# Light Metals 2013

## ELECTRODE TECHNOLOGY FOR ALUMINUM PRODUCTION

## Bake Furnace Design and Operation

*SESSION CHAIR*

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# HYDRO ALUMINIUM'S HISTORICAL EVOLUTION OF CLOSED TYPE ANODE BAKING FURNACE TECHNOLOGY

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## Abstract

The paper summarizes the historical evolution of the closed anode baking furnace technology from the Riedhammer design to the Hydro Aluminium concept in the Norwegian carbon plants; Årdal and Sunndal over the last 50 years.

The increasing demand for higher production and larger anodes during the last 30 years has required Hydro Aluminium (HAL) to design a proprietary high capacity HAL baking furnace concept. Some major aspects and challenges connected to the rebuilding of the furnaces are described, including maximum utilisation of the existing factory space, allowing a low CAPEX per annual production capacity.

Development of new repair and maintenance methods for critical refractory parts were essential in order to maintain a high anode quality and to extend the furnace service life.

Main improvements related to the process control, process safety and performance data of the current technological status are presented.

## Introduction

### Historical Development Sunndal Furnace

The production of prebaked anodes in Sunndal was initiated in connection of the paste plant start-up in 1968. The first anodes were produced in a closed type Riedhammer furnace with designed annual capacity of 54,000 tonnes.

Until 1984 the Norsk Hydro (ÅSV) had five anode baking furnaces of closed Riedhammer design in operation in Norway. The total annual production of these furnaces was 160,000 tonnes.

The need for higher metal production volumes and consequentially bigger anodes initiated a strategic plan for the carbon plants in Sunndal and Årdal to supply the company smelters with sufficient quantities of anodes with desired dimensions.

The plan was to design and construct two proprietary prototype sections. These were tested in the baking furnace at Sunndal in 1983.

The main design criterion for the test sections was to adapt the pit geometry to new anode dimensions and to maintain or increase production capacity.

The key assumption during the reconstruction of the furnace was that it should be done within the existing building, without major dimension changes to the existing concrete tub and that the distance between the head walls was maintained.

After a one year successful test period, the entire Riedhammer furnace was rebuilt according the design of the prototype sections. The Sunndal furnace was rebuild to 28 sections, each with 7 pits and was operated with two fires.

The annual production prior to reconstruction in 1984 (54,000 tonnes of baked anodes) increased to 63,000 tonnes (about 17 %) after the rebuilding.

With the next furnace retrofit in 1997 the Sunndal furnace achieved a further increase in capacity to 80,000 tonnes.

### Historical Development Årdal Furnaces

The very first production of prebaked anodes in ÅSV Årdal is dated back to 1958. Two closed Riedhammer type furnaces #1 and #2 were build with annual capacity of 18,000 and 15,000 tonnes. Due to demand for larger anodes, the height extension of furnace #1 was done in two steps; in 1971 and then 1980. Furnace #2 was modified in similar way in 1977. During the operational period both furnaces were also used for calcining of cathode blocks.

Årdal Furnace #1 and #2 were closed down in 1997 and 2010 mainly due to the operational economy and low pit capacity utilisation.

Figure 1. Construction site of the Riedhammer furnaces #1 and #2 in Årdal (1958).

Due to metal production expansion in Årdal, two new Riedhammer furnaces #3 and #4 were built in the beginning of the 70's. Each of the new furnaces had double the capacity of #1 and

#2 mainly because of the increased number of sections, one extra pit and shorter fire advance cycle.

In 1988, based on the operating results from the redesigned furnace at Sunndal, it was decided to rebuild furnace #3 in Årdal to the same concept, which was denominated as "HAL" concept. Baking furnace #3 had 30 sections and was operated by two fires. After reconstruction a production increase, from 34,000 tonnes to 53,000 tonnes (about 56 %), was achieved.

New designs of the refractory brick work structures were developed in order to obtain the ability to produce even larger anodes within the increased section load.

The reconstruction projects mentioned above are described as 1st Generation HAL Baking Furnace Technology, implemented within the existing concrete tub and without alteration of the factory buildings.

The gas cleaning and transportation facilities were upgraded to coincide with increased production and modification of the anode dimensions. The total reconstruction times (furnace shut down) varied from 80-130 days, except Årdal Furnace #3 where rebuilding was carried out in the stages during a period of 10 months and adjusted to the nearly normal production.

The last projects carried out were the rebuild of Årdal Furnace #4 in 1998 and modernization of Årdal Furnace #3 in 2004 to what we denote as 2nd generation HAL Baking Furnace Technology. Unlike 1st generation, the existing concrete tub was fully or partly renewed. The concrete tub was still located within the existing buildings, but it allowed adjustments of the length and width so that the pit geometry could be tailored to the necessary production capacity and the anode dimension.

Årdal Furnace # 4 had 30 sections and was operated by 2 fires and the initial production capacity in 1971 was 34,000 tonnes/y. Since the rebuild in December 1998, designed capacity was 102,000 tonnes/y. Reduced output due to limitations in the pit utilization and periods the furnace has been operated by one fire (50 % production) resulted in average production of 86,000 tonnes/y.

Årdal Furnace #3 was restarted after the reconstruction to HAL 2nd generation concept in April 2004. Design capacity was increased to 112,000 tonnes/y, but the average annual production has been 96,000 tonnes. Furnace #3 in Årdal achieved production increase of 110 % since the previous rebuild (HAL 1st) and an increase of 230 % compared to the original furnace design.

Currently the total production of the 3 furnaces with HAL technology in operation (furnace #3 and #4 in Årdal and Sunndal furnace) is approximately 290,000 tonnes/y.

Table I. Overview of historical evolution of baking furnace technology in ÅSV furnaces in Sunndal and Årdal.

| | **Sunndal furnace SNC** | **Årdal furnace #1 AAK1** | **Årdal furnace #2 AAK2** | **Årdal furnace #3 AAK3** | **Årdal furnace #4 AAK4** |
|---|---|---|---|---|---|
| Start operation | 1968 | 1958 | 1958 | 1970 | 1971 |
| Technology | Riedhammer | Riedhammer | Riedhammer | Riedhammer | Riedhammer |
| Annual capacity (t/y) | 54,000 | 18,000 | 15,000 | 34,000 | 34,000 |
| Number of fires | 2 | 2 | 2 | 2 | 2 |
| Number of sections | 28 | 24 | 24 | 30 | 30 |
| Number of pits/section | 6 | 4 | 4 | 5 | 5 |
| Number of anodes/section | 108 | 60 | 60 | 90 | 90 |
| Production rate (kg/pit/hour) | 514 | 257 | 214 | 388 | 388 |
| | | | | | |
| Start operation | 1984 | 1971 and 1980 | 1977 | 1989 | |
| Technology modification | HAL 1st gen | height extensions | height extension | HAL 1st gen | |
| Annual capacity (t/y) | 63,000 | 22,000 | 22,000 | 53,000 | |
| Number of fires | 2 | 2 | 2 | 2 | |
| Number of sections | 28 | 24 | 24 | 30 | |
| Number of pits/section | 7 | 4 | 4 | 5 | |
| Number of anodes/section | 126 | 60 | 60 | 105 | |
| Production rate (kg/pit/hour) | 514 | 314 | 314 | 605 | |
| | | prod. stop 1997 | prod. stop 2010 | | |
| | | | | | |
| Start operation | 1997 | | | 2004 | 1998 |
| Technology modification | HAL 1st gen | | | HAL 2nd gen | HAL 2nd gen |
| Annual capacity (t/y) | 80,000 | | | 112,000 | 102,000 |
| Number of fires | 2 | | | 2 | 2 |
| Number of sections | 28 | | | 30 | 30 |
| Number of pits/section | 7 | | | 7 | 7 |
| Number of anodes/section | 126 | | | 168 | 168 |
| Production rate (kg/pit/hour) | 652 | | | 913 | 832 |

## Main Features of Riedhammer and Hydro HAL Baking Furnace Technology

Both Riedhammer and HAL concepts are so called closed type furnaces with the vertical flue gas pattern.

The principle of the flue gas pattern for the Riedhammer furnace is shown in Figure 2. The exhaust gas enters from the previous section underneath the head wall and turns upwards through the firing shafts with counter flow firing. Under the section cover, the gas is distributed downwards into the flue wall channels and transferred via the bottom channel system into the next section. At the front of the fire zone, the exhaust manifold leads off gas from the exhaust take off duct to the ring main (Figure 6). In this way flue gas passes the whole fire zone and the heats up furnace sections.

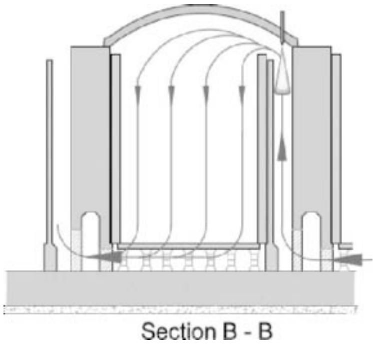

Figure 2. Schematic drawing of the flue gas pattern for closed type Riedhammer baking furnace.

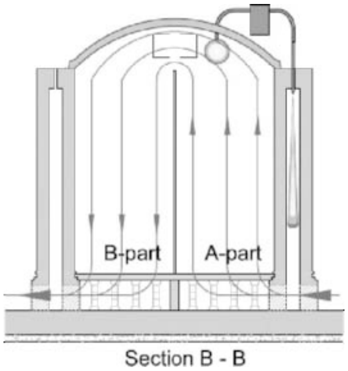

Figure 3. Schematic drawing of the flue gas pattern for closed type HAL baking furnace.

The Hydro closed type furnace design was developed with a different flue gas pattern, shown in Figure 3. The exhaust gas enters the section through the bottom part of the head wall directly to the flue wall. Flue walls and the bottom part of the pit are physically divided into A and B part by the dividing wall. After an energy input from downstream firing, the flue gas is channelled first upwards through the A part of the flue wall. In such way approximately 60 % of the fuel energy required per section is supplied. Under a section cover, the rest of the fuel energy input is injected from the vertically oriented cover burners and the flue gas is sent down stream through the B part beneath the pit floor. The exhaust manifold is connected directly from the section cover to the ring main at the first section in fire zone.

Distribution of gas and energy input between A and B part is the key feature of HAL concept which enables to operate the furnace with a high production rate per pit as shown in Table I [1].

## Rebuild to HAL 1st Generation Baking Furnace Technology

The main requirements and major aspects connected with rebuild of the Riedhammer to HAL technology are further discussed. The most challenging part during rebuild was to adopt the new furnace design into the existing building and same concrete tub.

This solution included step changes on previous essential furnace construction parts with simultaneous focus on low investment cost. All these changes were adjusted in order to avoid major changes in existing infrastructure assuming the shortest construction time without a large production loss.

The major cost saving was partly achieved by reduced amount of installed refractory compared to the previous furnace design (Table II). This was achieved through new headwall design which included removal of the firing shafts and the exhaust take off ducts [2]. In such way, the section width increased for two additional pits (Figure 5 and Figure 7). New headwall brickwork was more simple and required less brick types and tonnage installed.

Table II. Overview for tonnage of installed refractory material for furnaces.

| Installed refractory (t) | Riedhammer | HAL 1st generation | HAL 2nd generation |
|---|---|---|---|
| Sunndal furnace | 11,500 | 10,000 | |
| Årdal furnace #3 | 12,500 | 11,000 | 10,800 |
| Årdal furnace #4 | 12,500 | | 10,500 |

The increased section volume allowed loading of several larger anodes which resulted in a higher section load and improved furnace productivity.

The extension of section dimensions and new concept of the exhaust gas take off required construction of new section covers and exhaust manifold. The new HAL section cover design enables even distribution of the flue gas flow due to rectangular geometry of cross sectional area. In such way flue gas velocity gradients in the corners over outer and inner pits, were minimised [3,4].

The main operational advantage of the HAL section cover design is that all peripheral equipment (gas burners, thermocouples, additional air fans) are integrated in the cover.

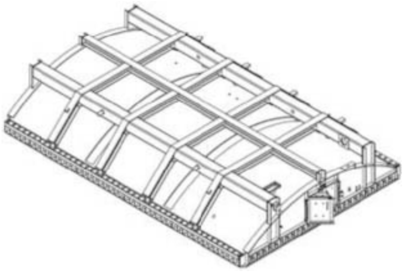

Figure 4. The new cover design for HAL furnace. The exhaust take off hatch is on the short side of the cover. Auxiliary equipment is integrated in the cover.

An increase of the cover width and length required modification of construction design. The original rigid cast iron frame was replaced with a flexible steel frame construction supported by a torsion stable steel structure. The new cover was designed with the intention to withstand mechanical and thermal stresses during the whole fire cycle. Thermal expansion measurements and thermo mechanical analysis were done prior to modifications of the cover bottom frame [5,6]. As a result, expansion joints at the long side of the steel frame were introduced. This measure helped also to reduce the mechanical stresses on the cover arch insulating brickwork.

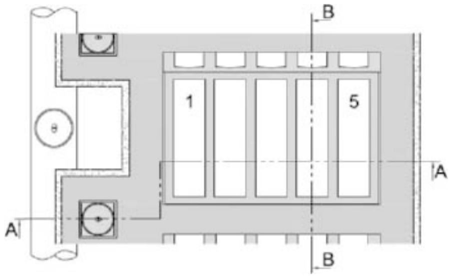

Figure 5. Top view of the Riedhammer design furnace #3 section from 1970. Exhaust take off duct is integrated in the headwall.

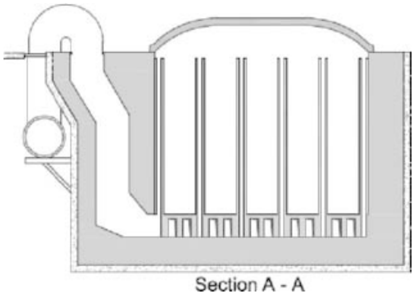

Figure 6. Cross sectional view of the Riedhammer design furnace #3 section from 1970. Section with 5 pits, exhaust manifold is connected to the exhaust outlet.

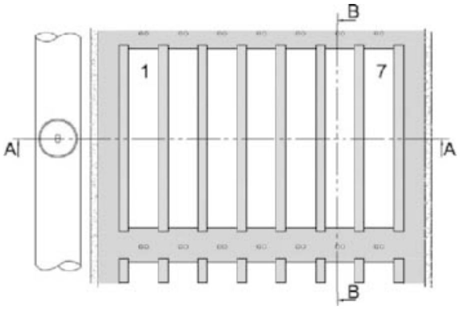

Figure 7. Top view of the HAL 2nd generation design furnace #3 section with 7 pits after retrofit in 2004.

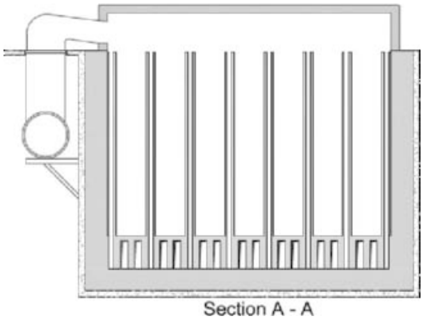

Figure 8. Cross sectional view of the HAL 2nd generation design furnace #3 section after retrofit in 2004. Direct exhaust take off is from the section cover.

### Rebuild from HAL 1st Generation to HAL 2nd Generation Baking Furnace Technology

Increasing amperage in pot rooms set persisting demand for larger anodes during the 90', which resulted in further evolution of HAL 1st generation baking furnace technology. Further retrofit of the furnaces involved a gradual rebuild of Sunndal and both Årdal furnaces #4 and #3.

Major modifications of the furnaces comprised dimensional changes in the concrete tub, both in length and width. The most remarkable change was the retrofit of furnace #3 where the amount of pits increased from 5 to 7 per section. Increased loading tonnage per section required calculations of strength and an evaluation of concrete tub thickness with respect to the wall stability and thermal stress [7].

The 3D finite element (FE) modelling of the furnace bottom structures was done in order to ensure sufficient bearing capacity and optimised flue gas flow distribution [8]. The same study evaluated several cases with various widths (cross sectional opening) of the fluewall bricks to show the effects on the flue gas pressure loss and the flow distribution in the flue wall.

Heat profile calculations, confirmed by the temperature measurements, enabled to reduce the sidewall thickness and furnace substructures height which increased the pit depth [9, 10].

Modelling and subsequent optimisation of the important furnace constructions allowed for a reduction in the amount of installed refractory without loosing its functional value. Lighter construction allowed operation with faster fire advance cycle and increased the furnace productivity.

After 4 years of operation of furnace #3, extensive modelling was conducted. 3D finite element (FE) model of a baking furnace and thermal and structural analyses helped to understand the mechanisms for stress build-up in the baking furnace. The FE-model was also used to compare pro and cons of different furnace design solutions [11].

### Refractory Maintenance

The Hydro furnace concept has adopted the continuous refractory maintenance strategy. This assumes that the maintenance of refractory parts is planned without loss of the furnace production. The furnace is in continuous operation during the regular maintenance; like change of the flue wall or pit floor. Production is stopped only during the major rebuild periods when the main furnace structures like sidewalls, bottom insulation and headwalls are replaced.

The evaluation of maintenance and the lifetime of baking furnace very often depend on the amount of fire cycles. For example furnace #4 in Årdal was originally build as a Riedhammer type furnace in 1971 was in continuous operation until rebuild in 1998. This means that the original headwalls, sidewalls bottom insulation and covers were 27 years old. Assuming average 17 cycles per year, the furnace had passed minimum 460 cycles during its service life time.

Another important fact was that the complexity (amount of special brick shapes) of the HAL design for the critical refractory structures was simplified. Thus less refractory tonnage was installed which reduced the heat capacity of the whole furnace structure and enabled to operate with faster fire advance cycles. Improved heat exchange between the anode and the flue wall was reflected in lower energy consumption.

Lifetime of the furnace refractory brickwork depends mainly on:

- Refractory quality
- Heat stress under the normal operation
- Mechanical load combined with the operational routines
- Routines for continuous maintenance under furnace operation

When the furnace structures of the new HAL furnaces were designed, selection of high refractory quality according to the installation position enabled customized solutions for the high heat and mechanical loaded structures as the head walls and bottom pillars.

Selection of the refractory quality resulted from the extensive test program which included the characterization and the evaluation of previous operational experience. The most important testing methods and the refractory properties were selected [12]. Testing included both, the characterization of the new materials and the analysis of used refractory which reflected ageing effect of thermal cycling. Results from testing helped to indentify and understand the thermo-mechanical and chemical stresses in the critical brickwork structures of the furnace.

In connection with the introduction of the HAL 2nd generation furnace design, new maintenance and repair methods were adopted. Evaluation of the baking furnace brickwork condition is based on inspection of sections with varying extent of damage.

General condition monitoring is done at least every 2 years. Sections with large deformations and displacements, especially the headwall, are checked at shorter intervals (4-6 months). Damage mechanisms and causalities for observed critical deformations were explained and the maintenance method solutions were proposed [13].

Routine follow up and the evaluation of the brickwork condition is important tool to predict and determine the timeframe for new renovation or modernization of the furnace. Therefore it is crucial to focus on the construction portions that are time-consuming and costly to maintain. Hence, the condition of the head walls will be crucial in determining when to rebuild the furnace.

Flue Wall Reparation Methods

During operation, the packing coke tends to stick to the fluewall and forms slag around anchor slots in the headwall. Blockage of the expansion joints in headwall will prevent the fluewall from free movement and cause deformation and cracking. A deformed fluewall causes narrowing of the pit and makes loading of anodes difficult. In addition, large cracks in the bottom of the flue wall will cause problems with excessive airburn of the anodes and packing coke. Packing coke runs under the pit floor and causes restrictions in the flue gas flow and prevents optimal heat distribution.

With introduction of so called “surgical reparation” of the flue wall and pit bottom, it is possible to replace only damaged part of the brickwork without changing the whole wall. This reduces maintenance time and cost significantly.

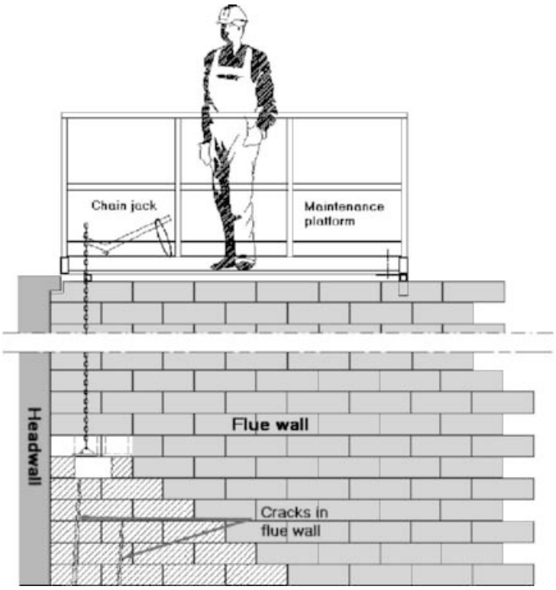

Figure 9. Schematic drawing of surgical reparation of the flue wall cracking in the bottom corner of pit. Damaged part of brickwork is demolished and rebuild while the rest of the wall is stabilised by the chain jack and maintenance platform.

Refractory Lifetime and Consumption

The combination of improved understanding of the stress build-up mechanisms (FE-modelling) and the operational experience has resulted in a major leap in the flue wall lifetime. This is exemplified by the life time distribution figures for the latest rebuilt of furnace #3 in 2004. The foreseen refractory maintenance consumption over the furnace lifetime of 20 years is close to 5 kg/tonnes baked anodes.

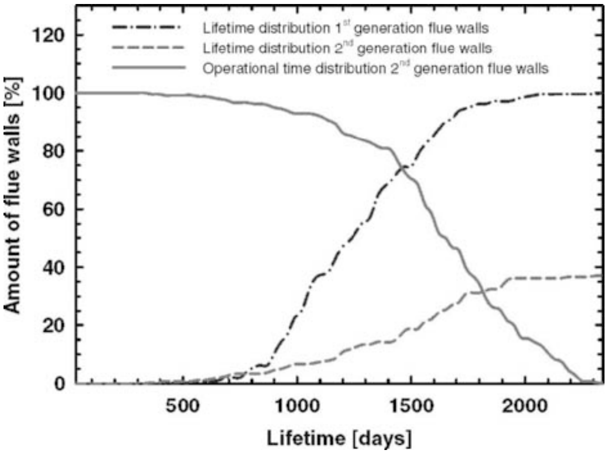

Figure 10. Lifetime distribution of 1st and 2nd generation of the flue walls at furnace #3.

The surgical maintenance of the flue walls gives a potential for further reduction of the maintenance cost and increased lifetime of furnace brickwork.

Furnace Design vs. Process Safety

The inherent design of the closed top baking furnaces enables the fire zones to be set to a safe state in case of loss of draft situations. The routines includes flaring of the pitch volatiles until an oxygen excess situation are re-established in the fire zones.

When surplus air is established in all fires, the normal operation can be re-established without any risk of forming flammable gas mixtures by restart of the draft.

The inherent design feature of the furnace, which allows the fire zones to be set to a safe state, forms the basis for the SIL2[a]-classified safety system of the HAL-furnace [14].

## Conclusion

Increased potline amperage and expanded metal production in ÅSV during the 80's resulted in a demand for larger anodes. As a consequence, a new HAL anode baking furnace concept was developed and introduced through 1st and 2nd generation evolutionary phase.

All rebuild changes were done with strong focus on the investment cost. The main dimensions of new baking furnace were adapted to the existing building with minor changes to the existing infrastructure. The reduced amount of installed refractory and the short reconstruction time without production loss had a positive effect on overall project cost.

Design modifications for the HAL 1st generation furnace were done without major dimensional changes on existing concrete tub and the distance between head walls.

Main features of the HAL 2nd generation furnace comprised of a partial renewal of the concrete tub. Adjustments of the length and width of the pit geometry were tailored to the anode dimension without the alteration of factory building.

After retrofit, the new HAL furnace section dimensions allowed operation with higher section load and production of larger anodes. New design of brickwork structures and less refractory tonnage installed enabled operating with faster fire advance cycles. As a result, considerable increase in the furnace capacity was achieved.

New section covers with integrated auxiliary equipment were developed in order to fit the new furnace section dimensions.

The Hydro furnace concept has adopted a continuous refractory maintenance strategy. This includes a routine follow up of the brickwork condition, and precise planning of the maintenance work with minor production disturbance. Developed surgical maintenance reparation methods assure maximum extend of the refractory brickwork life time and minimal maintenance cost.

Benefits from continuous refractory maintenance strategy are reflected in positive way on extended refractory lifetime of the flue walls and low specific consumption of refractory material.

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[a] Safety integrity level