The observation that can be made from these images is that the extent of damage to the friction inserts is quite high. This can be due to the low yield value and the softer mechanical properties of the material.

Figure 146 [57] [58] illustrates the 3 graphs of the recorded data during the tests of this test set. The red graph illustrates the pressure rise and pressure drop of the hydraulic pressure in the high-pressure hydraulic line. The blue and green graphs represent the displacement values of the displacement of the 13-Ton kibble.

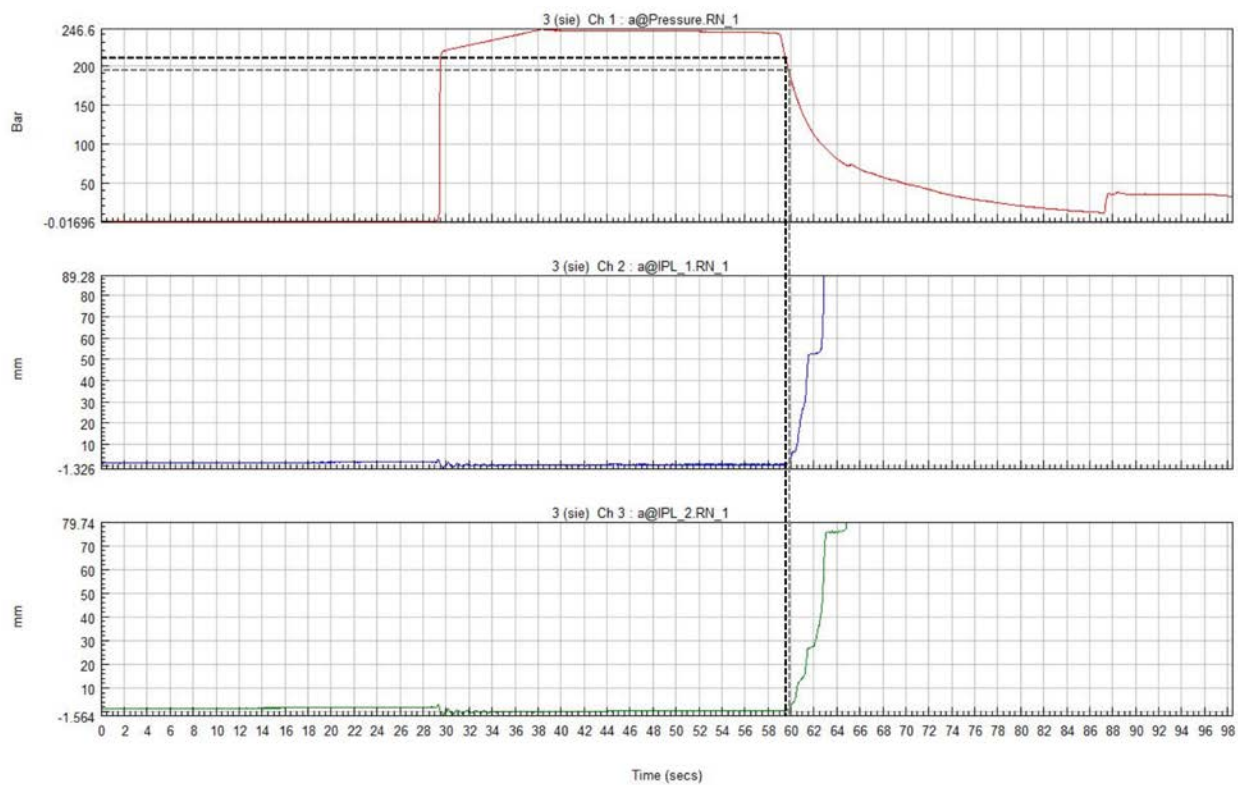


Figure 146: Friction test model set 3, Industrial lining friction shoe inserts with mild steel 355J friction insert results [57] [58].

Figure 146 [57] [58] illustrates the two required pressure values clearly. With these pressure values and the equation of slip pressure, the static and kinetic coefficient values can be calculated.

Test set 3	
μ_s	0.27
μ_k	0.25

Friction test model set 4: Industrial lining friction shoe insert with ZA Gold friction insert.



Figure 147: Friction test model set 4, Industrial lining friction shoe inserts with ZA Gold friction insert [58].

Figure 147 [58] illustrates photos of the friction test model set 4. The observation that can be made from these images is that the material is much softer than the first 3 test sets. There is more material worked away from the friction lining after the 3 tests than that of the metal friction lining. The assumption that can be made is that this type of friction shoe insert will have a shorter life span than that of the first three test sets.

Figure 148 [57] [58] illustrates the 3 graphs of the recorded data during the tests of this test set. The red graph illustrates the pressure rise and pressure drop of the hydraulic pressure in the high-pressure hydraulic line. The blue and green graphs represent the displacement values of the displacement of the 13-Ton kibble.

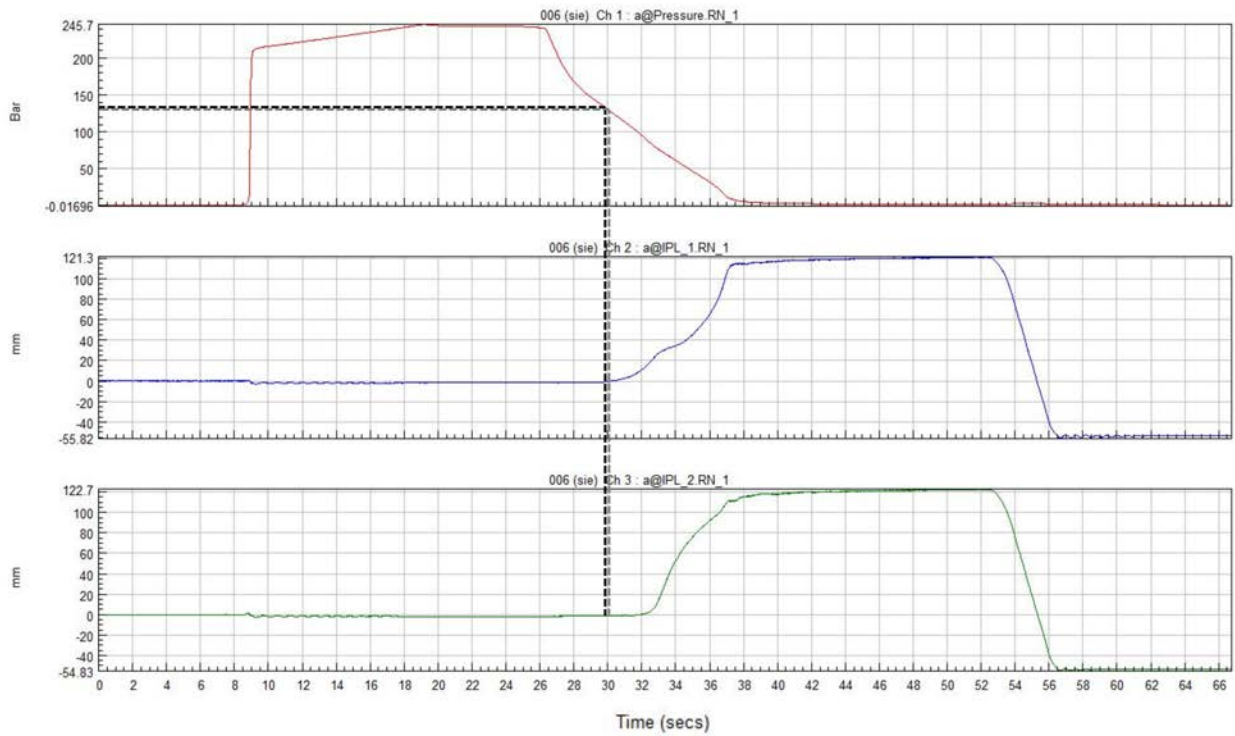


Figure 148: Friction test model set 4, Industrial lining friction shoe inserts with ZA Gold friction insert results [57] [58].

Figure 148 [57] [58] illustrates the two required pressure values clearly. With these pressure values and the equation of slip pressure, the static and kinetic coefficient values can be calculated.

Test set 4	
μ_s	0.45
μ_k	0.42

Friction test model set 5: Industrial lining friction shoe insert with D9010 friction insert.



Figure 149: Friction test model set 5, Industrial lining friction shoe inserts with D9010 friction inserts [58].

Figure 149 [58] illustrates photos of the friction test model set 5. The observations made from these photographs are similar to that of the test set 4. The only difference is that the extent of damage to this test set is more than that of the test set 4. This can be due to the material used for manufacturing the friction lining. This material is similar, but the manufacturing costs of the D9010 material are less than that of the ZA Gold.

Figure 150 [57] [58] illustrates the 3 graphs of the recorded data during the tests of this test set. The red graph illustrates the pressure rise and pressure drop of the hydraulic pressure in the high-pressure hydraulic line. The blue and green graphs represent the displacement values of the displacement of the 13-Ton kibble.

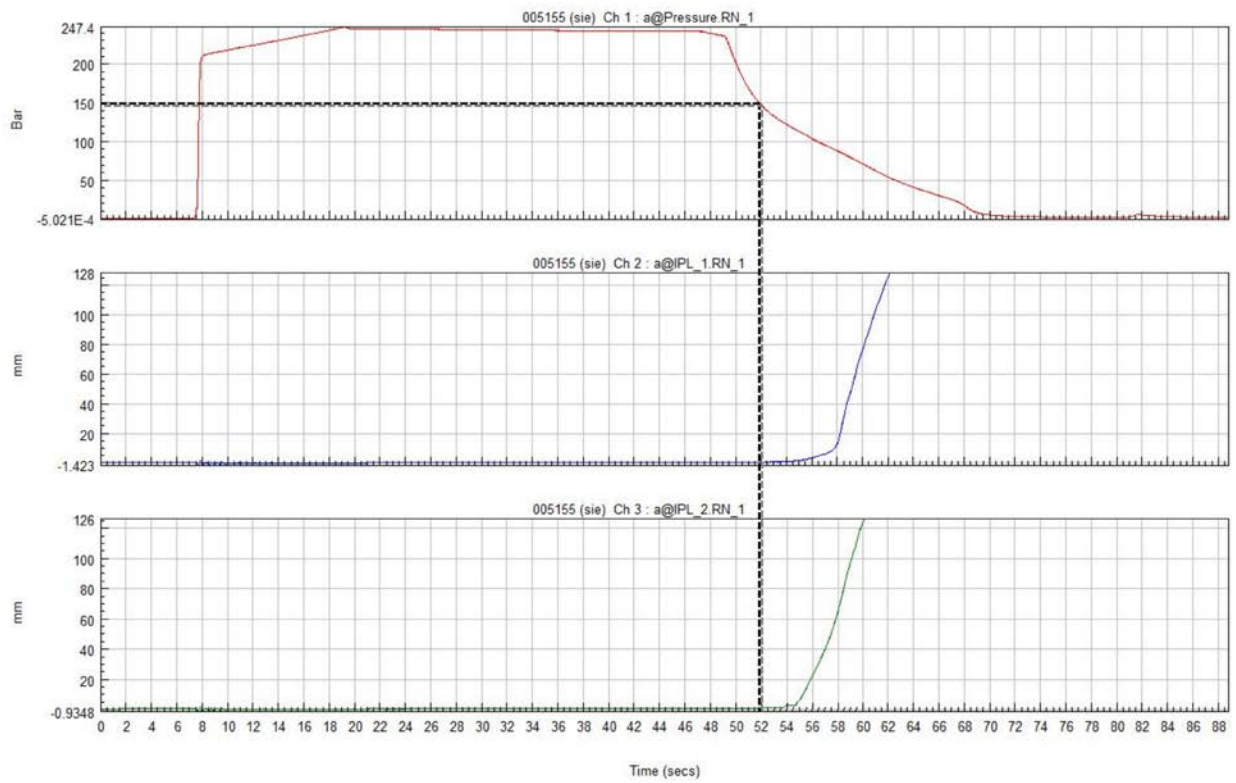


Figure 150: Friction test model set 5, Industrial lining friction shoe inserts with D9010 friction inserts results [57] [58].

Figure 150 [57] [58] illustrates the two required pressure values clearly. With these pressure values and the equation of slip pressure, the static and kinetic coefficient values can be calculated.

Test set 5	
μ_s	0.38
μ_k	0.35

7 Conclusion & summary

The static and kinetic coefficients of friction for the Levelok clamp shoe inserts were calculated from the conducted experiments outlined in this report. These values can be used for further calculations that require more reliable defined values. Thus, all objectives of the experiments were achieved and documented in this experimental results report.

The values of static & kinetic coefficients of friction for the five different test sets are summarized in Table 12 [58]:

Table 12: Report results of the friction insert tests [58].

Test set nr.	Coefficients	
	μ_s	μ_k
1	0.25	0.23
2	0.25	0.23
3	0.27	0.25
4	0.45	0.42
5	0.38	0.35

It was also found that the contact area of the friction insert does not influence the friction coefficients, but the contact area is directly proportional to the life span of the friction shoe insert. From Table 12 [58] it is also clear that the hardness of the friction lining material is inversely proportional to the coefficients of friction.

The experiments conducted in this report can be improved to get more accurate results. Some of these improvements include the use of a load cell to measure the weight of the clamped mass during testing to obtain a better idea of the kinetic friction force. There can also be looked at the way the kinetic snatch rope is implemented in the experimental setup. However, the author is satisfied that the values calculated are accurate enough for the objectives that need to be satisfied.

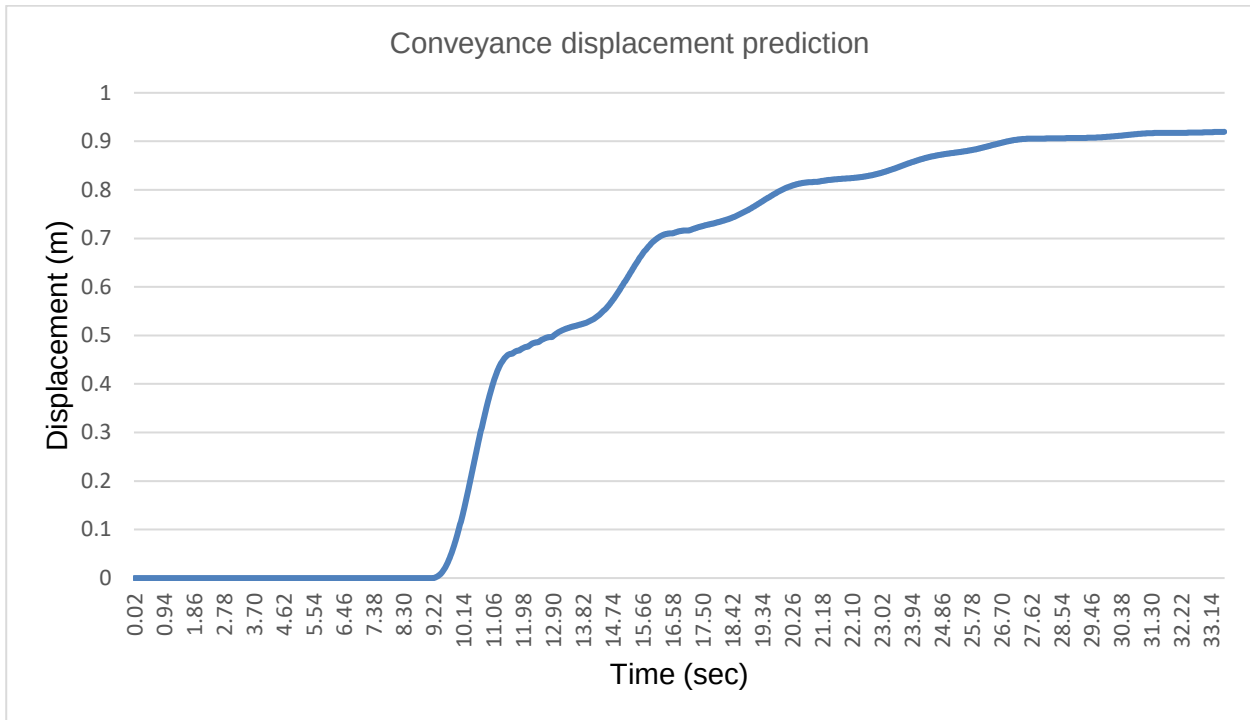
ANNEXURE H

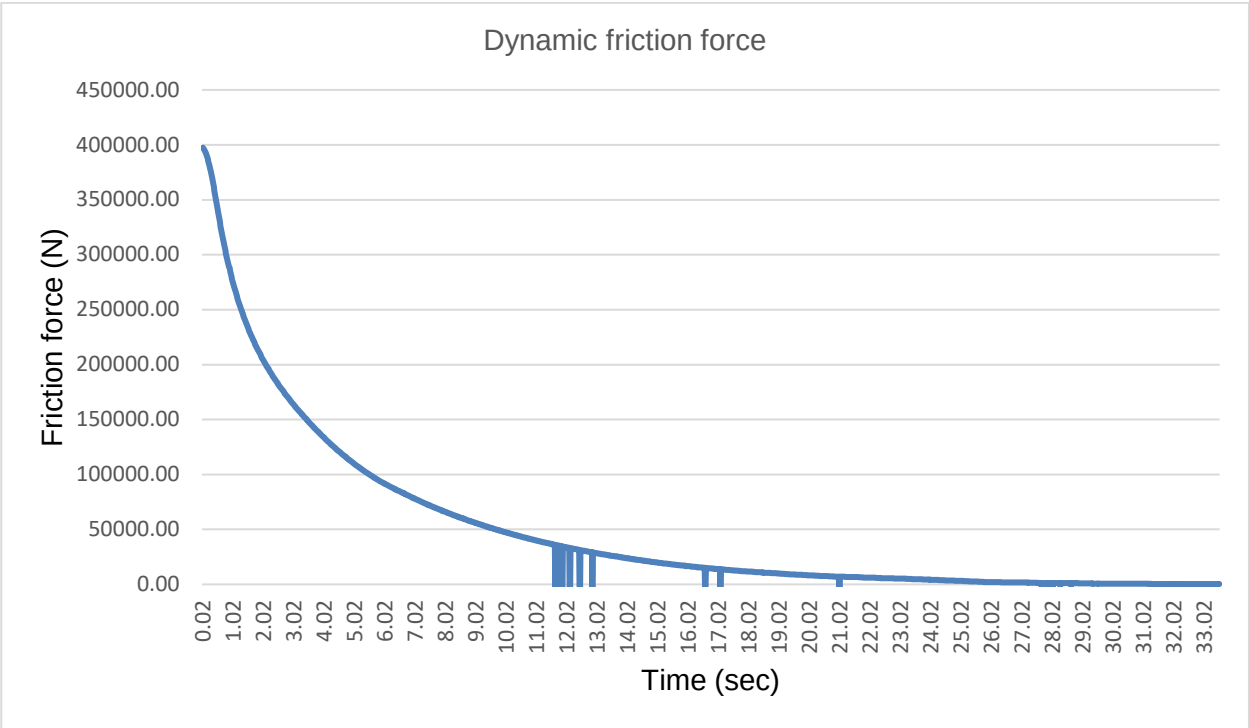
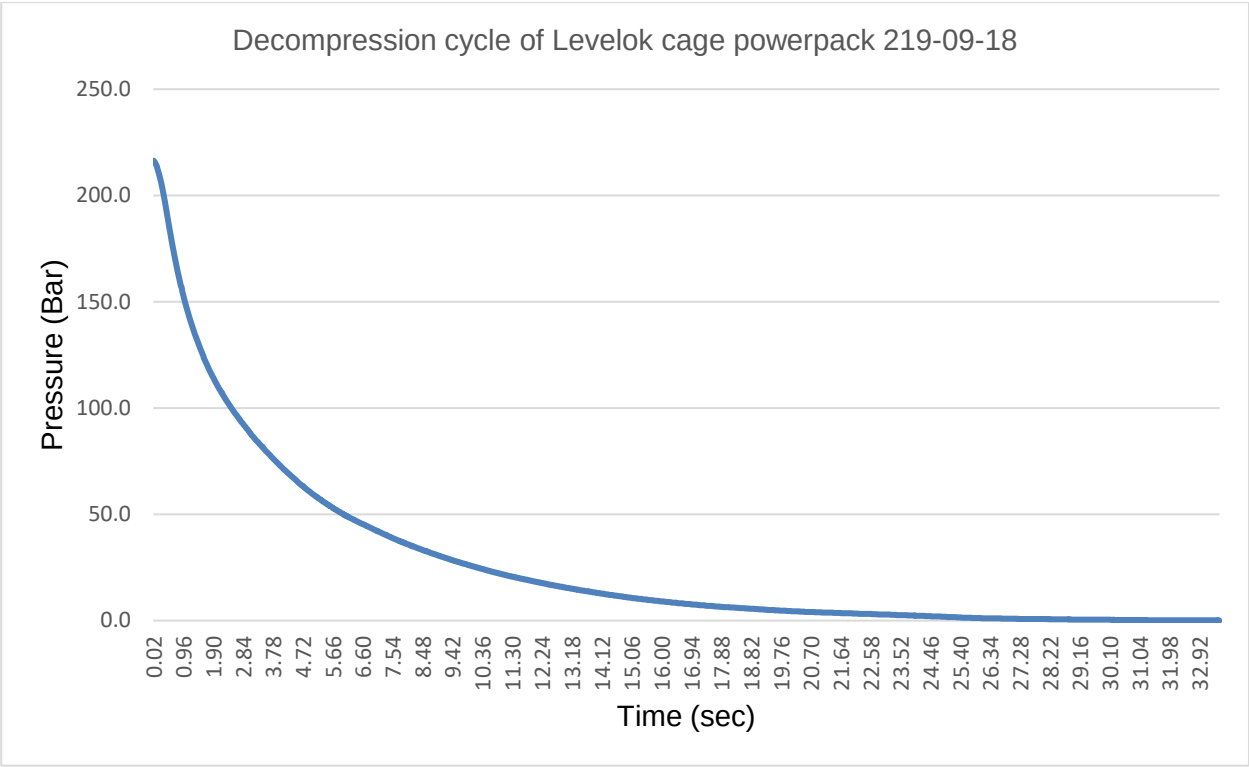
CONDUCTED DECOMPRESSION TEST WITH LEVELOK CAGE

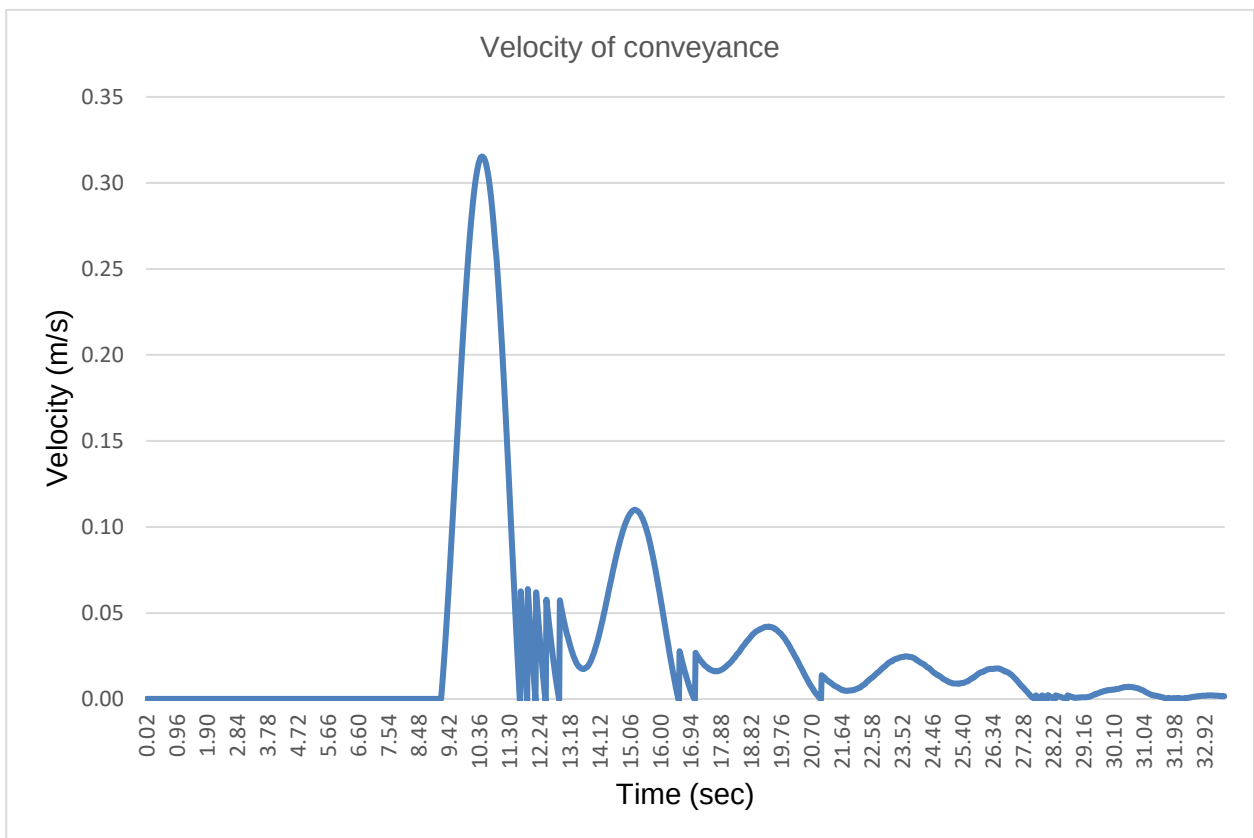
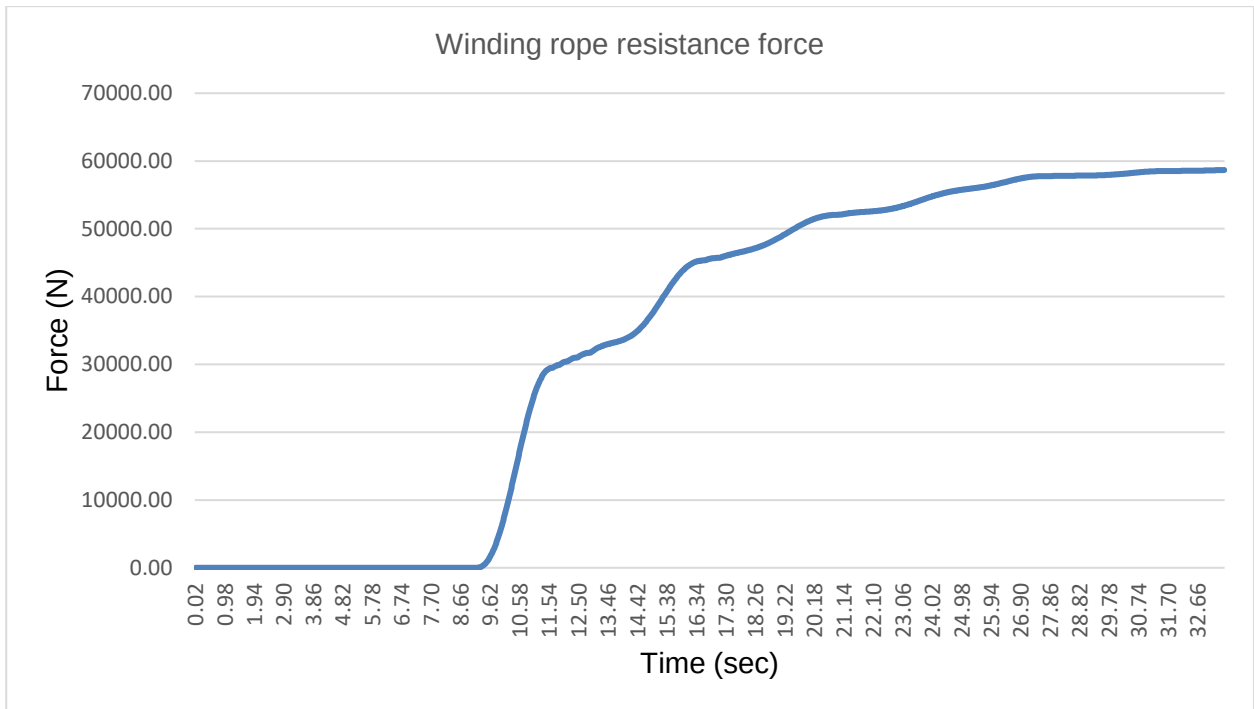
POWER PACK SERIAL NUMBER 219-09-18 USING THE EXCEL

MATHEMATICAL PREDICTION MODEL [62]

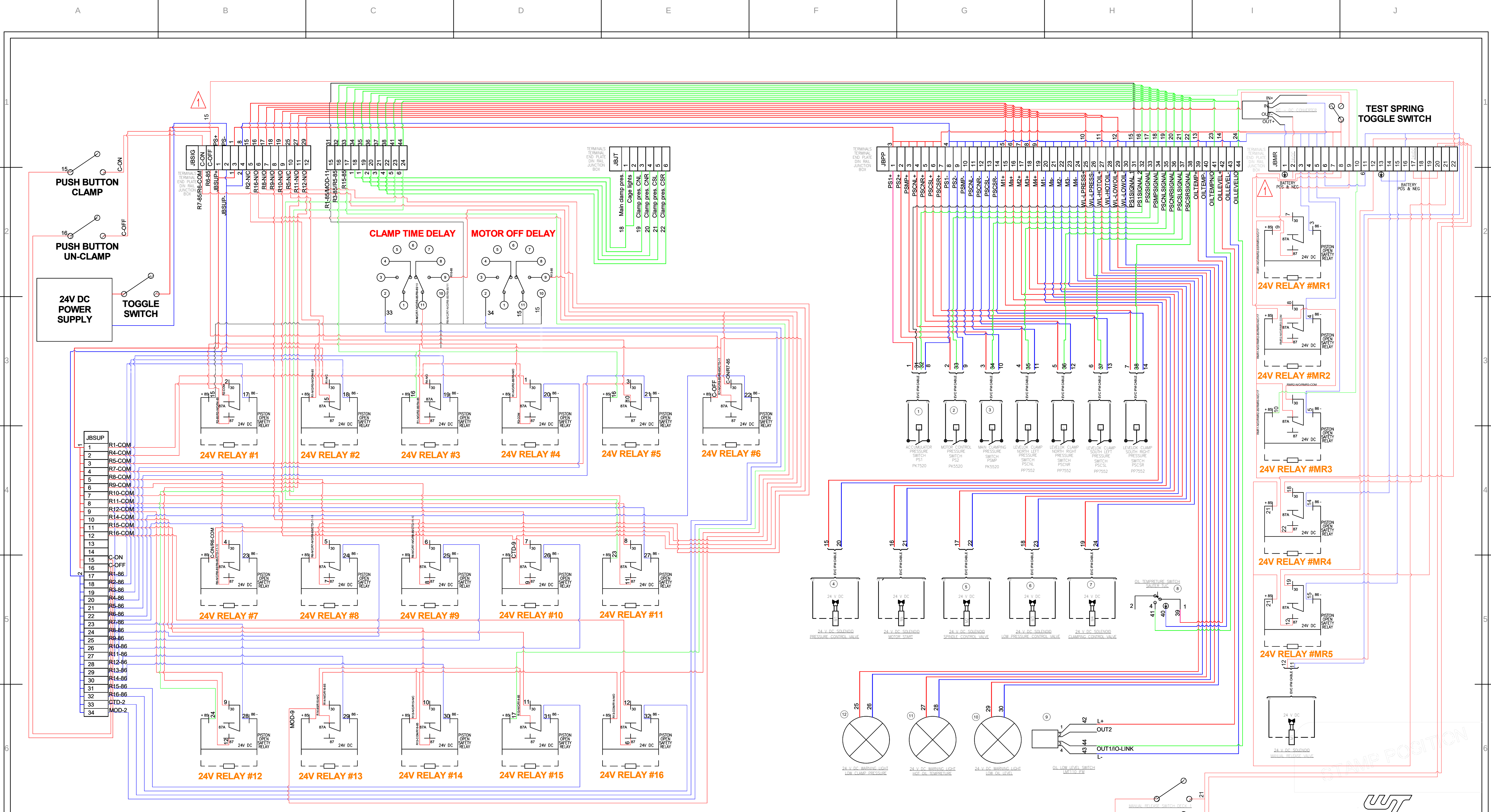
Constant variables		
Static friction coefficient	0.27	
Dynamic friction coefficient	0.25	
Distance to piston	0.18	m
Distance to shoes	0.154	m
Piston diameter	0.1	m
Nr. of clamps	4	
Rope spring constant	63795.88	N/m
Payload	6000	kg
Cage own mass	13500	kg
Rope length	2780	m
Rope metallic area	8.061E-04	m ²
Elastic constant	1.10E+11	Pa
Rope stretch under payload	0.922	m
Rope spring constant check	63795.88	N/m
Slip pressure	29.64	Bar
Static friction force	29400	N/m







ANNEXURE I
THE MK7 ELEC LEVELOK MAN, MATERIAL CAGE SYSTEM
ELECTRICAL CIRCUIT DIAGRAM [81]



										20 MANUAL RELEASE SWITCH DECK 1 MANUAL RELEASE SWITCH DECK 2 MANUAL RELEASE SWITCH DECK 1 MANUAL RELEASE SWITCH DECK 2 1										CONVEYANCES (PTY) LTD DATE RECEIVED : CONTRACT No. : JOB No. : APPROVED BY: PR. ENG./PR. TECH NAME REGISTRATION No. DATE ENGINEERING SOLUTIONS THROUGH INNOVATION DRAWN AND MANUFACTURED BY WJ CONVEYANCES (PTY) LTD. POTCHEPSROOM TEL (018) 294 3355 e-mail: wjeng@wjsol.co.za									
DRAWING No.		REFERENCE DRAWINGS		DRAWING No.		REFERENCE DRAWINGS		REVISIONS		REV	DATE	REVISED BY	CHECKED BY	REVISIONS		REV	DATE	REVISED BY	CHECKED BY	DRAWN DATE SIGN J.TALJAARD 13/11/19 CHECKED/ APPROVED DATE SIGN J.CLAASSEN COPYRIGHT WARNING THIS DRAWING IS THE PROPERTY OF WJ ENGINEERING POTCHEPSROOM AND BEING PRIVATE AND CONFIDENTIAL IT IS SUPPLIED UPON THE EXPRESS CONDITION THAT IT MUST NOT BE USED FOR ANY PURPOSE OR COPIED OR COMMUNICATED TO ANY OTHER PERSON OR CONCERN WITHOUT OUR WRITTEN CONSENT.									
DRAWING								TIMER WIRE CHANGE		1	25/11/20	J.T								24V DC LEVELOK MK7 ELEC POWER PACK WIRING DIAGRAM DO NOT SCALE - IF IN DOUBT, ASK THIS DRAWING IS AMENDED & TO BE READ IN CONJUNCTION WITH GENERAL ARRANGEMENT REV ALL PRINTS NOT CARRYING THIS AMENDMENT ARE CANCELLED									
																				DWG NO: PH8105 SHT 1 OF 1 REV 1									
A		B		C		D		E		F		G		H		I		J											