Institut de recherche
Robert-Sauvé en santé
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Safety of Mine Hoists Controlled by Electronic Programmable Systems

Appendix

Laurent Giraud
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Louis Germain
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STUDIES AND RESEARCH PROJECTS

RA-1121

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STUDIES AND RESEARCH PROJECTS

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This publication is a translation of the French original; only the original version (RA-1049) is authoritative.

PEER REVIEW
In compliance with IRSST policy, the research results published in this document have been peer-reviewed.

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ABSTRACT

With the rapid changes in new technology and the constant quest for greater return on investment, programmable electronic systems (PES) have progressively been implemented in all industries. The mining industry is no exception to this trend, and over time virtually all Quebec mines have equipped their hoists with systems of this kind. However, the introduction of these new technologies, which is necessary to boost mining productivity in Quebec, must go hand in hand with corresponding adjustments in occupational health and safety.

A survey of mining hoists being used in Quebec in 2016 showed that the overall profile of the industry has changed considerably since the first version of the data sheet, RF-421, was published in 2005: the vast majority of hoists are now controlled and monitored by PESs, and close to a third of hoists have been in operation for less than 10 years. At the same time, many older hoists have had their control systems updated. In light of these observations and of incidents that have occurred in recent years, it seemed a new version of data sheet RF-421 was needed—one that would reflect both the current situation in Quebec (significant differences between the newest and oldest hoists) as well as prevailing industry trends (greater loads and hoisting speeds, increasingly automated systems).

This appendix report describes the process and thinking that led to the drafting of new data sheet RF-1049, which was developed in conjunction with mine hoist experts and machine safety specialists. Although a large part of the content has been taken from data sheet RF-421, this update provided an opportunity to review its structure and organization so that, as far as possible, the information could be presented and arranged in the same way as in international standards. A further underlying objective of this new data sheet was to reconcile the current state of hoists now being used with the continuing trend toward greater automation and the integration of modern practices respecting the robustness (or reliability) of the control systems of future hoists.

This new data sheet, RF-1049, sets out the current state of the art regarding PES reliability and PES use to control hoists. It is intended for PES-controlled hoist users, owners and designers. It reviews information on the system safety objectives to be targeted for PES-controlled hoists. It in no way exempts designers or users from the obligation to comply with all legal and regulatory requirements related to their operations.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC:	alternating current
AOHS:	Act respecting occupational health and safety
CNESST:	Commission des normes, de l’équité, de la santé et de la sécurité du travail [Quebec labour standards and OHS board]
CSA:	Canadian Standards Association
DC:	direct current
E/E/PE:	electric/electronic/programmable electronic
IEC:	International Electrotechnical Commission
IRSST:	Institut de recherche Robert-Sauvé en santé et en sécurité du travail
ISO:	International Organization for Standardization
MSHA:	Mine Safety and Health Administration
NIOSH:	National Institute for Occupational Safety and Health
PES:	programmable electronic system
PFHD:	probability of dangerous failure per hour
PL:	performance level
ROHS:	Regulation respecting occupational health and safety
ROHSM:	Regulation respecting occupational health and safety in mines
SABS:	South African Bureau of Standards
SIL:	safety integrity level
SIS:	safety instrumented system
SRECS:	safety-related electrical control system (Note: The “traditional” safety circuit is part of the SRECS)
SRP/CS:	safety-related part of a control system

APPENDIX A: METHODOLOGY

The goal of this research project was to update data sheet RF-421 and thereby ensure greater safety for workers who have to work on or use the cages of mine hoists controlled by programmable electronic systems (PESs). For the purpose of the update, the researchers reviewed the changes in, and feedback on, control system safety and reliability standards, as well as changes in mining practices, including the automation of hoists and the obsolescence of some of the equipment still being used (Lilly, PES, electromechanical relays, etc.). The research also helped to eliminate grey areas that allowed room for the interpretation of certain recommendations, and lastly provided an opportunity to include in this appendix report the results of a formal risk analysis for adjusting risk control measures.

The methodology followed to achieve this goal is set out below.

A.I Assessment of facilities

The first part of the research project involved gathering information on Quebec mining facilities and the control systems they use for hoists, so that the researchers could estimate, as accurately as possible, the variability of the control systems used (electromechanical, electronic, programmable electronic), as well as the variability of the safety instrumented systems (or safety circuits) prescribed by regulation (ROHSM, 2018).

Most of the information below was collected using the database compiled by technologist Louis Germain as part of his duties at CanmetMINES:

- Age of hoist (mechanical part)
- Date and purpose of most recent major overhaul of control system
- Identification of type of suspended load: cage/skip/cage-skip
- Maximum number of workers authorized in cage
- Identification of type of control: mechanical, analog, digital (control PES)
- Identification of type of operating or monitoring controller:
    - Monitoring Lilly/PES
    - Operating mode of monitoring PES, if any
    - Monitored parameters (position of conveyance, speed, acceleration, etc.) and limit values
- Is there a written risk analysis for the hoist?
- Description of safety circuit or circuits:
    - Single-line diagram
    - Links with control PES
    - Links with monitoring PES

- Implementation of safety circuit decision module: analog, digital, etc.
- Parameters, sensors or information taken into account (e.g., overwind protection)

- Description of type of safety circuit actuators (emergency brakes):
  - Are they monitored?
  - If monitored, how is monitoring implemented?

Three preliminary visits were planned by the research team to allow them to make adjustments to the data collection tool and gather additional information on site. These preliminary visits provided an opportunity to observe an old hoist with a Lilly, a very recent hoist with several PESs and an intermediate-age hoist whose control system had been changed over time.

The descriptions of the organizational structures relating to companies' mine hoists were drawn up only at the time of the mine visits. Major differences were noted from one mine to the next. The general organizational structure for hoist maintenance and monitoring seemed quite amorphous and showed a certain degree of porosity between a number of different departments (general mechanical maintenance, general electrical maintenance, department in charge of measurement systems).

The 2016 hoist assessment for Quebec served as a baseline for adjusting the requirements and recommendations of the data sheet, so that solutions that were realistic, though nevertheless safe, could be proposed. The main statistics on Quebec's fleet of hoists are given in subsection B.

A.II Review of the literature

The review of the literature covers a large number of topics, and all members of the research team contributed to it, assisted by the staff of the documentation centre of the Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST). The review looked in particular at:

- The recommendations and requirements currently in force in the mining industry regarding PESs, in jurisdictions other than Quebec (other Canadian provinces and territories, South Africa, U.S.A., Australia). Some of the references needed were collected as part of an expert assessment of the modernization of mine conveyance safety catches and the three resulting papers (Galy and Giraud, 2016a, 2016b; Giraud and Galy, 2018)
- Machine safety standards and control system standards, as well as standard CSA M421 on the use of electricity in mines
- Recent research work (from the 10 years since the publication of data sheet RF-421) concerning control and braking systems, monitoring, production cycles, etc.
- The risk estimation and evaluation methods used to determine whether the risk control measures implemented are appropriate for the targeted risk level
- Changes in hoisting systems, especially the switch from electromechanical control systems to computerized control systems
- The research findings and recommendations made by the National Institute for Occupational Safety and Health (NIOSH) regarding PESs in the mining industry
- Overall system safety evaluation methods: layers of safety, lines of defence (organizational, structural, etc.), defence-in-depth concept (Garbolino and Guarnieri, 2012; Iddir, 2012a, 2012b, 2014)

The review provided an opportunity to identify the standards that apply to hoist control systems and to see how legislators in other Canadian provinces and in other countries have taken changes in these standards into consideration (Galy and Giraud, 2016b). The developments of the past 10 years in technology and standards have determined the emerging trends in hoist control and monitoring systems and have provided a basis for formulating recommendations that should remain valid for a number of years yet.

The part of the literature review devoted to changes in hoist technology, which also relies on Louis Germain's extensive knowledge of hoist systems, is presented in subsection C.

The part of the review dedicated to standards and regulations governing machine safety can be found in subsection D.

A.III Analysis of generic risk for hoists

As stated in data sheet RF-421, the initial risk analysis was "based on an informal risk analysis, developed from the experience of users, manufacturers and Commission de la Santé et de la Sécurité du Travail (CSST) inspectors."[1] In light of technological changes and recent accidents, a decision was made to base the update of the data sheet on a more formal generic risk analysis, so as to gain a better understanding of the problems associated with the new technologies being used and to be able to estimate, as accurately as possible, the probabilities of failure of the risk control measures employed to guarantee the safety of the hoists currently in operation in Quebec. By generic, we mean that the risk analysis conducted by the research team can be applied to most of the hoists used in Quebec mines, provided certain factors are adjusted.

The reference documents cited in this regard when data sheet RF-421 was drawn up in 2005 are now well known, and some of them have been updated. Note that standard ISO 12100 (2010), which has replaced standard ISO 14121 (2007), proposes a structured risk assessment method that could be used. This method first prescribes conducting a risk analysis that itself includes the stages of determining the limits of the hoist, identifying the hazards and estimating the risk. Following the risk analysis, the risk evaluation step involves making a judgment about the safety of the machine. The combination of the two steps is called the risk assessment.

Risk assessment (ISO 12100):

1. Risk analysis:
    a. Determination of the limits of the machinery
    b. Hazard identification
    c. Risk estimation (determining the level of risk)
2. Risk evaluation (judgment about the safety of the machine)

As was the case for the drafting of data sheet RF-421, the analysis was based on stakeholders' experiences. In addition, the site visits made by the research team as part of their hoist assessment provided data for the generic risk analysis.

[1] The CSST became the CNESST in June 2015 after it was merged with the Commission de l'équité salariale [pay equity board] and the Commission des normes du travail [labour standards board].

The risk analysis performed and the detailed method that was followed are presented in subsection E.

A.IV Summary of data and drafting of new associated data sheet

Once all the data had been gathered and the general risk analysis completed, the new data sheet associated with this appendix report was written up. The new data sheet contains:

- an introduction and an explanation of the area of application
- a list of definitions
- the general principles prescribed and recommended for the general structure of a hoist's control and monitoring systems, with two figures to illustrate the general structure, both current and future, of these systems
- a list of safety functions, with the tests and associated periodic checks
- technical requirements for control and monitoring PESs as well as the safety-related electrical control system (SRECS)
- procedural and organizational requirements
- a list of reference materials

APPENDIX B: STATISTICS ON HOIST FLEET IN OPERATION IN QUEBEC

In 2016, there were 19 mine shafts in operation in Quebec. Only one of the 19 is equipped with a Blair-type hoist, while two are equipped with friction hoists. All the others have drum hoists (single or double drum). This appendix provides an overview of the characteristics of these hoists.

B.I Shafts

Of the 19 mine shafts in operation, six (31.6%) were dug before 1990, 10 (52.6%) between 1990 and 2010 and the last three (15.8%) after 2010 (Figure 1). Most of the shafts are between 1,500 and 3,000 feet deep (53%) (Figure 1). The depth of the other shafts is less than 1,500 feet (11%), 3,000 to 4,500 feet (26%) or over 4,500 feet (11%).

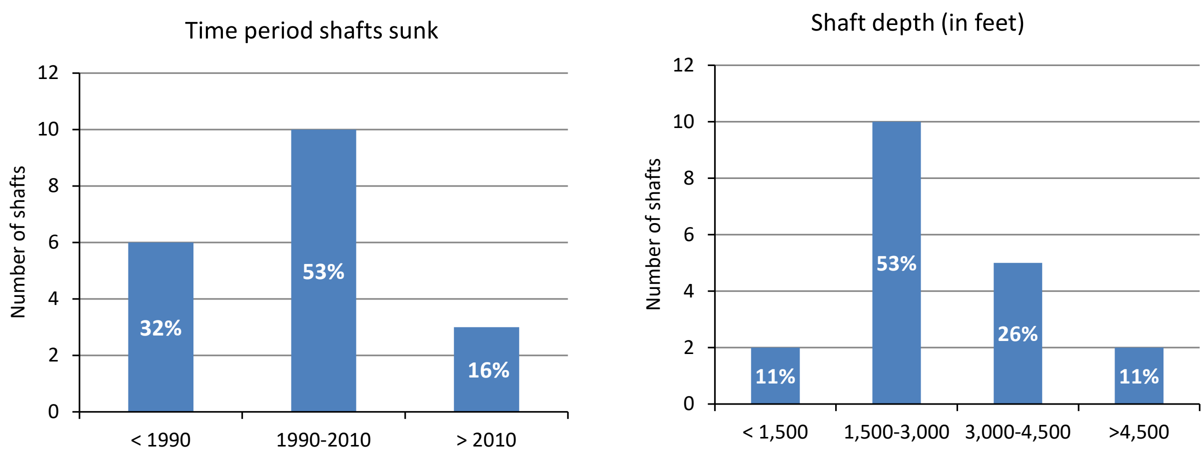

Figure 1. Age and depth of shafts

B.II Hoists

In 2016, when the data were collected, there were 31 hoists in operation in Quebec on which the mechanical part dated from 1929 to 2015 (Figure 2). Note that the number of hoists is greater than the number of shafts because one shaft can be equipped with several hoists (see subsection C.I).

The time intervals for the age of hoists are not continuous, as there are periods when no new hoists were installed: for instance, there are no hoists with a mechanical part dating from 1993–2007 (Figure 2).

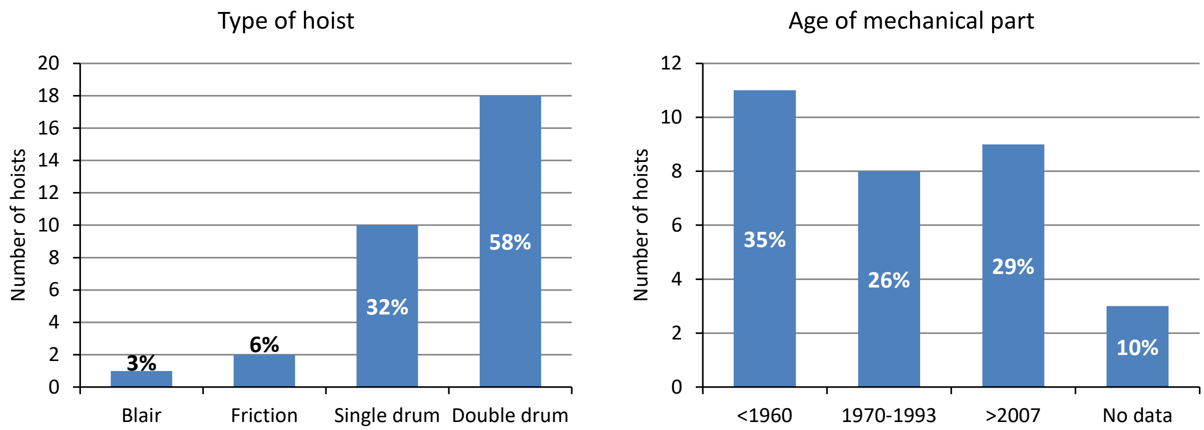

Figure 2. Type and age of hoists

Some hoists have relatively old mechanical parts, but their control systems have been updated. For instance, some hoists from the 1960s or 1970s are equipped with very recent PESs (Figure 3). In Figure 3, the three diamonds at the far right represent hoists that have mechanical parts whose age is not known exactly (but they are second-hand hoists of a certain age).

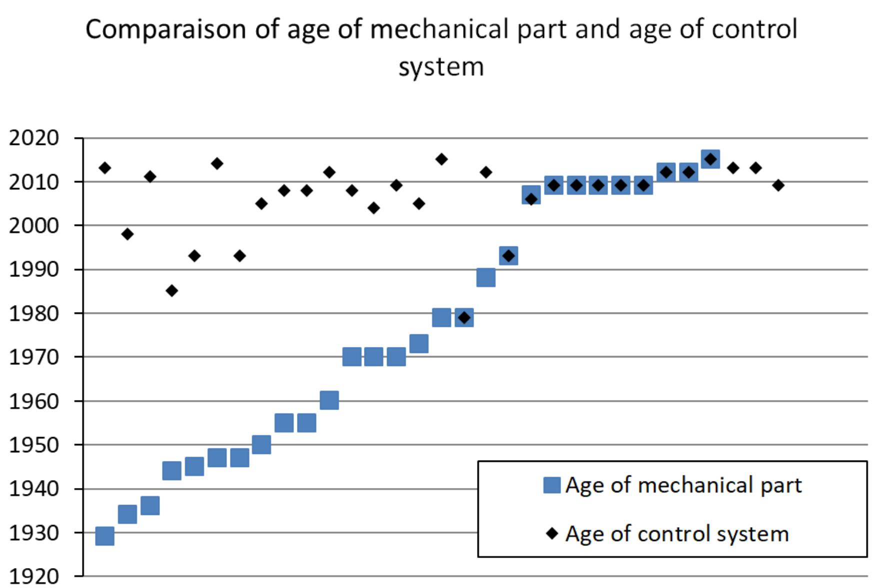

Figure 3. Age of mechanical part and control system

B.III Type of conveyance and hoist speed

The intervals of the number of people that a cage can hold are not continuous because some type of cages are not used in Quebec: e.g., there are no 80-person cages (Figure 4).

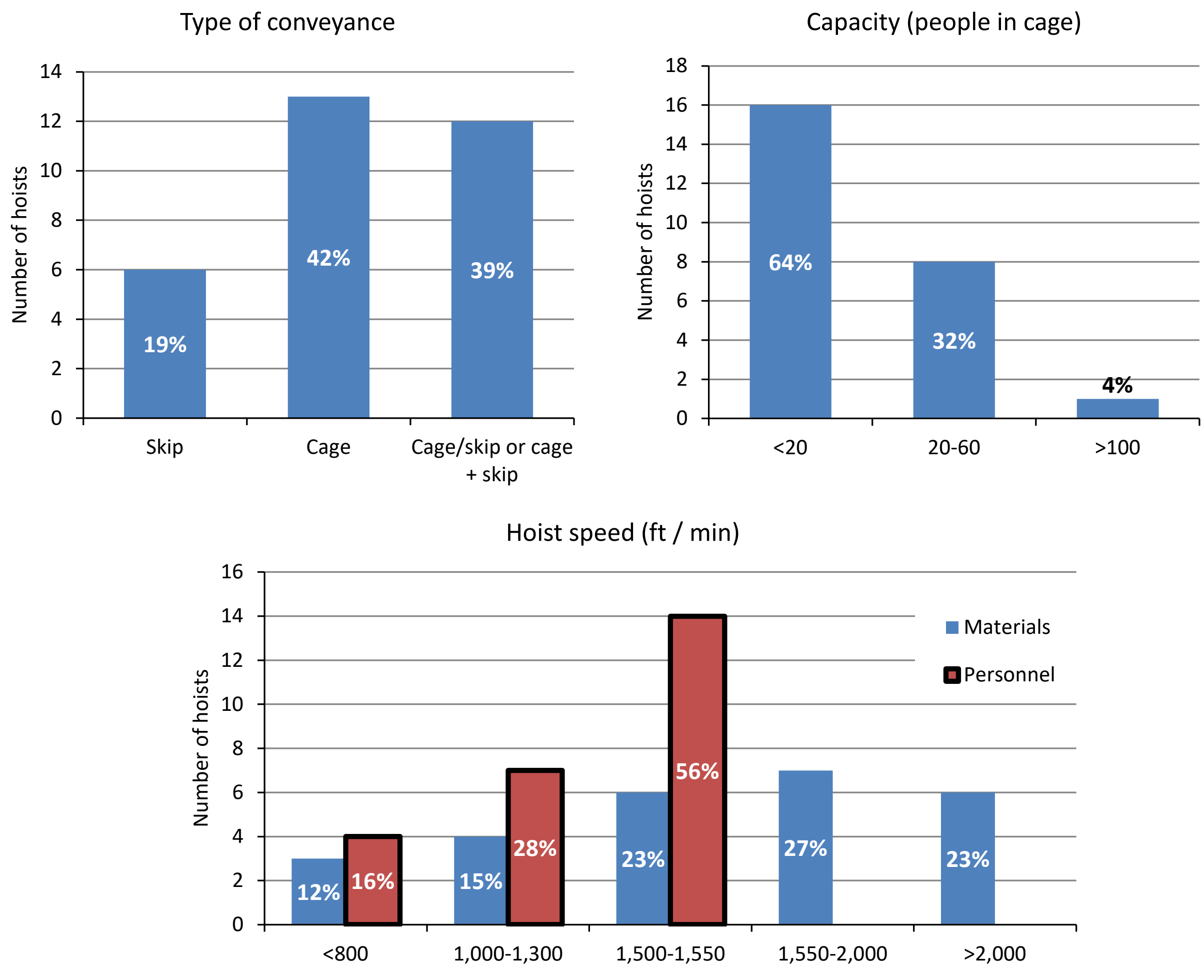

Figure 4. Type of conveyance, capacity and hoist speed

The graph of maximum hoist speed as a function of shaft depth (Figure 5) shows a clear upward trend for the materials hoisting speed when shafts are deeper. Conversely, regardless of the depth of the shaft, the speed at which workers are hoisted is limited to around 1,500 feet per minute (the maximum authorized under the Regulation respecting occupational health and safety in mines [ROHSM] is 8 m/s, i.e., 1,574 ft/min, if the regulatory testing of section 242 is not done).

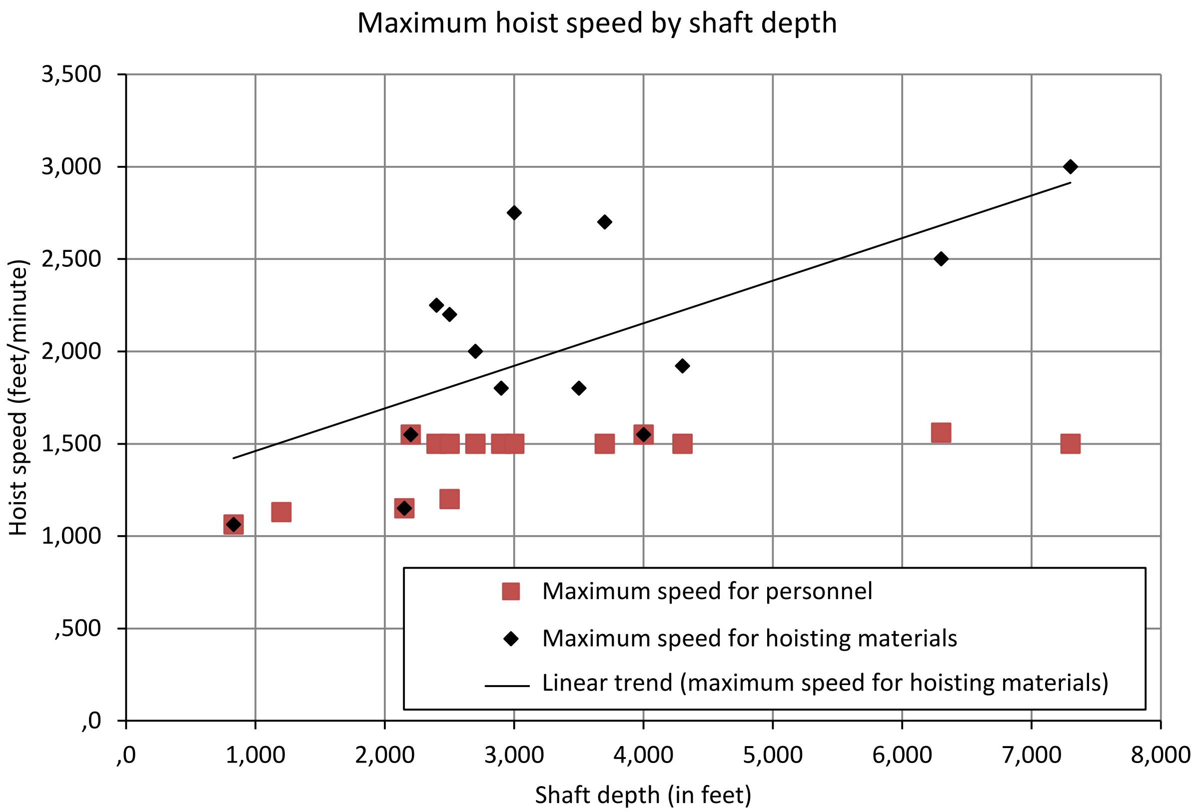

Figure 5. Maximum speed of conveyance by shaft depth

B.IV Braking systems

Figure 6 provides details on the various types of brakes used (disc or parallel post), the control[2] of the emergency brake, the number of emergency brake systems and the physical means of applying the emergency brakes (springs, the Earth's gravity or compressed air).[3]

[2] Progressive braking refers to a braking system calibrated to keep deceleration below the limit set by the ROHSM. Controlled braking refers to a braking system that continuously calculates cage deceleration and adjusts the braking force through a control loop.

[3] For further information about braking devices, see the *Guide sur les machines d'extraction* published by the CNESST (https://www.cnesst.gouv.qc.ca/publications/200/Pages/dc_200_16121.aspx).

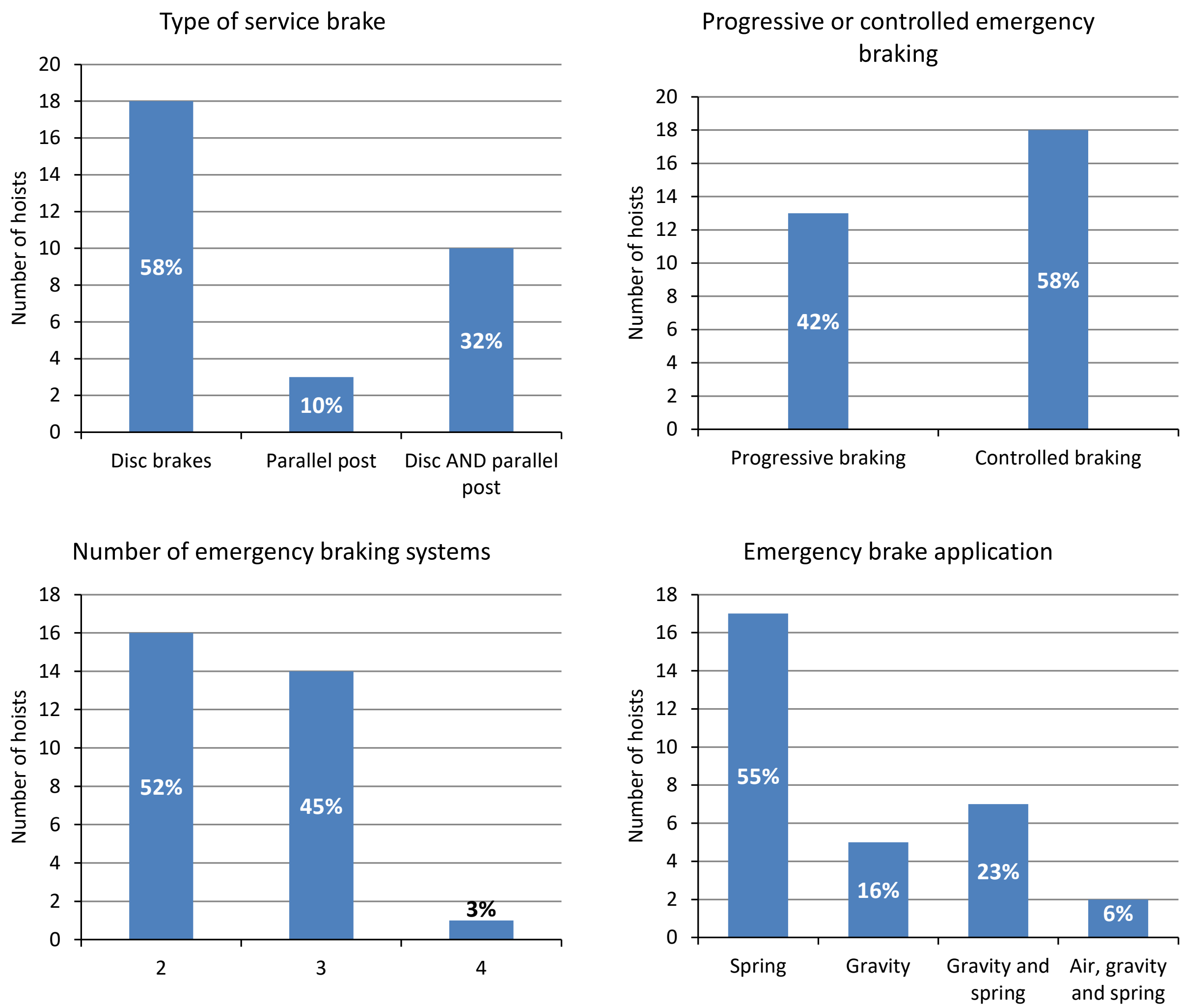

Figure 6. Braking systems

B.V Control

Figure 7 sets out the details of the different types of controls used for mine hoists (electromechanical relays, analog or digital PESs), the types of monitoring used (mechanical or electronic with PES) as well as the number of operating modes available. Note that the operating modes indicated vary widely from one mine to the next and from one hoist manufacturer to the next.

In 2016, most hoists were controlled by a PES (Figure 7), and monitoring was also implemented by means of a PES in most cases, instead of the traditional mechanical controllers, which are tending to disappear.

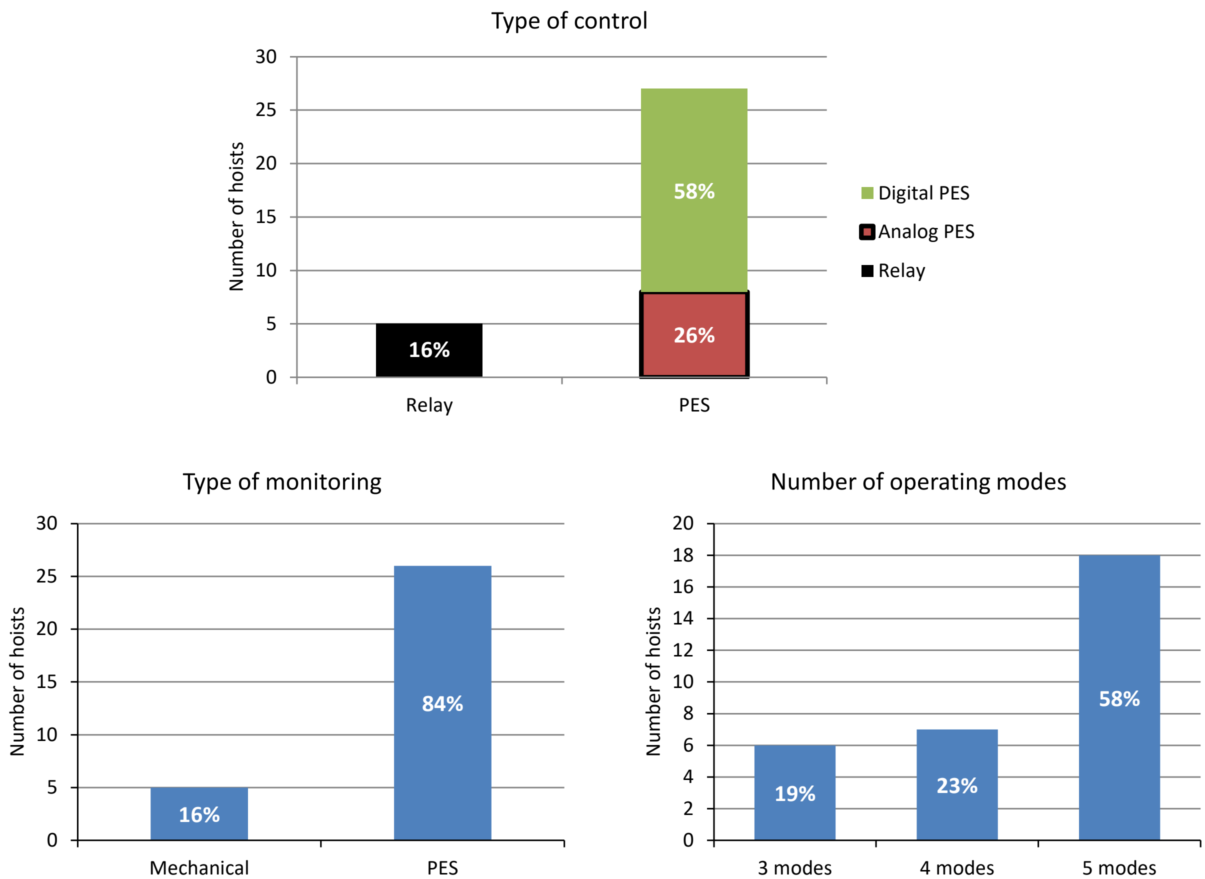

Figure 7. Control systems

B.VI General assessment for Quebec

Since the publication of the first version of data sheet RF-421, the profile of the hoists used in Quebec has evolved:

- The vast majority of mine hoists are controlled and monitored by PESs
- A significant percentage of hoists are very recent (less than 10 years old)
- The control systems of many older hoists have been updated
- Hoisting speeds remain limited to around 1,500 feet by minute for personnel (by regulation), but high-speed hoists are starting to be installed, in very deep shafts
- Disc brakes are now the most common type of braking system and are gradually replacing traditional parallel post brakes
- Most hoists are equipped with controlled braking systems that limit the force in the rope, in the event of an emergency stop
- There is no direct relationship between the age of a shaft or hoist, and the type of braking or control system on the hoist

APPENDIX C: CHANGES IN MINE HOISTS AND MINING PRACTICES IN QUEBEC

Ever since the start of underground mining, hoists have been used to cut the cost of bringing the ore to the surface. Hoists are essential to make underground mining cost-efficient when the ore sits at a depth of over 300 m (1,000 ft). The number and size of these machines have continued to change over the years.

In the 1930s to 1950s, hoist drums generally had a diameter of around 2.4 m (8 ft) or less. With only one rope per drum, shaft depth was limited to about 760 m (2,500 ft). Between the 1950s and 1990s, drum diameter increased to 4.3 m (14 ft), making it possible to reach depths of up to 1,220 m (4,000 ft). Subsequently, in the 1990s, a first hoist with a 4.9 m (16 ft) drum was installed, enabling even greater depths (of over 1,220 m) to be mined, but at the same time giving rise to other technical problems associated with the increased depth. The largest drums used in Quebec are now 6.4 m (21 ft) in diameter, and the first hoist with a drum that size was installed in 2010.

C.I Technological changes in hoists

Hoists are used to transport workers and equipment and to bring ore up to the surface. A mine shaft more than 30 m (100 ft) deep has to have a compartment used exclusively for conveying workers. In the old days, ladderways (manways) or stairways were used, but now motorized devices (Mary-Ann or Marianne) are used for moving people. Currently, a shaft may contain three different hoists: one solely for moving people (a motorized device for the transport of persons), one for moving people and equipment, and a third for bringing ore up to the surface. In this case, the mine shaft is divided into 4 or 5 compartments, and each hoist operates in its own compartment or compartments. The compartment or compartments of two hoists that share the same shaft are isolated from one another.

Automating hoists can optimize cycle times and make operations more cost-effective. Mining companies have to keep an open mind about new technology, while ensuring a high level of safety in all installations used for moving people and equipment and for bringing ore to the surface.

C.I.I Programmable logic control systems

In Quebec, some fully manual hoists are still being used, meaning that the operator, or hoistman, controls the application of the brakes and the speed of the conveyances throughout their travel. In addition to a control lever, these hoists, which use wound rotor motors, are equipped with one or two service brake levers controlled by the operator. The operator controls the departure and destination, as well as the speed at which the conveyances travel. Prior to each conveyance movement, the operator has to take into account the imbalance between the compartments to prevent any brusque reverse movements. These hoists require constant attention to be paid to the intensity of the motor current during movements. The actions and concentration demanded of the operator of a hoist with a wound rotor motor are completely different from those of a modern, automated hoist.

The hoists installed recently, in the last 15 years or so, are all relatively similar. They are equipped with devices that monitor the operator at all times by means of programmable logic controllers

(PLCs). These hoists must have at least two PESs, one for controlling and the other for monitoring movement limits. Both PESs can open the safety circuit and, as a result, cut power to the motor and apply the emergency brakes. The safety circuit is external to the PESs. The speed control lever is operational only if the starting conditions are met. The control PES analyses the positions of the conveyances in relation to shaft travel limits and adjusts the operating speed accordingly. In normal operating mode, many limits preset by the designers are programmed into the PES, which restricts the operator to managing conveyance points of departure and destination.

The increase in the number of protections implemented with PESs meant that a data sheet (RF-421) on the safety of hoists controlled by these programmable systems had to be introduced into the Quebec regulations in 2005. As an indication of these changes, it is worth noting that in the mid-1990s, there were just three hoists monitored by PESs (Fortin and Demers, 2011). By 2005, over 60% of the hoists in Quebec were equipped with monitoring PESs (Paques and Germain, 2005) and by 2016, this proportion had risen to 84%.

C.I.II Speed controllers

Under Quebec regulations, hoists in Quebec must be equipped with a speed controller on each drum. The main purpose of the controller is to set travel limits in the shaft and to monitor the maximum speed within these limits. Overspeed may not exceed 120% of the maximum operating speed. The first controller of this kind was built and patented by Roybell in 1905; it was driven mechanically by gear sets with the drum. In some respects, it was similar to today's Lilly controller. On the other hand, it was much larger and performed only a small number of functions.

The first PESs were installed in Quebec in the 1980s and had encoding functions that established the travel position. The first PES speed monitor using encoders was installed in parallel with a Model C Lilly-type mechanical speed controller in 1987 with a view to replacing it. Since 1993, these mechanical controllers have gradually been replaced by PESs and their encoders, as mining companies have invested in upgrading their existing hoists. All new facilities are now equipped with PESs.

C.I.III Safety circuits

Under Quebec regulations, hoists in Quebec must be equipped with a safety circuit. Formerly, i.e., before the advent of PESs, safety circuits were entirely wired, and all the contacts resulting from protections were in series to supply the main relay. The safety circuit had to be powered at all times to allow normal operation of the hoist. An opening of the safety circuit (main relay open) would trigger the emergency braking system and open the power supply to the motor or motors.

With PESs, the operating principle is similar. There is an external emergency circuit with a main relay that must be powered at all times to allow normal operation of the hoist. The two contacts of each PES are connected in series with the emergency stop buttons as well as a few other protections directly wired to the emergency circuit. Each PES manages its protections and takes the state of the main emergency circuit into account. In the event of an opening of the safety circuit (main relay open), it triggers the emergency braking system and opens the power supply to the motor or motors. With multiple PESs, the braking system generally contains as many channels as the number of PESs used, and each braking channel is governed by a deceleration instruction established at the time of commissioning. The deceleration instruction is independent from one PES to the next, and a failure on one braking channel will not necessarily cause a complete application of the braking system.

C.I.IV Shift to AC motors

Asynchronous AC motors are used on the new hoists; at present, 38% of the hoists in Quebec are equipped with asynchronous AC motors. The new generation of AC-to-AC converters allow good control at very low speeds.

Approximately 45% of the hoists in operation in Quebec are equipped with direct courant (DC) motors. They all have AC-to-DC converters and there are no Ward Leonard configurations for speed control. A DC motor combined with a converter needs a supplementary safety device in the event of electrical system failure.

Asynchronous AC and DC motors provide acceleration, maintain constant speed and ensure deceleration of the drums at values preprogrammed by the control PES. Under normal circumstances, the service brakes are applied through the PESs and serve to keep the machine stationary between trips. The maximum speed instruction is applied by the control PES to the converter and depends on the position of the conveyance in the shaft, among other things. The operator, even if the control lever is pushed to maximum speed, is limited by the overspeed protection.

AC motors with asynchronous wound rotors and resistances are still being used on 16% of the hoists in operation in Quebec. This type of motor allows only one manual mode, and the operator has to use at least two control levers. To move the conveyance, the operator releases the drum brakes using one control lever and applies torque to the motors with the other lever. The hoist operator must be aware of the imbalance between compartments in order to anticipate the movement of the conveyances when he releases the service brakes.

The operator could easily reach the overspeed protection, especially the limits of travel in the shaft. He therefore has to control the speed of the motor before the overspeed protection is reached.

C.I.V Changes in braking systems

Generally speaking, hoists must have two independent braking systems, each of them capable of stopping the conveyance while controlling the deceleration speed (Galloway and Tiley, 1986). The brakes ensure two functions: service braking and emergency braking. The brake systems are generally sized to withstand twice the maximum static load at the bottom of the shaft, so as to allow for changes in the shaft and loss of performance over time[4] (Galloway and Tiley, 1986).

The earliest mechanical brake systems consisted of drum brakes generally powered by compressed air or oil pressure (ABB, 2011). Nowadays, hydraulic disc brake systems are used for new installations (Leonida, 2013). Brake systems can now be implemented that control deceleration as a function of a certain number of parameters (ABB, 2011; Sparg, 1995).

[4] Under section 225 of the ROHSM, at the start of each shift the hoist operator must check that each braking device can hold the maximum load.

Under Quebec regulations, hoists in Quebec must be equipped with at least two separate braking systems (Figure 6), with each being able to retard and stop the hoist even in the most unfavourable conditions and to maintain the hoist in a stopped position. These braking systems serve as service brakes and emergency brakes. They are combined with high-performance speed controllers and no longer need to be able to withstand major variations in temperature during normal operation, as used to be the case. For these reasons, the new hoists are equipped with brake callipers mounted around a disc rather than the traditional parallel post brakes, which were strong and designed to absorb heat.

The number of brake callipers depends on the loads transported by the hoist, and they must be activated by at least two separate channels, with each being able to stop the hoist under a maximum payload of ore or workers. The minimum deceleration rates that each channel must meet are 1.5 m/s^2 (5 ft/s^2) with workers and 0.9 m/s^2 (3 ft/s^2) with ore. The most recent hoist has four separate braking systems, so four channels. Each channel has its own PES, its own control valves and its own pressure release holes, all independent of the other channels. PES performance now allows fast control over deceleration during an emergency stop.

C.I.VI Operating consoles

Approximately 20% of hoist operating consoles in Quebec are still old generation models that feature indicator lights, push buttons, dials, selector switches, keys and other discrete devices. At new facilities, the consoles have only an operating interface and a few buttons and selector switches. The operating consoles of more recent hoists feature human-machine interfaces. These interfaces can display virtually all the parameters measured or controlled by the PES. The software records the data and serves as a “black box” in the event of failures. There are often two (or even three) consoles that the operator can use to control the same hoist. There is what’s called the main operating console, close to the drum, and one or more remote consoles, connected through communications networks. However, this configuration was not anticipated by legislators.

C.I.VII Elevator mode control and remote control

Thanks to technological enhancements made to mine hoists, automatic and remote operating modes are now possible. Automatic mode was already being used by a number of mining companies, as it enabled a single operator to run two or three hoists. Another innovation was introduced in the first decade of the 2000s whereby no tender needs to be assigned to the conveyance when workers are underground. Up to that point, the tender was responsible for enforcing regulations that applied to any transportation of personnel or equipment. For example, the conveyance tender oversaw the number of people who could enter the cage, closed the landing doors as well as the cage doors and then gave the required departure signals.

It is important for the “machine” operator to be equivalent to the human operator; if not, provisions must be made accordingly. A comparison can be drawn with a building’s elevator, although a mine is quite different from a public building where the doors of the elevator shaft (mine shaft) and those of the elevator car (cage) open simultaneously and automatically when the car is in the right position. Only maintenance staff are allowed access to the elevator shaft.

In automatic mode with or without a conveyance tender, it is preferable for access to the shaft to be restricted by an electrically activated locking system. This access to the conveyance would be unlocked only when the cage is in the right position and permission to access it has been activated. In addition, for the departure control to be operational, a switch must confirm that the cage door is closed properly (ROHSM sec. 253.1).

C.II Visual and sound signal code

A feature common to all manually operated hoists is the signal code. The code, mandatory for any hoist movement, has been developed and applied to ensure worker safety. In manual mode, i.e., with a conveyance tender and a hoist operator, these sound and visual signals must be used in a clear, orderly manner for all conveyance movements. The signal code is regulated by numerous sections of the Regulation respecting occupational health and safety in mines (ROHSM, 2018).

A February 2010 amendment to section 269 stipulates that “The signal code prescribed by Schedule II shall be used for moving a conveyance in any underground mine using a hoist, except when the movement of the conveyance is controlled in automatic or semi-automatic mode.”

This means hoist movements may be made without these signals in order to raise ore and transport personnel. However, all periodical maintenance must be performed in manual mode.

C.III Steel wire rope safety factor and South African standards

With increasing shaft depth, the steel wire rope safety factor has become the main constraint on hoisting ore. The weight of the rope eventually becomes greater than the payload to be hoisted, to the point where the ore payload has to be reduced in order to meet the traditional safety factor of 5 at the headsheave. To help mines stay economically viable under these conditions, a new technology developed successfully in South Africa was introduced in Quebec in the first decade of the 2000s to monitor a decline in this safety factor.

The approach taken in South Africa consists in reducing and constantly monitoring the dynamic stress on the hoisting ropes due to acceleration and deceleration. This makes it possible to hoist larger loads of ore, while still maintaining a safety margin close to the conventional factor of 5. The most important point in South African standard SABS 0294 (2000) is the continuous monitoring of the suspended weight. The static and dynamic stresses on the steel wire hoisting ropes must always be less than 40% of the ropes’ breaking strength. The introduction of a new control component, i.e., load cells, provides a means of monitoring the suspended weight at all times. The continuous monitoring of the condition of the steel wire rope is also a new means of protection that is regulated to bring the safety factor below 5.

Quebec was the first province in Canada to allow the use of this South African technology in deep mines, in 1999–2000. Ontario has recently amended section 228 12.1 of its regulations to allow the use of South African codes of practice (Ontario regulation 854, 2017). The increase in the ore that can be transported, thanks to this new technology, makes a considerable difference in the profitability of deep mines.

French versions of South African practice codes SABS 0293 (1996) and SABS 0294 (2000) are available from the CNESST, while the adaptation of the codes, produced by CanmetMINES for Quebec, is available from the CNESST and CanmetMINES (CanmetMines, 2002).

C.IV Annual inspections

The purpose of annual deceleration testing, which is carried out by an agency independent of the manufacturer and the mine, is to assess the performance of each braking system, speed controller and safety device, to ensure that conveyances will never exceed the deceleration, speed or travel limits, even under the most unfavourable conditions.

The testing is done with or without a load and the data are collected on graph paper with an instrument that records the speed of the drum, the motor current, brake release pressure and other relevant signals as a function of time. Analysis of the graphs indicates the performance of each braking system, as well as that of the overspeed controllers.

Through a simulation of the most unfavourable conditions, the data collected for the graph analysis can be used to calculate maximum decelerations and speeds that could be reached, as well as the required stopping distances. The results provide a diagnosis of the condition of the hoist’s various components, from which comments and recommendations can be made.

The state of the hoisting plant and the various safety systems are also assessed by the independent agency. Following the inspection, the agency submits a report to mine management.

APPENDIX D: STANDARDS AND REGULATIONS RELATING TO RISK MANAGEMENT AND SRECS

This appendix is essentially an updated summary of the technical report produced by Giraud and Galy (2015).

D.I Regulatory and standards framework in Quebec, elsewhere in Canada and in the United States respecting mine hoists

In Quebec, there are two regulations under the Act respecting occupational health and safety (AOHS, 2018) that set out the requirements pertaining to mine hoists: the ROHSM and the Regulation respecting occupational health and safety (ROHS, 2018). Since 2009, Quebec has been the only province that refers to a relatively comprehensive document on mine hoists controlled by PESs, i.e., data sheet RF-421.

In Canada, mining regulations differ little from one province to the next. Some of them seem slightly more exhaustive than others with respect to the guidance they provide for the operation of PES-controlled hoists (Galy and Giraud, 2016b). However, none of them proposes an overall method for risk reduction.

From a normative standpoint, only standard CAN/CSA-M421 (2011) deals with electronic control systems for hoists, but it does not propose any overall risk reduction method either.

In the United States, federal regulations do not specifically regulate the safety of hoists controlled by PESs. Initially, the Mine Safety and Health Administration (MSHA) sought to set applicable post-installation recommendations to reduce the frequency of incidents. It was soon realized, however, that that approach was inadequate for complex programmable systems. The NIOSH then published a series of information circulars and guides to help hoist designers apply the recommendations of standard IEC 61508.

D.I.I Standard CSA M421

Quebec and British Columbia explicitly cite standard CSA M421 “Use of electricity in mining” in the sections of their regulations concerned specifically with hoists. Five other Canadian provinces cite standard CSA M421 and stipulate that “all electrical equipment” must meet or exceed the requirements of the standard (Table 1). In these provinces, standard CSA M421 must be used for the design of mine hoist safety circuits.

Table 1. Provincial regulations citing standard CSA M421

Province	Section regarding hoists	Other sections	Year
Quebec	476 (subject to sec. 232–235 safety circuits)	476	1985
Ontario	–	–	–
Saskatchewan	–	–	–
Yukon	–	–	–
Northwest Territories	13.01–14.04 *electrical equipment*	–	1993
British Columbia	7.6.8, 7.6.11, 7.7.1	5.1.1, 8.1.3	2000
New Brunswick	21 *all electrical equipment*	–	1993
Nova Scotia	194 *an electrical installation*	52, 491	2000
Manitoba	11.3(1)*	6.28, 12.15	Latest version
Nunavut	13.01–14.04 *electrical equipment*	–	1993
Newfoundland and Labrador	617, 678 *electrical equipment*	685	Latest version

*There is no precise definition of an “electrical installation” in Manitoba.

There have been five versions of standard CSA M421 since it was first published in 1985: 1985, 1993, 2000, 2011 and 2016 (CAN/CSA-M421, 1985, 1993, 2000, 2011, 2016). The 1985 and 1993 versions are quite similar, as are the 2000 and 2011 versions. As far as hoists are concerned, major changes were introduced in 2000, with the noteworthy addition of a clause stating that the emergency stop switch must be independent of the computer’s logic decisions (5.8.3.6 in the 2000 version, 6.9.3.4 in the 2011 version), the addition of a depth indicator and a mandatory high-water level probe, and the addition of Annex C, though only informative, on hoists and more specifically their electronic control systems. In 2016, section 6.9.3.4 became 6.10.3.4, and paragraph d) was amended slightly: the manual switch must now provide “control reliable safety control systems,” in accordance with the definition given in section 8.2.5 of CSA Z432. The 2016 version of standard CSA M421 refers to the 2004 version of CSA Z432 (2004). It should be noted, however, that the most recent version of standard CSA Z432 (2016) has completely abandoned the concept of “control reliable system” used in the 2004 version, and instead refers to the safety integrity levels (SIL) of standard IEC 62061 (2005) and to the performance levels (PL) of standard ISO 13849-1 (2015). The authors of this data sheet therefore recommend using the approach of standard CSA M421, 2011, or demonstrating that the required SIL or PL is achieved in the case of an emergency stop switch linked to the system’s safety logic.

D.I.II NIOSH recommendations

The NIOSH has published a series of recommendations (Mowrey, Fisher, Sammarco, and Fries, 2002; Sammarco, 2005, 2006; Sammarco and Fisher, 2001; Sammarco, Fisher, and Jobes, 2001; Sammarco, Fisher, Welsh, and Pazuchanics, 2001; Sammarco and Flynt, 2006; Sammarco and Fries, 2003) based on standard IEC 61508 (2010) that set out best practices for programmable systems in eight parts (initially nine parts were planned, but in the end No. 7 was never published) (Figure 8).

Part 1 is a general introduction noting that the primary cause of accidents and incidents involving programmable systems is a problem at the specification phase (44%), and that the second biggest cause is modification (21%). This part emphasizes the need to adopt a life cycle approach to hoists, as recommended in standard IEC 61508 (2010).

Part 2, titled *System Safety*, is chiefly based on standard IEC 61508 (2010) and refers to some additional standards. It includes recommendations regarding interlocking (6.6.3.13) and the reuse of equipment or code (6.6.3.14). It also points out that the interface used by the operator must be regarded as a safety function (6.6.4.13) and should meet a number of criteria (e.g., cancel the ongoing operation in a single stage and lead to a safe state). There must be maintenance and diagnostic interfaces, and it is essential that they not allow code to be changed. Part 2 also makes recommendations about training content for programmable control system users and notes that the level of training should correspond to the safety integrity level (SIL) (6.9.5).

Part 3 concerns software safety and is likewise largely based on standard IEC 61508. Part 4 deals with the *Safety File*, which is the document that brings together all information relating to E/E/PE system safety. In essence, it is a “proof of safety” of the hoist and shows that the safety level achieved is appropriate for the intended use of the hoist. This part could be used to define a generic document that could apply to future hoists.

Part 5 concerns the independent functional safety assessment. The higher the SIL in question, the higher the level of independence of the person assessing the functional safety must be.

Parts 6, 8 and 9 are guides to be used in conjunction with parts 2, 4 and 5 respectively. Part 7, which was never published, was intended to be a guide to part 3 on software safety.

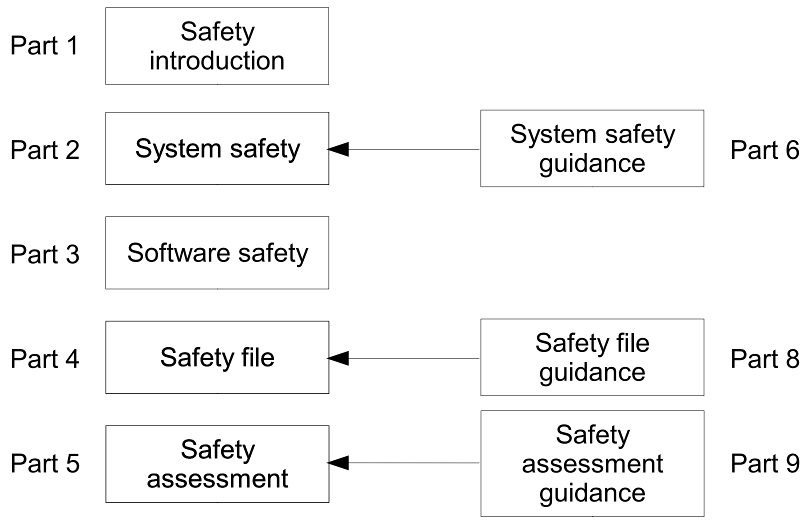

Figure 8. Guides published by the NIOSH

D.II Standards governing control systems

Two sets of international standards can be used for the appropriate design of a hoist's SRECS.

On the one hand, there is standard **ISO 13849-1** (2015), titled "Safety of machinery − Safety-related parts of control systems − Part 1: General principles for design"; it comes under the more basic type-A machinery safety standard, ISO 12100 (2010). On the other hand, there is also parent standard **IEC 61508** (2010) and the various derived standards, two of which are relevant in this case: IEC 61511 (2016) for industrial processes and IEC 62061 for machines, the latter being titled "Safety of machinery: Functional safety of electrical, electronic and programmable electronic control systems" (2005).

Standard ISO 13849-1 applies to all control systems for all machines, whereas IEC 62061 applies solely to machine control systems that use electrical, electronic or programmable electronic systems (Figure 9).

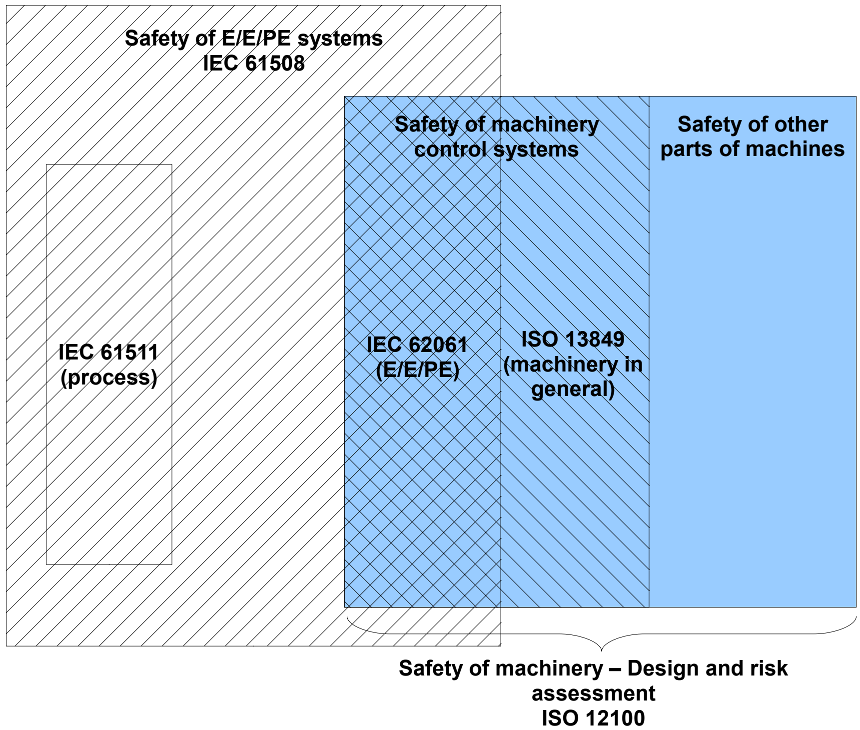

Figure 9. Areas of application of IEC and ISO standards

D.II.I ISO 13849 (machinery control systems)

Under standard ISO 13849, the capability of a safety-related part of a control system (SRP/CS) to perform its safety function is evaluated through the performance level PL (5 levels going from PL a to PL e), which is approximately equivalent to the security integrity level (SIL) in the IEC 61508 set of standards. The performance level is determined a priori, during the risk estimation, which means that the importance of the safety function in the overall reduction of risk can also be determined (Baudoin and Bello, 2013a).

If several SRP/CSs are used in series, the PL of each SRP/CS must be defined and then the overall PL. The PL of the overall safety function will be reduced, either to the lowest performance level of the series, or to a lower level if all the PLs are equal. The standard provides a table that can be used to estimate the drop in the PL depending on the configuration.

Different safety function architectures (categories B, 1, 2, 3 and 4) are proposed in the standard, and the requirements for each category are specified.

D.II.II IEC 61508, 61511 and 62061

IEC 61508 is a "performance-based" standard. That means that, in contrast with so-called determinist and prescriptive standards, the user is the one who, by means of risk analysis and evaluation, determines the performance levels that must be met by the safety-related electric/electronic/programmable electronic (E/E/PE) system (ISA, 2005). Standard IEC 61508 is the "parent" standard, and several sector standards are derived from it (Figure 10) (e.g., EN 50126 for railway applications, IEC 61513 for nuclear power). IEC 61511, especially in its non-normative parts, provides answers to frequently asked questions (ISA, 2005).

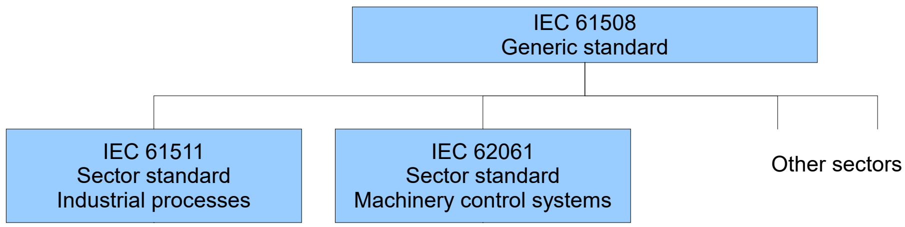

Figure 10. Structure of standards
(Adapted from ISA, 2005)

The status of standard IEC 61508 means that it can be used as follows (ISA, 2005):

- As a reference for generic requirements for safety-related E/E/PE systems when there is no sector or product standard, or when these requirements are not appropriate
- By E/E/PE component or subsystem manufacturers in all sectors (e.g., equipment and software for sensors, intelligent actuators, programmable controllers)
- By system builders/integrators to satisfy the requirements of safety-related E/E/PE systems
- By users to specify safety function requirements to be met and the performance of these safety functions
- To facilitate the maintenance of safety-related E/E/PE systems with respect to the “as-built” safety integrity level
- To provide a technical framework for evaluation and certification services
- As a basis for evaluating safety life cycle activities

One of the problems associated with the standard is the fact that someone must make a commitment with respect to tolerable risk. Standard IEC 61508 provides guidelines on the minimum level of independence in relation to possible consequences (harm) (Table 2). The more serious the consequences, the stricter the requirements respecting the independence of decision makers must be. For instance, for multiple fatalities or a catastrophe (the crash of a cage carrying over 20 miners can be regarded as a catastrophe just like an explosion in a refinery), the standard recommends that an independent organization be responsible for evaluating the functional safety (other than the mine or the hoist manufacturer). So, for a hoist, depending on the size of the cage, the “consequences” column could be C or D.

Table 2. Independence of people responsible for evaluating the functional safety of safety-related E/E/PE systems
(Adapted from IEC 61508-1, 2010)

Minimum level of independence	Consequences			
	A	B	C	D
Independent person	X	X1	Y	Y
Independent department		X2	X1	Y
Independent organization			X2	X
Notes: see paragraphs 8.2.15 to 8.2.17 of the standard for details A – minor injury (for example, temporary loss of function); B – serious permanent injury to one or more persons, death of one person; C – death of several people; D – very many people killed X – minimum level, Y – insufficient, X1 or X2 – one or the other, provide detailed rationale for choice (see 8.2.16)				

Standards IEC 61508, 61511 and 62061 can be used to calculate the SILs of safety instrumented systems (SIS) (IEC 61508, 2010; IEC 61511, 2016; IEC 62061, 2005). It is important not to confuse the different methods of calculating the SIL: standard IEC 61508 is primarily intended for equipment manufacturers, standard IEC 61511 for industrial process designers and integrators, and standard IEC 62061 for safety-related E/E/PE control system designers and integrators. For mine hoists, the standard that applies is therefore either IEC 61508 or IEC 62061. However, standard IEC 62061 does not deal with SIL 4, which does exist in standard IEC 61508.

D.II.III Unification of the two standards

From 2012 to 2015, the ISO and the IEC set up a working group within the ISO TC199 committee to look at merging two standards, ISO 13849 and IEC 62061, into a single one that was temporarily numbered ISO/IEC 17305 (ISO/TR 23849, 2010). But the proposed merger raised some thorny issues, as security integrity levels, referred to as SILs in standard IEC 61508, and performance levels, referred to as PLs in ISO 13849, are not strictly equivalent. There are even cases where the levels contradict one another (Buchweiler, 2009):

- In around half the cases: same SIL
- In around the other half: difference of one safety integrity level
- In a few cases: difference of two safety integrity levels

This probable divergence could have serious consequences for safety as a result of reducing safety levels. In 2015, the ISO TC199 committee therefore decided to abandon the proposed merger.

D.III Levels of contribution to risk reduction (SIL or PL)

To identify SISs and define their levels of contribution to risk reduction, the risks and their consequences need to be specified. The following data are required (Adjadj and Charpentier, 2007; Lanternier and Adjadj, 2008):

- Description of processes and installations
- History of recorded incidents and accidents

- Identification and characterization of hazard potentials and estimation of their effects
- Results of risk analyses

In an informative annex, standard IEC 62061 sets out a method for assigning safety integrity levels (SILs). Standard ISO 13849 states that a required performance level (PL_r) must be determined and documented, and refers to relevant guidelines included, likewise, in an informative annex.

D.III.I Under standard ISO 13849-1

Standard ISO 13849-1 specifies five performance levels (PLs), which are defined according to the probability of a dangerous failure per hour of the safety function. The five levels, numbered from "a" to "e," are based on a range of probabilities of dangerous failure per hour (Table 3).

Table 3. Performance levels (PLs) of standard ISO 13849-1

PL	Average probability of a dangerous failure per hour (1/h)
a	$\geq 10^{-5}$ to $< 10^{-4}$
b	$\geq 3 \times 10^{-6}$ to $< 10^{-5}$
c	$\geq 10^{-6}$ to $< 3 \times 10^{-6}$
d	$\geq 10^{-7}$ to $< 10^{-6}$
e	$\geq 10^{-8}$ to $< 10^{-7}$

However, standard ISO 13849-1 also notes that the average probability of dangerous failure per hour is not the only thing to consider when determining the "associated" performance level: systematic faults, common-cause failures and diagnostic coverage, for instance, must also be considered.

As for standard IEC 62061, the required performance level (PL_r) depends on the contribution of the SIS to risk reduction for a given safety function. The standard indicates that the level PL a is mainly used in the case of slight, reversible injury.

D.III.II Under standards IEC 61511 and IEC 62061

Standard IEC 61511 defines two qualitative methods for determining the SIL: the risk graph and the criticality matrix (probability/severity matrix). A semi-quantitative method can also be used to determine the probability of SIS failure.

SIS design is a function of the required SIL (Iddir, 2012a) and the type of demand on the SIS (Table 4): low demand/on demand (threshold overrun alarm), or high demand/continuous. In the first case, demand must be in the order of 1 per year or below the frequency of periodic tests so that a failure can be detected before a hazardous event occurs. In the second case, the SIS is considered to meet the high demand criterion when the frequency of the operating demands is greater than once a year, or greater than the frequency of the periodic tests. If we take the case of an SIL 3 under low demand with a probability of failure equal to 5×10^{-4}, this same SIL 3, when considered under a high-demand operating mode, will have to have a probability of failure of

5×10^{-8} (i.e., 10,000 times less), because hourly demand in a high-demand operating mode is being compared with annual demand in a low-demand operating mode.

Table 4. Definition of SILs by demand mode

Safety integrity level (SIL)	Probability of dangerous failure per year	Risk reduction factor
Low demand operating mode		
1	10^{-1} to 10^{-2}	10 to 100
2	10^{-2} to 10^{-3}	100 to 1,000
3	10^{-3} to 10^{-4}	1,000 to 10,000
4	10^{-4} to 10^{-5}	10,000 to 100,000
High demand operating mode		
1	10^{-5} to 10^{-6}	10 to 100
2	10^{-6} to 10^{-7}	100 to 1,000
3	10^{-7} to 10^{-8}	1,000 to 10,000
4	10^{-8} to 10^{-9}	10,000 to 100,000

In the case of mine hoists, an example of an SIS under low demand is the overwind protection or the associated braking system, whereas an SIS that monitors speed as a function of conveyance position will be under high demand.

For machinery, standard IEC 62061 provides a method for assigning safety integrity levels (SILs). The method uses four parameters:

- severity of harm – Se
- probability of occurrence of that harm – Cl = Fr + Pr + Av, which consists of three parameters:
  - frequency and duration of the exposure of persons to the hazard – Fr
  - probability of occurrence of a hazardous event – Pr
  - possibilities to avoid or limit the harm – Av

Once Se and Cl have been defined, a matrix can be created to identify the required SIL for each safety function (Baudoin and Bello, 2013b; Buchweiler, 2008). It is worth noting that standard IEC 62061 uses the same safety integrity levels as IEC 61511, but there is no level 4 in IEC 62061, as if a machine could not cause a catastrophe equivalent to an industrial process catastrophe. Yet a hoist carrying 50 workers that goes “crazy” with a non-operational emergency stop can surely lead to a catastrophe equivalent to one caused by an industrial process.

D.III.III SIL and PL equivalence

The safety integrity levels and the performance levels of the two previous references can be compared (Table 5) (ISO/TR 23849, 2010). However, the equivalence is not perfect, as for a safety function under strong demand (in continuous mode), the equivalence between the probabilities of dangerous failure per year and per hour is based on 10,000 operating hours per year. Yet a calendar year corresponds to approximately 8,766 hours on average,[5] which gives a difference of around 14%.

According to standard ISO 13849-1 (4.5.1), there is no equivalence between SIL 4 and a PL. The reason given is that SIL 4 is reserved for "catastrophic events" possible in the processing industry and that the scale is not appropriate for dealing with machine risks. But as mentioned earlier in subsection D.III.I, the crash of a cage carrying the maximum authorized number of passengers could well be perceived by society as a "catastrophic event."

Table 5. SIL and PFHD equivalence

Safety integrity level (SIL) IEC 61508	Probability of dangerous failure per year	Probability of dangerous failure per hour (PFHD)	Performance level (PL) ISO 13849
-	-	10^{-5} to 10^{-4}	a
1	10^{-1} to 10^{-2}	3×10^{-6} to 10^{-5}	b
1	10^{-1} to 10^{-2}	10^{-6} to 3×10^{-6}	c
2	10^{-2} to 10^{-3}	10^{-7} to 10^{-6}	d
3	10^{-3} to 10^{-4}	10^{-8} to 10^{-7}	e
4	10^{-4} to 10^{-5}	10^{-9} to 10^{-8}	-

[5] The solar year has an estimated length of 365 days, 5 hours, 48 minutes and 45.25 seconds.

APPENDIX E: RISK ANALYSIS

E.I Introduction

Based on the definition given in standard ISO 12100 (2010),[6] a mining hoist can be considered to be part of the range of application and so be the subject of the risk reduction process advocated in the standard. This process consists in carrying out an analysis that will eventually help identify, in conjunction with workers, the preventive measures most appropriate for the different work environments. The purpose of the risk analysis conducted for this project was to identify the risks and hazardous situations related to the use of programmable electronic systems (PESs) for hoists, but especially to ensure that the safety functions implemented by these same PESs covered all of the reasonably foreseeable hazardous situations.

Since the publication of data sheet RF-421 in 2005, a number of machinery safety standards have been updated. Two major standards respecting the robustness of safety-related control circuits have now become reference documents in industry and their use continues to expand. Standard IEC 62061 (2005) and standard ISO 13849-1 (2015), respecting the “reliability” of safety-related control systems, recommend carrying out a risk assessment[7] and propose, each in its own separate way, a risk estimation method for determining a level of reliability appropriate to the situations described in the risk analysis.

The application of the prescriptions in the standards regarding the need to perform a risk analysis therefore stems from the updating of the data sheet associated with this appendix report. The aim of this work was to identify the safety functions through which the hoist PESs can have an influence on the safety of people.

As stated in the 2005 version of data sheet RF-421, the initial risk analysis “was based on an informal risk analysis, developed thanks to the experience of users, manufacturers and CSST inspectors.” In light of technological changes, it was decided that the updating of data sheet RF-421 needed to be based on a more formal risk analysis, with a view to gaining a better understanding of the problems associated with the new technologies in use and estimating the required levels of reliability of the protective measures used to guarantee the safety of hoists in Quebec.

The main objective of conducting a risk analysis was therefore to identify the safety functions for the hazardous situations created by the hoist over which the PES can have an influence.

[6] Section 3.1 of standard ISO 12100:2010.
[7] According to the definition given in section 3.17 of standard ISO 12100:2010, a risk assessment consists of a risk analysis and a risk evaluation.

E.II Methodology

As the ultimate goal of data sheet RF-421 is to ensure the safety of workers who have to work on hoists controlled by programmable electronic systems (PESs), the methodology followed for the revision of the data sheet is based on the prescriptive requirements detailed in standards IEC 62061 and ISO 13849, which both recommend carrying out a risk analysis in accordance with the principles set out in standard ISO 12100.[8]

Given that the mine hoists used in Quebec are not all the same, and given the scope of the work that covering all of them would have entailed, it was decided that a “generic” risk analysis would be conducted to identify the hazardous situations associated with a typical hoist and the safety functions that the hoist PESs should perform. As was the case for the drafting of data sheet RF-421, the analysis process is based partly on the experience of the stakeholders, but also on information gathered in the course of visits to various sites, the findings of recent accident reports and the interpretation of other relevant standards, such as ISO 22559-1 (2014)[9] respecting the safety requirements for lifts.

In accordance with the prescriptions of standard ISO 13849 (sec. 4.2.2), designers must decide on the contribution to risk reduction that each part of a safety-related control system (SRP/CS) must make, based on the information gathered during the risk analysis. This contribution does not include the overall risk of the machine, but only the part of the risk that is reduced through the application of special safety functions. Similarly, standard IEC 62061 (sec. 5.2.1.1 and 5.2.2) does not propose any detailed prescriptions regarding the risk analysis procedure, but recommends using the results of the assessment to identify all the safety functions considered necessary.

The procedure followed therefore consisted, first, in drawing up a list of hoist safety functions based on all sources of information deemed relevant. Once this information had been collected, a risk analysis session was held in which a number of OHS experts and stakeholders took part. During the session the results of the risk analysis were either confirmed or invalidated.

The session produced a list of safety functions in which subfunctions were also identified. These functions and subfunctions should cover all reasonably foreseeable hazardous situations that might occur in the context of using a typical hoist.

[8] Standard IEC 62061 cites standard ISO 14121 (2007) as a model for risk assessment, but that standard was withdrawn and replaced by standard ISO 12100 in 2010.
[9] Standard ISO 22559-1 was replaced by standard ISO 8100-20 in August 2018.

E.III Formal risk analysis

E.III.I Sources of information and list of initial safety functions

A number of documents and sources of information were used to draw up the preliminary list of safety functions and subfunctions that hoist PESs should perform or monitor:

- As stated above, the 2005 version of data sheet RF-421 was used as a major source of the safety functions. Under the Quebec Regulation respecting occupational health and safety in mines (ROHSM), it has been mandatory since 2009 to apply the concepts set out in the data sheet. Its content has therefore been the subject of indirect, but continuous validation since that time.
- The ROHSM itself has been a major source of the safety functions that hoists must meet, whether PES controlled or not. As the ROHSM lists only the devices with which hoists must be equipped, and not the safety functions themselves, the devices first had to be matched up with the corresponding functions.
- The analysis of recent accident investigations involving mine hoists was also combed through to add further content to the list of functions. The safety functions that could have helped prevent the accidents were identified.
- Standards SABS 0294 (2000) and CSA M421:2011 (2011) were also used to identify certain protections that should be included on hoists.
- Given that there did not seem to be any other standards documents of this kind on hoists and given the similarities with lifts when hoists are used to transport people, it was decided that standard ISO 22559-1 needed to be included and therefore served as a primary reference in drawing up the list of functions presented at the risk analysis session. This list seemed to cover all the safety functions required for regulating all the generic hazardous situations associated with hoists.
- Standard EN 81-20:2014 (2014) on the safety rules for the construction and installation of lifts was also used as a reference. It provides a list of some 50 electric safety devices that can be used to implement the safety functions and the corresponding SILs.
- The *Registre des appareils servant à l'extraction* [register of hoisting equipment], put together by CanmetMINES and used for the purpose of inspecting mine hoists in Quebec, also served as a reference document for drawing up the list of safety functions and subfunctions.

So, using these sources of information to confirm the essential safety requirements for transporting people in a load carrying unit under standard ISO 22559-1, the preliminary list of safety functions used in the risk analysis session was drawn up. This initial list was intended as a basis for discussion of hoist safety in general, and the purpose of the safety functions on the list was to:

1. Prevent the movement of the conveyance if it is overloaded
2. Prevent falls outside of the conveyance
3. Limit the vertical travel of the conveyance
4. Protect the motor and electrical system
5. Protect the braking systems
6. Protect operation
7. Protect the resetting or locking of the safety circuits
8. Avoid a collision of the conveyance with any obstacle in the shaft
9. Prevent any movement of the conveyance in a flooded area of the shaft
10. Prevent rope failure
11. Protect the sinking of a shaft

E.III.II List of hazards and preventive measures

The hazards associated with hoists are essentially related to gravity (cage falling in the shaft), the kinetic energy associated with movements of the cage in the shaft (crash of the cage against an obstacle in the shaft) and the possibility of drowning at the bottom of the shaft.

The following hazards were not taken into account in the risk analysis: noise, vibrations, temperature, fire, explosion, natural disaster (e.g., earthquake), asphyxiation other than by drowning, various types of radiation (magnetic, electric or other).

Risk reduction measures, beyond the control system, are limited for this specific machinery. It is impossible to eliminate the danger of gravity, which applies at all times at and under the Earth's surface. In contrast, for kinetic energy, the main preventive measure is the hoist's speed profile and compliance with it. Lastly, to address the hazard of drowning at the bottom of the shaft, each shaft is equipped with a water pumping system.

E.III.III Risk analysis session with experts

Following the method recommended in standard ISO 12100, as well as the one suggested in standard ISO 14798:2009 (2009) for risk assessment and reduction procedures for lifts (elevators), escalators and moving walks, a team of experts was established to look at the various previously identified safety functions (Table 6). The purpose of the risk analysis session was to confirm that the preliminary list of safety functions was as exhaustive as possible and that it covered all the hazards the team members could reasonably foresee.

In accordance with the recommendations in the standards, session participants were chosen with a view to encompassing the broadest possible range of knowledge and interests with regard to hoists. The eight team members came from a wide variety of backgrounds and brought their respective expertise and knowledge of these systems.

Table 6. Risk analysis session participants

Name	Company or group represented	Title of participant
Réal Bourbonnière	Consultant	Machine safety consultant serving as session moderator
Bertrand Galy	IRSST	Researcher
Laurent Giraud	IRSST	Researcher
Louis Germain	CanmetMINES Natural Resources Canada	Senior Hoist Technician
Mario St-Pierre	CNESST	Inspector and Expert Advisor, CNESST, Mining
Christian Quirion	Employers' association	Maintenance Superintendent, Hoists
Marc Robitaille	Labour union	Electronics Technician, Mining
Alain Gilbert	Manufacturer	Engineering Supervisor, Hoisting Systems – Manufacturer of Hoist Control Systems
Michel Girard	Engineering consulting firm	Consultant, Project Manager – Electricity and Automation, for mining engineering company

The purpose of this two-day session, which was held following a review presentation on the main points in the standards regarding control system reliability, was first to determine whether the list of safety functions seemed to be complete, in the opinion of the session participants, in the sense that it covered all reasonably foreseeable hazardous situations. The safety functions were presented and then discussed with respect to scenarios that might occur.

Subsequently, session participants were together asked to determine a level of "integrity" based on the recommendations of standard IEC 62061 for each function. The approach advocated in standard IEC 62061 was preferred over the one proposed in standard ISO 13849. This choice was based partly on the fact that the systems used in hoists are considered to be complex and always involve programmable electronic systems (PESs), which are dealt with in data sheet RF-421. Also, standard EN 81-20 refers to the SILs in standard IEC 62061. Last, it seems that standard IEC 62061 is already being applied by some manufacturers who design hoist control systems.

In accordance with the procedure proposed in the standard, the SILs of the safety functions had to be determined on the basis of the accident scenarios imagined by the session participants, with participants assigning point values for the following four risk factors:

1. Severity of harm (values from 1 to 4)
2. Frequency and duration of the exposure of persons to the hazard (values from 2 to 5)
3. Probability of occurrence of a hazardous event (values from 1 to 5)
4. Possibilities to avoid or limit the harm (values of 1, 3 or 5)

Each safety function was associated with one or more hazardous events, which themselves were associated or not with one or more means of protection. Several accident scenarios could be imagined for each function, and so for each scenario the risk estimation was redone. These risk estimations conducted by the participants served to determine the safety integrity level (SIL) required for each safety function. After the initial list of functions and proposed changes had been discussed, SILs were assigned only for functions deemed relevant and included in the final document.

E.IV Results

E.IV.I Safety functions

In the discussions held at the risk analysis session, the research team was able to identify the important safety functions and edit the list to incorporate safety subfunctions and protective devices deemed necessary and that would have an impact on the greatest possible number of hazardous situations. Some of the original functions were merged, while others were developed based on the risk analysis session discussions.

The list of safety functions, presented in chapter 4 of the associated data sheet, constitutes the final result of the risk analysis review:

1. Conveyance speed and travel protection (upper and lower limits of travel in the shaft)
2. Protection against a collision of one or more conveyances with any obstacle in the shaft or the flooded area
3. Protection of personnel and safety devices (automatic mode and manual mode)
4. Emergency stop device and enabling device
5. Safety circuit reset protection
6. Electrical system, motor and kinematic chain protection
7. Braking system protection
8. Specific protections (e.g., deep mine, friction pulley, Blair)
9. PES operation protection
10. Shaft sinking protection

This list of safety functions is generic, in the sense that it is intended to reflect the specific characteristics of the greatest possible number of types of hoists. Included in each safety function are a number of subfunctions and protective devices (e.g., overwind protection) required to achieve the respective prevention objectives.

E.IV.II SIL

All the original functions as well as their scenarios were assigned a safety integrity level of SIL 3, in accordance with the method prescribed in standard IEC 62061.

It is important to note, however, that during the two-day risk analysis session, the "probability of the occurrence of a hazardous event" was chosen freely by the participants, who pointed out that existing protection systems reduce the probability and that very few incidents of this kind had occurred. This approach conflicts with the principle proposed in the standard, whereby the most unfavourable default value (Pr = 5) of this parameter should be chosen, except if there are good reasons to reduce the value.

It is interesting to note, nevertheless, that although lower values were selected for this factor, as was the case during the risk estimation, SIL 3 was still achieved. These results are understandable in the context of an accident involving a hoist conveyance carrying people who suffer very severe injuries (irreversible Se = 4), in which the frequency and duration of exposure are still the same and that were estimated here to have a high value[10] (Fr = 5) and, lastly, for which the possibility of avoiding or limiting the harm is thought to be very low (impossible, or Av = 5), given that the people are "trapped" in the cage.

It should be kept in mind that, according to the procedure (A.2.2 of standard IEC 62061), the highest SIL of the different scenarios must be assigned to each safety function.

The tables below summarize the risk estimation results for each of the six initial safety functions (subsection E.III.I) for which a thorough estimation was conducted. The point values assigned to each factor are listed, for the scenarios imagined and described for a given function.

[10] The conveyance makes approximately 80 trips per day, taking about 15 minutes per trip, or four trips per hour, for around 20 hours each day. Around 25% of the trips are for moving people, while the other 75% are for equipment and materials (proportion varies depending on the hoist) This value will be used systematically in all the scenarios examined.

Table 7. Safety function "Limits on vertical travel of conveyance"

Function			**SIL**
Limits on vertical travel of conveyance			3
The purpose of this safety function is to limit the vertical travel of the conveyance so as to prevent any uncontrolled movement beyond the prescribed travel limits (*Ref. ISO 22559-1, adapted from 6.4.5*)			-
Scenario 1: Ultimate upper mechanical limit reached. Material and human harm beyond this travel limit			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	2	Rare. The worst-case scenario is the one where the conveyance is travelling at full speed	-
Possibility of avoiding or limiting harm	5	Impossible to avoid harm if the hazardous event occurs	-
Scenario 2: Programmed operational limit reached at full speed, approximately four feet above the dumping position			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	2	Rare. The worst-case scenario is the one where the conveyance is travelling at full speed	-
Possibility of avoiding or limiting harm	5	Impossible to avoid harm if the hazardous event occurs	-

Table 8. Safety function “Braking system protection”

Function			**SIL**
Braking system protection			3
The purpose of this safety function is to guarantee the smooth operation of the hoist’s service brakes and emergency brake. It is a subfunction of the overall safety function, the purpose of which is to prevent uncontrolled movements of the cage (*Ref. ISO 22559-1 6.4.6*)			-
Scenario 1: Generic situation in which the hoist fails to brake			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	2	Rare	-
Possibility of avoiding or limiting harm	5	Impossible to avoid harm if the hazardous event occurs	-

Table 9. Safety function “Operation protection”

Function			**SIL**
Operation protection			3
The purpose of this safety function is to guarantee the smooth operation of the hoist. As soon as certain preset parameters leave their normal range (speed as a function of conveyance position, brake partially applied when cage is moving) or as soon as a fault is detected (signal of safety device failing to operate), it must bring the conveyance safely to a stop or trigger an alarm			-
Scenario 1: Generic situation in which there is a loss of control of the speed-position pair (includes the entire system, braking as well)			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	2	Rare	-
Possibility of avoiding or limiting harm	5	Impossible to avoid harm if the hazardous event occurs	-

Table 10. Safety function "Avoid a collision of the conveyance with any obstacle in the shaft"

Function			**SIL**
Avoid a collision of the conveyance with any obstacle in the shaft			3
The purpose of this safety function is to avoid a collision of the conveyance with any obstacle in the shaft (*Ref. ISO 22559-1, adapted from 6.4.7*)			-
Scenario 1: Collision of the cage with the safety door for workers in the shaft (it is possible to allow the conveyance to come to rest nearby). The rope can go through the door, or not, depending on the form of the door			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	4	Probable. This value was chosen because the position of the door is detected by means of a single switch	-
Possibility of avoiding or limiting harm	5	Virtually impossible to avoid harm if the hazardous event occurs	-
Scenario 2: Collision of the cage with automatic/retractable chairs (skip or cage)			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	4	Probable. It is estimated that one accident a year can occur under this scenario	-
Possibility of avoiding or limiting harm	5	Virtually impossible to avoid harm if the hazardous event occurs	-

Table 11. Safety function "Avoid a collision of the conveyance with any obstacle in the shaft" (cont'd)

Function			
Scenario 3: Risk of major impact if water accumulates at the bottom of the shaft			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	2	The probability of occurrence of this event is considered to be rare, as there is little likelihood that water will accumulate to a high level	-
Possibility of avoiding or limiting harm	5	Virtually impossible to avoid harm if the hazardous event occurs	-
Scenario 4: Collision of a skip with a fully deployed automatic chair			3
Severity	4	Fatal or significant irreversible injury. There is a risk of rock being dumped or of part of a chair falling (beam or other part) in another compartment as a result of the collision	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	2	The probability of occurrence of this event is deemed to be very low. It would only occur if an operator made a mistake when the sensor of the chair's position has been disabled (bypassed)	-
Possibility of avoiding or limiting harm	5	The probability of avoiding harm is considered to be very low if the hazardous event does take place	-

Table 12. Safety function "Prevent any movement of the conveyance in a flooded area of the shaft"

Function			**SIL**
Prevent any movement of the conveyance in a flooded area of the shaft			3
The purpose of this safety function is to prevent any movement of the conveyance in a flooded area of the shaft			-
Scenario 1: Generic situation in which the cage is lowered into water at the bottom of the shaft			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	2	Rare	-
Possibility of avoiding or limiting harm	5	Impossible to avoid harm if the hazardous event occurs	-

Table 13. Safety function "Prevent rope failure"

Function			**SIL**
Prevent rope failure			3
The purpose of this safety function is to avoid failure of the rope. As soon as certain preset parameters leave their normal range (load on the rope, loss of metallic area) or as soon as a fault is detected (anomaly at rope surface), the conveyance must be brought safely to a stop or an alarm must be triggered			-
Scenario 1: Failure of the rope following overloading of the conveyance when it is stopped (skip full and people in cage)			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	1	Very rare, given that the rope is designed with a minimum safety factor of 5 and that the conveyance is designed not to allow an overload	-
Possibility of avoiding or limiting harm	5	Impossible to avoid harm if the hazardous event occurs	-

Table 14. Safety function "Prevent rope failure" (cont'd)

Function			**SIL**
Prevent rope failure			3
Scenario 2: Failure of the rope following overloading of the conveyance when it is stopped (loading of explosives and people in cage)			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The transportation of people is a very frequent occurrence during a shift	-
Probability of occurrence of a hazardous event	1	Very rare, given that the rope is designed with a safety factor of 5 and that the conveyance is designed not to allow an overload	-
Possibility of avoiding or limiting harm	5	Impossible to avoid harm if the hazardous event occurs	-
Scenario 3: Detection of a sudden change in the load during (upward) movement of the conveyance, rope taut. Possible causes: skip door open, guides, obstacle or obstruction not detected			3
Severity	4	Fatal or significant irreversible injury	-
Frequency and duration of exposure	5	Frequent. The conveyance makes approximately 80 trips per day, taking about 15 minutes per trip, or four trips per hour, for around 20 hours each day. Around 25% of the trips are for moving people, while the other 75% are for equipment and materials (proportion varies depending on the hoist)	
Probability of occurrence of a hazardous event	2	Rare, given the fact that inspections are performed weekly	-
Possibility of avoiding or limiting harm	5	Impossible to avoid harm if the hazardous event occurs	-

The results show that, generally speaking, the consequences of a hazardous event are virtually always deemed major (serious). The frequency of exposure to the hazardous situation is likewise very often deemed to be high, given the frequency with which the hoist is used to transport people each day, like an elevator. Also, when a hazardous event does occur, there is virtually no possibility of the workers in the cage avoiding it. The only criterion that seems to cause variations in the overall results is the actual probability of occurrence.

As some of the initial functions presented at the risk analysis session were merged and others were created as a result of the session discussions, the SILs were not established for all 10 of the safety functions included in the final list of the data sheet. Only four of the safety functions on the final list, i.e., functions 1, 2, 7 and 8 presented above (subsection E.IV.I), are derived directly from the results of the risk estimation and the assignment of SILs to six of the initial functions.

Nevertheless, in light of the fact that a hoist's SRECS will be used to monitor all of the hoist's safety functions and that, as a matter of principle, the SRECS must have an SIL or a PL equivalent or superior to that required for each individual safety function, a hoist's SRECS must have the characteristics of a system designed to meet the requirements of SIL 3, in compliance with IEC 62061, if at a minimum, any single one of the safety functions requires an SIL 3.

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