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Äspö Hard Rock Laboratory

Retrieval of deposited canister for spent nuclear fuel

Freeing – slurrying of saturated bentonite buffer around a canister at Äspö HRL

Technology, equipment and results in connection with freeing for the Canister Retrieval Test

Bo Nirvin
Svensk Kärnbränslehantering AB

January 2007

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

Äspö Hard Rock
Laboratory

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Keywords: Buffer, Freeing, Removing of bentonite, Hydrodynamic removal, Dewatering

Abstract

Svensk Kärnbränslehantering AB, SKB (the Swedish Nuclear Fuel and Waste Management Co), works continuously to develop methods for deposition of spent nuclear fuel in a deep repository.

The purpose of the deep repository is, after encapsulation, to dispose of the spent nuclear fuel in deposition tunnels at a depth of about 500 m in the Swedish basement rock.

The fuel is enclosed in copper canisters, which are deposited one by one in holes bored vertically in the bottom of the deposition tunnels and surrounded by bentonite clay.

The tunnels are sealed and groundwater seeps into the deposition holes. The bentonite swells and is transformed into a plastic clay that fills up the space around the canister. The swelling also gives rise to a fairly high pressure in the bentonite clay.

It may for various reasons be necessary to retrieve one or more canisters from their deposition holes. Before a deposited canister with spent nuclear fuel can be retrieved it must first be freed. **Freeing** involves removing the buffer around the canister, in which a fairly high pressure has developed. Dismantling of the plug and removal of the backfill material in a deposition tunnel has not been studied in this connection.

In previously executed development projects, four different types of techniques have been studied for freeing of a canister surrounded by a bentonite buffer in a vertical deposition hole: *mechanical removal, hydrodynamic removal, thermal removal* and *electrical removal*.

Comparison and evaluation of these techniques resulted in the choice of *hydrodynamic removal* as a technique for freeing the canister.

The hydrodynamic technique used for slurrying of the buffer entails flushing the buffer with a weak calcium chloride solution under turbulent flow conditions, causing its high mechanical integrity to be reduced to the low mechanical integrity of the liquid slurry. This hydrodynamic technique acts on the buffer both chemically and mechanically.

During the slurrying process, the generated slurry is washed away, dislodging the canister and making it accessible for the following step in the retrieval operation.

A special tool has been developed for hydrodynamic removal. The one part of the tool is characterized by its ability to bring about an effective redistribution of the liquid volume by means of a propeller. The other part is characterized by its ability to lift up the liquid and bring about movement internally or out of the deposition hole by means of a suitably designed suction nozzle and pumps.

The **freeing process** integrates two sub-processes: slurrying of the bentonite buffer and reduction of the volume of the generated sludge by dewatering in a decanter centrifuge. The two steps of the freeing process, *slurrying* and *dewatering*, are carried out in one integrated process.

In previous full-scale tests, a process time of about 210 hours has been determined for freeing of a canister embedded in a bentonite buffer weighing about 16,500 kg.

The results of the slurrying tests show that the efficiency of the slurrying process is about 90 kg $_{\text{dry bentonite}}$/hour.

Energy consumption with this process time is about 23,000 kWh/deposition hole *(slurrying + dewatering*). *Energy consumption* in the main step of the technique (*slurrying*) is only about 3,000 kWh/deposition hole.

After installation and fine adjustment of the freeing equipment in the Äspö HRL's retrieval tunnel, remaining buffer around the deposited copper canister was to be removed using the hydrodynamic technique. In trouble-free operation, the hydrodynamic technique worked very well for dissolution and removal of bentonite.

During freeing in this special retrieval operation, a large number of disturbances occurred caused by equipment installed in and around the bentonite such as tubes, cables, wetting mats, strings etc. In actual deposition, the buffer will consist solely of pure bentonite.

Due to the number of interruptions caused by the aforementioned disturbances, a correct assessment of the efficiency of the hydrodynamic process, based on the freeing of the canister deposited in the Retrieval Niche, is not possible. Some idea of its efficiency in one day of trouble-free operation can be deduced, however. The total data collection time was 7 hours and 2 minutes. During this time, 656 kg of bentonite was slurried and dewatered, giving a slurrying efficiency of about 93.3 kg of bentonite/hour. With this efficiency, it should be possible to free a copper canister embedded in a bentonite buffer (2 blocks above the canister and 10 rings covering the entire canister height) of about 16.5 tonnes in just under 180 hours.

Compared with the predicted result of 200–220 hours obtained from the full-scale laboratory trials of freeing of a copper canister, a slightly better result has been achieved.

In trouble-free freeing of a copper canister in an authentic environment, there are great opportunities for improving the process and the equipment. With a well developed process and efficient equipment, the freeing time can approach the theoretical maximum capacity of the chemistry for disintegrating the bentonite. The time to free a canister completely embedded in a bentonite buffer can probably be reduced considerably.

In the completed freeing trial, we have shown that the method works, which was the main purpose of this project.

Sammanfattning

Svensk Kärnbränslehantering AB, SKB, arbetar kontinuerligt med att utveckla metoder för deponering av använt kärnbränsle i ett djupförvar.

Syftet med djupförvaret är att efter inkapsling slutförvara det använda bränslet i deponeringstunnlar på cirka 500 m djup i det svenska urberget.

Bränslet är inneslutet i kopparkapslar som deponeras en och en i hål borrade vertikalt i botten av deponeringstunnlarna och omges av bentonitlera.

Tunnlarna försluts och grundvatten tränger in i deponeringshålen, bentoniten sväller och övergår till en plastisk lera som fyller upp hela utrymmet runt kapseln. Svällningen medför också att ett ganska högt tryck uppstår i bentonitleran.

Det kan av skilda skäl uppstå behov av att återta en eller flera kapslar från sina deponeringshål. För att återta en deponerad kapsel med använt kärnbränsle måste den först friläggas. **Friläggning** innebär att bufferten som utvecklat ett relativt högt tryck kring kapseln avlägsnas. Rivning av plugg och borttaggande av återfyllnadsmaterialet i en deponeringstunnel har inte studerats i detta sammanhang.

I tidigare genomförda utvecklingsarbeten har fyra olika typer av tekniker studerats för friläggning av en kapsel som är omgiven av en bentonitbuffert i ett vertikalt deponeringshål: *mekanisk bearbetning, hydrodynamisk avverkning, termisk påverkan* och *elektrisk påverkan*.

Jämförelse och utvärdering av dessa tekniker resulterade i att tekniken för friläggning valdes inom teknikområdet *hydrodynamisk avverkning*.

Den för uppslamningen använda hydrodynamiska tekniken innebär att en svag kalciumkloridlösning spolas och sköljs över bufferten under turbulenta flödesförhållanden varvid dess höga mekaniska integritet reduceras till det flytande slammets låga mekaniska integritet. Denna hydrodynamiska teknik påverkar bufferten både kemiskt och mekaniskt.

Under uppslamningen förs det genererade slammet omgående bort och därmed blir den omslutna kapseln lösgjord och tillgänglig för nästkommande arbetsmoment i en återtagsoperation.

För den hydrodynamiska tekniken har ett speciellt verktyg utvecklats. Ena delen av verktyget karakteriseras av att kunna åstadkomma en effektiv omfördelning av vätskevolymen med hjälp av propellerdrift. Den andra delen karakteriseras av att kunna lyfta upp vätskan och åstadkomma förflyttning internt eller ut ur deponeringshålet med hjälp av ett lämpligt utformat sugmunstycke och pumpar.

Den för friläggning utvecklade **friläggningsprocessen** integrerar två delprocesser: uppslamning av bentonitbufferten samt reducering av det genererade slammets volym genom avvattning i en dekantercentrifug. Friläggningens två arbetsmoment, *uppslamning* och *avvattning*, utförs i en integrerad process.

Vid tidigare fullskaletester har en processtid på cirka 210 timmar identifierats för friläggning av en kapsel inbäddad i en bentonitbuffert på cirka 16 500 kg.

Resultaten från uppslamningstesterna visar att effektiviteten vid uppslamning är cirka 90 kg $_{\text{torr bentonit}}$/timme.

Energiåtgången med denna processtid blir cirka 23 000 kWh/deponeringshål (*uppslamning* + *avvattning*). För teknikens huvudmoment (*uppslamning*) blir *energiåtgången* endast cirka 3 000 kWh/deponeringshål.

Efter installation och intrimning av friläggningsutrustningen i Äspölaboratoriets återtagstunnel skulle resterande buffert kring den deponerade kopparkapseln avlägsnas med den hydrodynamiska tekniken. Vid störningsfri drift fungerade den hydrodynamiska tekniken mycket väl vid upplösning och borttransport av bentonit.

Vid friläggningen för denna speciella återtagsoperation förekom ett stort antal störningar orsakade av i och kring bentoniten installerad teknisk utrustning som rör, kablar bevätningsmattor, snören m.m. Vid verklig deponering kommer bufferten att bestå endast av ren bentonit.

På grund av mängden avbrott orsakade av ovanstående störningar är en korrekt bedömning av den hydrodynamiska processens effektivitet, med utgångspunkt från friläggningen av den i Återtaget deponerade kapseln, inte möjligt. En viss uppfattning av effektiviteten vid en dags störningsfri drift kan dock utläsas. En sammanhängande tid för datainsamling var 7 timmar och 2 minuter. Under denna tid uppslammades och avvattnades 656 kg bentonit vilket ger en uppslamningseffektivitet av ca 93,3 kg bentonit/timma. Med denna effektivitet bör en kopparkapsel inbäddad i en bentonitbuffert (2 block över kapseln och 10 ringar täckande hela kapselhöjden) på ca 16,5 ton kunna friläggas på knappt 180 timmar.

Jämfört med ett prognostiserat resultat på 200 – 220 timmar från de laboratoriemässiga fullskaleförsöken med friläggning av en kopparkapsel så har ett något bättre resultat uppnåtts.

Vid störningsfri friläggning av en kopparkapsel i autentisk miljö finns stora möjligheter att vidareutveckla processen och utrustningen. Med en väl utvecklad process och effektiv utrustning kan tiden för friläggning närma sig tiden för kemins maximala förmåga att desintegrera bentoniten. Tiden för friläggning av en kapsel, fullständigt inbäddad i en bentonitbuffert, kan troligen reduceras åtskilligt.

Vi har med genomfört friläggningsförsök visat att metoden fungerar vilket var huvudsyftet med detta projekt.

Contents

1 Background and purpose

Svensk Kärnbränslehantering AB, SKB (the Swedish Nuclear Fuel and Waste Management Co), works continuously to develop methods for deposition of spent nuclear fuel in a deep repository.

The purpose of the deep repository is to dispose of the spent nuclear fuel after encapsulation.

The deep repository for encapsulated fuel consists of deposition tunnels at a depth of about 500 m in the Swedish basement rock. The fuel is enclosed in copper canisters with a steel insert. The copper shell provides good corrosion resistance, while the steel insert provides mechanical strength.

The canisters are deposited one by one in holes bored vertically in the bottom of the deposition tunnels and surrounded by bentonite clay. This deposition method goes under the name KBS-3V, where the V stands for vertical deposition holes. The bentonite clay holds the canisters in place and prevents throughflow of groundwater. This prevents or retards the transport of substances to and from the canister.

The bentonite is applied in the form of compacted blocks and rings that surround the canister. The arrangement is illustrated in Figure 1-1 below. First a block is placed in the bottom of the hole and rings are stacked on top to a height corresponding to the height of the canister. After the canister has been placed inside the bentonite rings, additional bentonite blocks are placed on top of the canister to a height of about 1.5 m.

After the tunnel has been sealed, groundwater penetrates into the deposition hole, and the bentonite swells and is transformed into a plastic clay that fills up the entire space around the canister. The swelling also gives rise to a fairly high pressure in the bentonite clay, which contributes to the desired function as a barrier between canister and rock.

Svensk Kärnbränslehantering AB's (SKB, the Swedish Nuclear Fuel and Waste Management Co) programme for implementation of a deep repository for spent nuclear fuel also includes the possibility of retrieving deposited canisters.

It may for various reasons prove necessary to retrieve the canisters from their deposition holes. The deep repository must be designed so it is possible to retrieve deposited canisters. However, this requirement may not lead to any deterioration in the long-term performance of the repository. Retrieval may prove necessary for all canisters in the first stage of the deep repository if another method for disposing of or utilizing nuclear fuel should be preferred in the future. Retrieval of a large number of canisters in a later phase must also be possible. It must also be possible to retrieve an individual canister from a deposition hole if one or more of the safety requirements are not met.

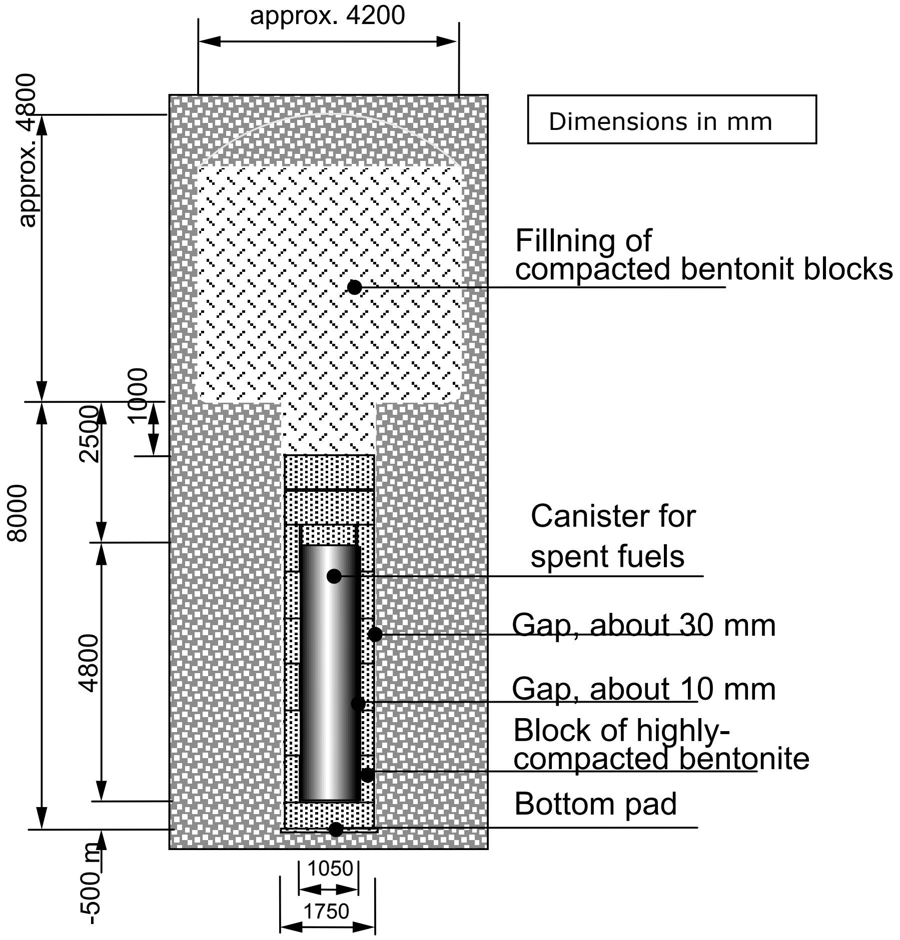


Figure 1-1. *Cross-section of deposition tunnel, schematic drawing.*

Before a deposited canister with spent nuclear fuel can be retrieved it must first be freed. **Freeing** involves **slurrying** and removing the buffer around the canister, in which a fairly high pressure has developed, so much that its grip is released or loosened**.** The high mechanical integrity of the buffer, which has been achieved by water saturation and swelling, is reduced to the low mechanical integrity of the liquid slurry, thereby dislodging the canister and making it accessible for the following step in the retrieval operation.

The **technique** identified for slurrying is a hydrodynamic technique which entails flushing the buffer with a weak calcium chloride solution under turbulent flow conditions and immediately removing the generated slurry from the slurrying chamber. This hydrodynamic technique acts on the buffer both chemically, due to the interaction of the salt solution with the montmorillonite in the bentonite, and mechanically due to the energy content of the slurrying liquid.

The slurrying process entails flooding the front face of the bentonite buffer with a salt solution so that the free surface of the static liquid volume is at least 1 metre above the top end of the canister. The hydrodynamic tool is then installed in this static liquid volume.

The type and design of the hydrodynamic tool has been identified in previous studies /1/ and /2/. The one part of the tool is characterized by its ability to bring about an effective redistribution of the liquid volume by means of a propeller. The other part is characterized by its ability to lift up the liquid and bring about movement internally in the static volume or out of it by means of a suitably designed suction nozzle and pumps.

The **freeing process** integrates two sub-processes: slurrying of the bentonite buffer and reduction of the volume of the generated sludge by dewatering in a decanter centrifuge.

Retrieval, regarded as a technical operation, represents different levels of technical difficulties depending on the saturation level of the surrounding bentonite buffer. When the buffer has become saturated and a respectably high swelling pressure has developed, the operation becomes most demanding from a technical and economic point of view /3/. The developed freeing process is intended for retrieval from a completely saturated bentonite buffer whose size/volume is categorized as follows:

- complete buffer: fills up the free space around the deposited canister and the entire space between the upper end of the canister and the floor of the deposition tunnel, and thereby contains about 21 tonnes of bentonite,
- reduced buffer: fills up the free space around the deposited canister and approximately one metre of the volume between the upper end of the canister and the floor of the deposition tunnel, and thereby contains about 16.5 tonnes of bentonite (the other – upper – half of this volume is removed by another technique, for example “digging”).

This report describes the freeing of a full-scale experimental canister that has been emplaced in a deposition hole at the Äspö HRL.

The main objective was to verify the chosen technique for freeing of a copper canister embedded in a saturated bentonite buffer. Any improvements and modifications of equipment and method that can be identified during the freeing work will be implemented in the process equipment and the method.

2 Preceding development work

In previously executed development projects, four different types of techniques have been studied for freeing of a canister surrounded by a bentonite buffer in a vertical deposition hole: *mechanical removal, hydrodynamic removal, thermal removal* and *electrical removal*.

Comparison and evaluation of these techniques resulted in the choice of *hydrodynamic removal* as a technique for freeing the canister.

The specific design of the technique is based on flushing of the front face of the bentonite buffer with a *salt solution* (containing several percent by weight calcium chloride) using a *low-pressure hydrodynamic technique.* The technique creates a chemical/mechanical action that results in radical degradation of the high mechanical integrity of the buffer.

The technique selected for freeing consists of two separate techniques: Firstly a technique for *slurrying* of the bentonite buffer (the buffer's high mechanical integrity is converted to the properties of the liquid slurry), and secondly a technique for *dewatering* of generated slurry.

The central element of the freeing technique is *slurrying*, while the sole purpose of *dewatering* is to reduce the handling difficulties caused by the large volume of slurry in the deposition hole.

The *freeing efficiency* is determined by the slurrying efficiency (the dewatering efficiency is adjusted according to the slurrying efficiency). The results of the tests on a laboratory and pilot scale gave a predicted **process time** for freeing of a canister under authentic conditions (buffer properties, volume) of 210–220 hours for a "reduced buffer".

Dewatering of slurry can be done in several different ways (pressing, sieving, sedimentation, with or without filter aid, with or without flocculant)) /5/. Completed studies and evaluations indicated that forced sedimentation (decanting) is a suitable technology.

The *freeing equipment* developed before and during the full-scale tests contains components for both slurrying and dewatering.

The freeing equipment, at the development level used for the concluding full-scale tests, constitutes the *design core* for the future (standard) equipment that has now been used for retrieval/freeing of deposited canisters in the Äspö HRL.

The developed equipment will be further improved on the basis of the experience gained when the equipment is used in the Äspö HRL.

3 Retrieval

3.1 Introduction

Deposited canisters may need to be retrieved from the deposition holes for various reasons. In the case of individual canisters, the reason may be suspicion of damage that may have occurred during deposition. On a larger scale, retrieval may be done if the selected site turns out to be completely unsuitable or if another disposal method has been decided on at a late stage.

When a canister has been deposited with its buffer, water will gradually wet the buffer. The water makes the bentonite swell and gradually increases its grip on the canister. As long as the bentonite blocks are dry the canister can easily be lifted out of its hole with the deposition machine. The swollen bentonite later holds the canister in such a firm grip that the bentonite has to be removed to enable the canister to be retrieved.

One factor that complicates the retrieval of a canister containing spent fuel is the radiation from the canister, which requires radiation shielding during the procedure. In the hydrodynamic technique, the salt solution or the liquid with slurry serves as sufficient radiation shielding during the work, provided it covers the canister up to a certain level.

3.2 Retrieval process

The handling procedure during retrieval of a deposited canister is greatly affected by when retrieval is done. Retrieval immediately after deposition can be done with the equipment used to deposit the canister. The process is most difficult when the buffer material has begun to swell. The buffer material holds the canister in a firm grip, making it impossible to lift the canister out of the deposition hole. The canister must then be freed by removing the bentonite using a suitable method.

After the bentonite has absorbed water it becomes more difficult to handle. Due to the swelling of the bentonite different equipment is required, for example mechanical removal or chemical dissolution of the bentonite with liquid.

Removal of a saturated and swollen bentonite can be time-consuming with the hydrodynamic technique, but no great difficulties have been observed and are not expected to occur in the future either. After the bentonite has been removed the canister can be handled with the radiation-shielded deposition machine.

3.3 Freeing

Retrieval of a deposited canister entails that the canister is moved from its deposition position to a radiation-shielded environment outside the deposition hole. The basic prerequisite for retrieval is that the canister is not held in place by additional forces besides the canister’s own weight.

This means that the canister must be freed from the grip of the surrounding bentonite buffer.

Freeing the canister from the surrounding bentonite buffer is a complex operation dependent on various factors such as accessibility, safety, space and, not least, suitable technology.

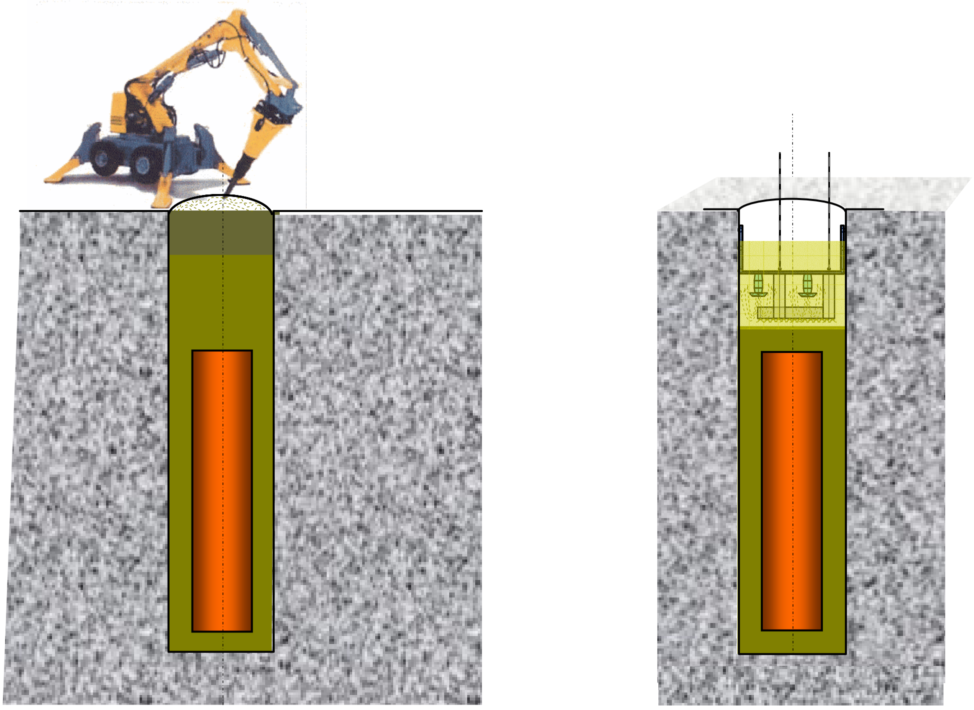


Figure 3-1. *Freeing by a combination of hydrodynamic and some other technique.*

The degree of difficulty of the operation is determined by the saturation of the surrounding buffer, which is in turn dependent on the time that has elapsed between deposition and retrieval.

The longer this time, the greater the saturation of the buffer and thereby the greater the difficulty of the freeing operation.

Making a canister accessible and movable in a deposition hole entails emptying the upper cylindrical part of the hole, between the mouth of the hole and the upper end of the canister, completely of its contents, and separating the mantle surface of the canister from the buffer. A complete freeing can be carried out with a combination of a hydrodynamic technique and another technique, such as digging (see Figure 3-1 above).

4 Techniques

4.1 Hydrodynamic technique

The hydrodynamic technique and its concrete design are characterized by relatively low energy consumption (*slurrying* < 15 kW, *dewatering* ≈ 110 kW) and by good prospects of being able to build a system (freeing equipment) with high *system efficiency* that is an expression of high *technical performance* and *reliability.*

The desired *technical performance* of the system has been achieved by the use of several identical machine components (pumps, mixers) for the same function. This ensures high *probability of function, availability* and thereby *reliability.*

Assessment of the system based on the various components of *reliability* (*functionality, maintainability, maintenance reliability*) also confirms the assessment of good prospects of high *system efficiency.*

4.1.1 Slurrying

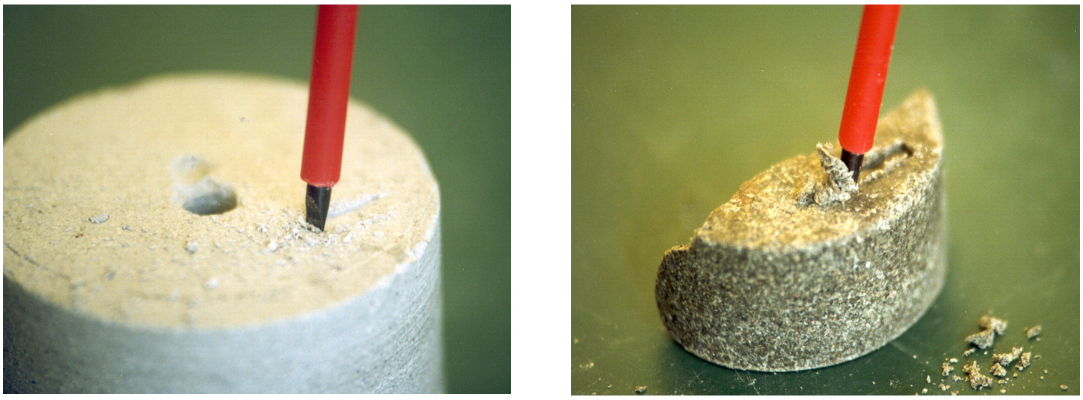
During *low-pressure hydrodynamic removal* , the high mechanical integrity of the water-saturated bentonite buffer is converted to the properties of the liquid slurry.

The mechanical properties of the water-saturated buffer can be elucidated from the properties of the compacted, unsaturated buffer components (rings and blocks). The properties were determined in buffer components that were made of bentonite MX-80 with uniaxial compaction, compaction pressure about 100 MPa, water ratio about 16%, density about 2.1 g/cm^3):

- modulus of elasticity (E): 321.7 MPa,
- Poisson's ratio (ν): 0.21,
- stress at break (σ_{BREAK}): 2.4±0.8 MPa,
- strain at break (ε): 0.6%.

Water saturation in a closed volume (after deposition in a deposition hole) entails firstly a change in the properties of the material (the bentonite) from moderately linearly elastic (highly compacted bentonite before swelling, see properties above) to plastic, and secondly a buildup of internal pressure (swelling pressure).

The sum effect of these two changes is that the lower mechanical properties of the plastic behaviour do not appear due to the high swelling pressure. Only a small relaxed volume of limited depth at the surface where the buffer's grip on the bentonite is broken (where the swelling pressure can drop) can exhibit the plastic behaviour. Image 4-1 below illustrates this situation.



a. b.

Image 4-1. *"Shaving" in bentonite: a. unsaturated, b. saturated. (Photo: Pal Kalbantner, ÅF).*

The material properties of the water-saturated bentonite (mechanical integrity, the high "stickiness" of the relaxed volume, content of abrasive components, etc.) and other additional properties (energy consumption, latent risk of causing canister damage, sensitivity to canister's actual position, hazardous properties of the resultant by-product, etc.) were the reasons for the conclusions that water-saturated bentonite buffer should be removed by low-pressure hydrodynamic *slurrying*.

4.1.2 Dewatering

Slurrying that is carried out using studied and identified operating parameters results in large volumes of slurry (about 300 m^3 per "reduced buffer").

In order to reduce the associated space and handling requirements, the primarily generated large slurry volumes should be kept within the process and only a reduced volume should be "released" outside. For this purpose, *dewatering* is integrated in the hydrodynamic technique and comprises the second main step after *slurrying*.

The most natural way to reduce the volume of the slurry is mechanical dewatering by means of forced sedimentation in a decanter centrifuge.

4.2 Slurrying

Low-pressure hydrodynamic removal is based on flushing of the front face of the bentonite buffer with a *salt solution*. The salt solution and its concentration ($CaCl_2$ solution with a concentration of $4\%_{\text{weight}}$) have been determined in previous development work based on the following properties:

- the calcium chloride solution's verified ability to bring about disintegration of the bentonite,
- the calcium chloride's verified ability to facilitate the flocculation of particles in sodium-based slurry.

The principal components of the slurrying equipment are pumps (3), mixers (3) and a special annular nozzle. With their help the compacted bentonite is converted to slurry.

The *low-pressure hydrodynamic slurrying* process, and the equipment that works with this technique and is made up of the principal components mentioned above, have been investigated on the basis of three fundamental criteria: *usability*, *feasibility* and *efficiency*.

4.2.1 Usability

The *usability* criterion entails a requirement on the capability of both the technique and the equipment to maintain *system efficiency* at the desired level, under the conditions judged to be characteristic for the planned deep repository.

A previous investigation revealed significant advantages for the selected technique compared with the other investigated techniques, namely:

- the simultaneous chemical and mechanical action erodes the compacted bentonite and maintains continuity,
- the secondary function of the salt solution/slurry (radiation protection); the primary function is to erode/carry the bentonite),
- low risk of canister damage,
- low sensitivity to the position of the canister in the deposition hole,
- no need for bulky load-bearing or positioning structural parts (compared with equipment that works with one of the mechanical freeing techniques).

4.2.2 Feasibility

The *feasibility* criterion entails a requirement that the technique should permit construction and operation of a realistic (based on today's technical and economic preferences) system or process with high *system efficiency*.

A previous investigation identified the following properties of the equipment and the process:

- the process components represent a mature technology in the form of pumps, mixers etc.; this means that the complexity level of the equipment is low,
- simple to introduce similar machine components for the same function to achieve reliability,
- low energy consumption.

4.2.3 Efficiency

For measurement of the time needed for the slurrying of a given amount of bentonite, tests have been carried out on three different scales: laboratory, pilot and full scale. Due to the high scale dependence of the required process time, the figures from the pilot-scale tests can only serve as a basis for an estimation of the time required for a full-scale (authentic) slurrying, while the figures from the full-scale tests can be regarded as directly applicable (adequate).

The figures from the full-scale tests suggest a process time of about 210 hours for the freeing of a canister embedded in a "reduced bentonite buffer" with a total bentonite weight of about 16,500 kg.

Based on this process time, *energy consumption* is about 23,000 kWh/deposition hole for the reduced reference technique (*slurrying* + *dewatering*). The *energy consumption* for the main step of the reference technique (*slurrying*) is only about 3,000 kWh/deposition hole.

4.3 Dewatering

Bentonite slurry is a suspension consisting of a solid phase and a liquid phase.

Filtration, sieving and sedimentation techniques can be used for dewatering of suspensions. The technique used can then be supplemented by the use of various additives such as solid or dissolved filter aids (coagulants, flocculants).

4.3.1 Dewatering techniques

Dewatering of slurry can be done in several different ways (pressing, sieving, sedimentation, with or without filter aid, with or without flocculant).

The principle of filtration and sieving for separation of the solid from the liquid phase in the suspension is the same. Both techniques entail allowing the liquid phase to pass through a partition while the solid phase remains on the input side. The passage can be forced by a drive gradient in the form of applied pressure. The difference between filtration and sieving lies in the design of the equipment.

Sedimentation utilizes gravity, either natural (*g*) or artificial (*ng*). Sedimentation based on natural gravity (*g*) requires large areas and has limitations in separated particle size and time for separation.

Sedimentation based on artificial gravity (rotation) has a lower area requirement and a lower limit for separated particle size. Gravity values in an ordinary process plant (decanter) lie between 2,000 and 4,000 *g*. A medium-sized decanter ($\varnothing_{\text{rotating drum}}$: 353 mm, length $_{\text{rotating drum}}$: about 860 mm, rpm: about 4,000 rev/min) is comparable to sedimentation based on natural gravity (*g*), which utilizes a sedimentation area of about 1,200 m^2.

4.3.2 Choice of dewatering technique

The conclusion of completed laboratory investigations is that the "bentonite slurry" suspension can be dewatered with or without additives using all investigated methods. A balanced appraisal of different results reveals the following three possibilities:

- dewatering in filter press (belt filter) under pressure using solid filter aid,
- dewatering in sieve belt press after pretreatment with flocculant,
- dewatering in decanter if the bentonite content of the entering slurry is permitted to be less than $20\%_{\text{weight}}$.

The choice has taken into account the fact that use of filter aid generally entails increased material handling. For example: use of inorganic filter aid entails handling of 30% more material per weight of dry bentonite.

In view of the above, dewatering methods accompanied by the use of additives have not been preferred in the dewatering technique.

Another reason for this judgement was that the chosen slurrying liquid (calcium chloride solution) already in itself has a positive dewatering property. The multivalency of the calcium ion (compared with the sodium ion in the bentonite) facilitates flocculation of the particles in the slurry.

Regarding the bentonite content of the generated slurry, it has been found that the process time for the freeing process is about 25% shorter if the bentonite content of the slurry is around $5\text{–}6\%_{\text{weight}}$, compared with a bentonite content of around $20\%_{\text{weight}}$.

The conclusion of these considerations regarding additives and the bentonite content of the slurry is that sedimentation with artificial forced gravity has been chosen for dewatering of bentonite slurry. Suitable process equipment for this purpose is a decanter.

A decanter with a horizontal drive shaft has been chosen for *dewatering* of bentonite slurry generated during *slurrying*.

4.4 Materials

4.4.1 Buffer

The buffer around the copper canister consists of bentonite blocks and bentonite rings. At the bottom, underneath the canister, is a block, around the canister are ten rings, and on top of the canister is another block.

The bentonite bodies, consisting of MX-80 bentonite, had been compacted by Clay Technology AB at Hydrowell AB in Ystad.

Approximate values for the bentonite bodies:
block – weight about 2,100 kg, of which about 1,800 kg of bentonite, Ø about 1,640 mm and height about 500 mm
ring – weight about 1,250 kg, of which about 1,070 kg of bentonite, $Ø_{\text{outside}}$ about 1,640 mm, $Ø_{\text{inside}}$ about 1,070 mm and height about 500 mm.

4.4.2 Solvent for slurrying

A salt solution ($CaCl_2$ solution with a concentration of $4\%_{\text{weight}}$) has been identified in previous development work as best suited for dissolution of the bentonite buffer /4/.

The choice of salt solution was based on the following two properties, the first of which is essential for slurrying while the second is good for dewatering:

- the calcium chloride solution's verified ability to bring about disintegration of the bentonite,
- the calcium chloride's verified ability to facilitate the flocculation of particles in sodium-based slurry.

5 The freeing equipment

The freeing equipment is put together so that the two steps in the freeing process, *slurrying* and *dewatering*, can be carried out in an integrated process.

The slurrying technique, which comprises the heart of the freeing process, brings about a chemical and a mechanical action on the buffer.

In order to initiate and maintain a chemical action, all that is required is to keep the bentonite buffer and the salt solution in contact with each other.

In order to generate and maintain a mechanical action, devices and components that impart kinetic energy to the liquid are required. The imparted energy is characterized by the impulse generated by the components used /2/.

The part of the equipment that is intended for slurrying is characterized by low-pressure hydrodynamic technique, while the part intended to reduce the volume of the generated slurry is characterized by the use of a decanter.

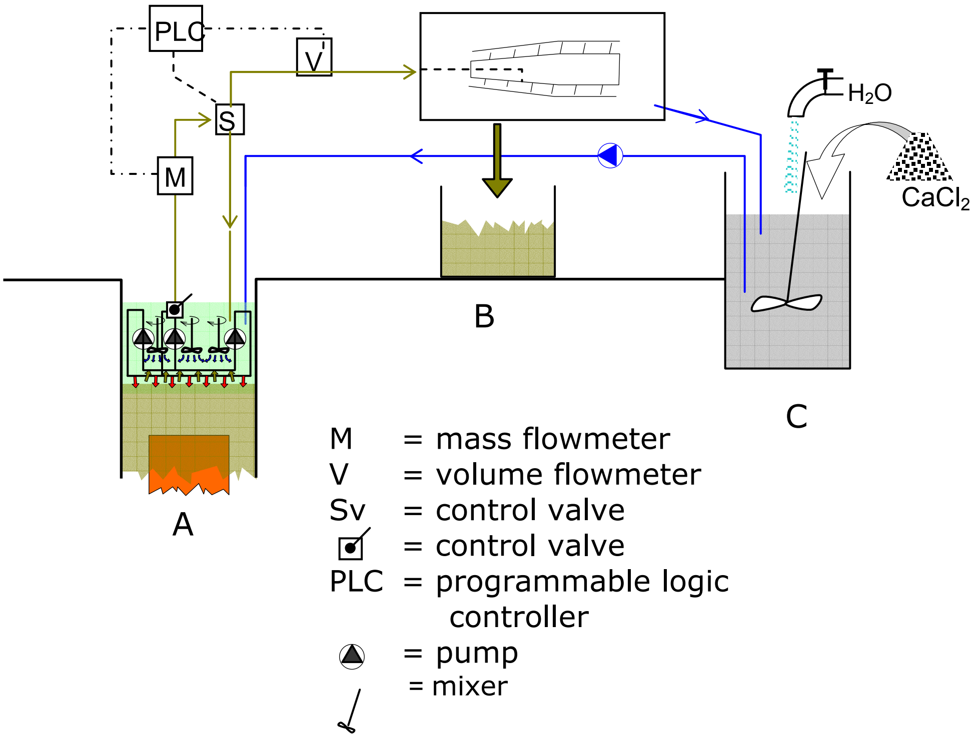


***Figure 5-1.** Schematic illustration of the freeing equipment. (Appendix 1).*

Part “A” corresponds to the deposition hole with a given volume of salt solution above the bentonite buffer and with the slurrying equipment in the working position. Part “B” corresponds to the decanter with discharge of dewatered bentonite and clarified liquid. Part “C” corresponds to the blending vessel for preparation of salt solution and checking of the clarified liquid.

5.1 Slurrying equipment

Full-scale slurrying tests were carried out in SKB's hard rock laboratory on Äspö between September 2002 and March 2003. A prototype slurrying system was built for these tests. The equipment was constantly modified and improved during the course of the tests. The most recent design was tested during the last two slurrying tests.

This prototype equipment comprises the model for the recommended slurrying system.

The principal process components in the slurrying system are three commercial mixers and a special annular nozzle with three integrated pumps.

The special nozzle contains an annular three-part chamber that works as an annular suction nozzle.

The pumps are integrated with the special nozzle so that the suction side of each pump only communicates with one suction chamber. The outlets from the pumps are directed against the front face of the buffer. The outlet from one pump is furthermore fitted with a branch that leads one stream to the mass flow sensor and, if necessary, further to the dewatering equipment.

The three mixers are installed in a vertical position with the generated liquid stream directed against the front face of the buffer.

The liquid level in the deposition hole is kept within set limits by the addition of more salt solution. This make-up input is regulated by the programmable logic controller (PLC).

Information on values of density, flow and level are obtained from appropriate instrumentation. Collected data are handled via an 8-channel INTAB AAC-2 PC-logger and recorded by appropriate software (EasyView 5 from Intab Interface-Teknik AB).

The data collection has been programmed so that the current values of the variables programmed for recording are read off every fifth second. A mean value is calculated from twelve such readings (which makes one mean value per minute), which is then recorded in the data file. When the data file is subsequently processed using the "Reduction" function, the recorded number is reduced to the desired number. For example, "Red 1/5" means that the printout contains values from every fifth minute.

5.1.1 Freeing equipment

(Appendix 1).

Solvent

A salt solution ($CaCl_2$ solution with a concentration of $4\%_{\text{weight}}$) has been identified in previous development work as best suited for dissolution of the bentonite buffer /3/.

Preparation vessel

Free-standing vessels should preferably be used for preparation of solvent and checking/adjustment of the salt content in the clarified liquid. The cylindrical vessels are made of glass-reinforced Reichhold 9100 vinyl ester:

- two vessels (∅ 1.6 m, H = 1.1 m) for preparation and storage of salt solution,
- one vessel (∅ 1.6 m, H = 1.1 m) for handling of clarified liquid

Nozzle

The special suction nozzle is made of titanium to resist attack by the salt solution and wear when hard abrasive particles continuously pass through the tool.

The inside diameter of the special annular nozzle is slightly larger than the outside diameter of the copper canister. Inside diameter: $\varnothing_{\text{inside}}$ = 1,090 mm. The outside diameter of the canister is 1,050 mm. The equipment must fit inside the deposition hole ∅ = 1,750 mm.

The special annular nozzle is composed of three segments as shown in Figure 5-2.

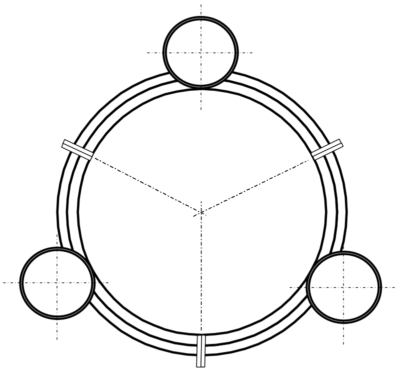


Figure 5-2. *Plan view – special nozzle composed of three segments.*

A pump is integrated in each segment so that the suction side of the pump only communicates with the suction chamber. This is accomplished by installing the pump to the suction chamber in the sleeve intended for this purpose (Images 5-1 and 5-2).

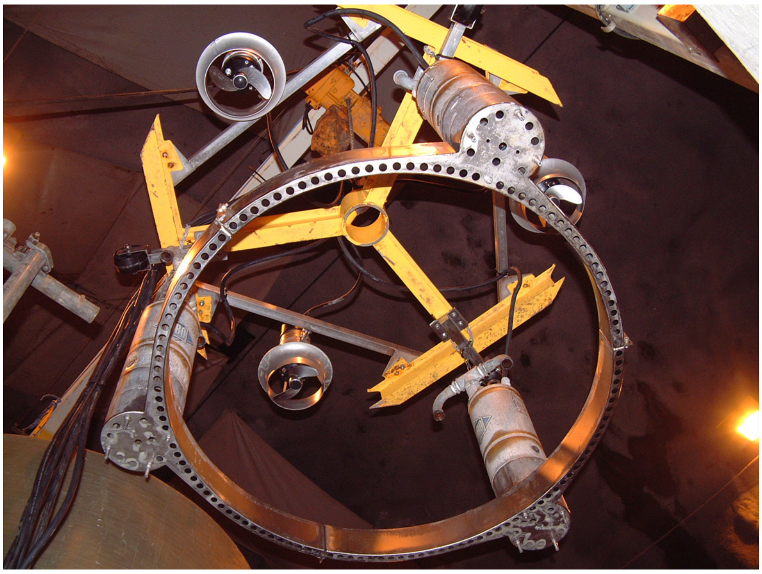


Image 5-1. *Suction nozzle, pumps connected to suction chambers.* (Photo: Bo Nirvin, SKB).

The suction nozzle's total suction area per segment should roughly correspond to the pump's total suction area (Image 5-2).

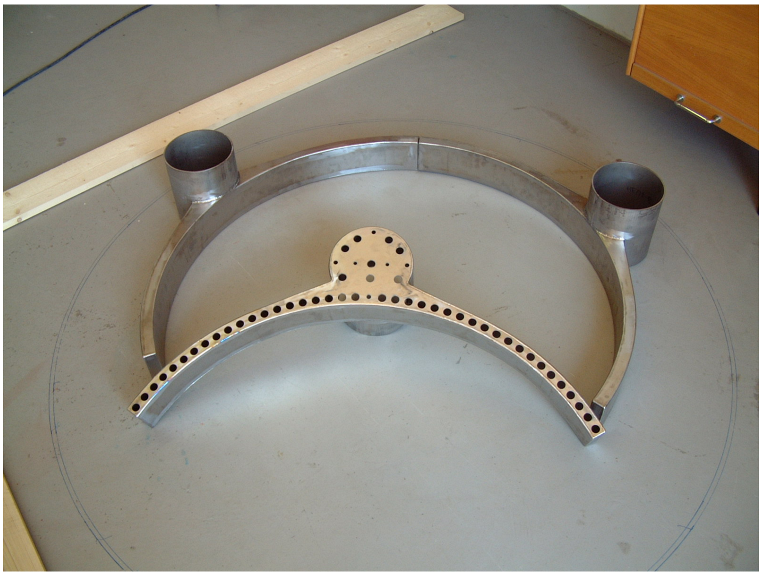


Image 5-2. *Suction nozzle, one segment is shown upside-down.* (Photo: Bo Nirvin, SKB).

Pumps

The selected pumps in the slurrying process are from Flygt, of type Bibo 2071 LT 212 (Image 5-3 and Figure 5-3). These pumps are conventional submersible drainage pumps.

Rated output power: 3 kW. Rotation: 2,800 r/min.

The pumps are used in the process for two different purposes. Firstly, each pump drives an internal circulation in the vessel via the annular nozzle, and secondly, one of the pumps expels generated slurry via a control valve to a connected discharge hose. Each pump has a maximum flow of about 16 l/s.

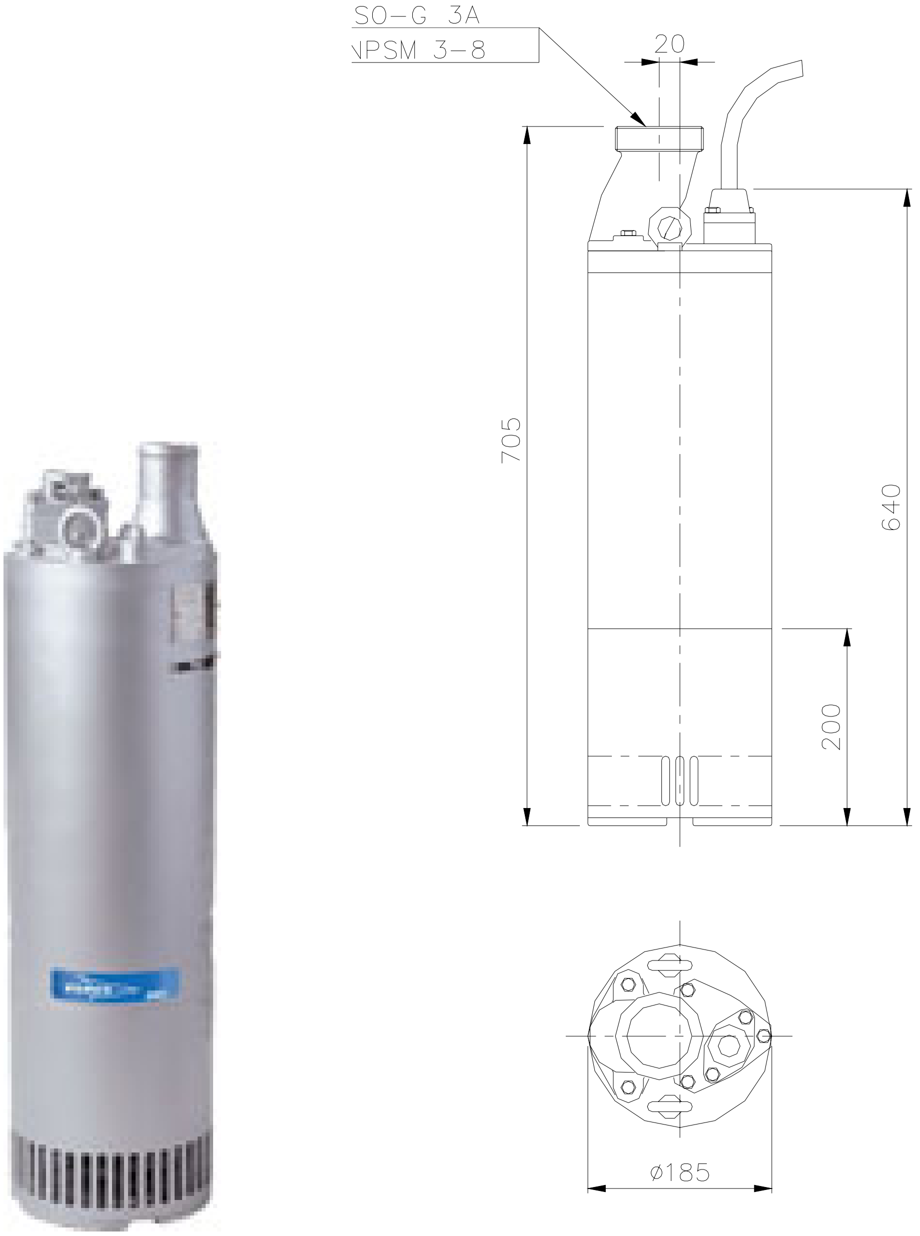
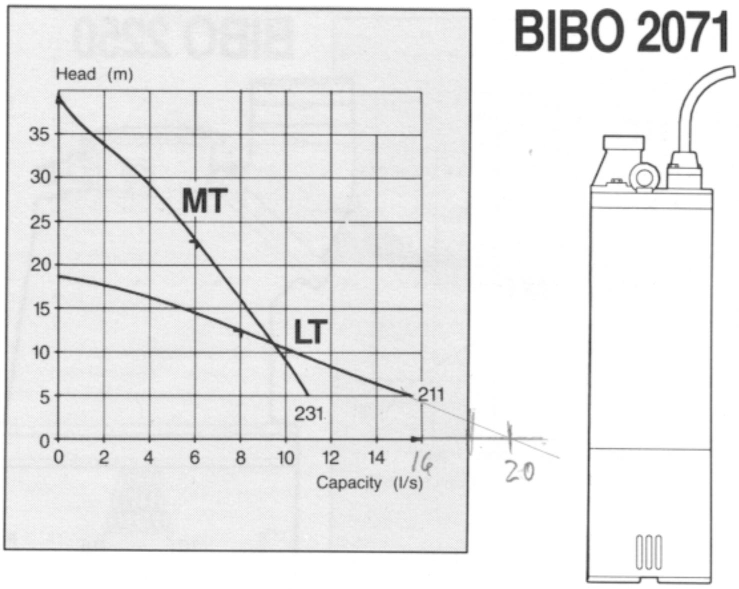


Image 5-3. *Pump, Flygt Bibo 2071 LT 212. (From Flygt product catalogue).*

The hydrodynamic prerequisites for internal circulation in the vessel are in part already provided by the annular geometry of the special nozzle. Pipe fittings necessary for this circulation are sized so that the increase in flow resistance is negligible.



Technical data	LT	MT
IMPELLER CODE	211	231
PHASE	3~	3~
SPEED OF ROTATION	2800 rpm	2800 rpm
OUTPUT POWER	3 kW	3 kW
INPUT POWER	3.9 kW	3.9 kW
WEIGHT	28 kg	31 kg

Figure 5-3. *Submersible pump BIBO 2071, pump curves and data.*
(From Flygt product catalogue).

Discharge pumping of slurry takes place with a flow rate that matches the capacity of the decanter. This means that the control valve and the connected discharge hose on the pump that pumps out the slurry are sized so that the pump's operating point does not deviate appreciably from that of the other pumps.

Mixers

The submersible pumps selected for the slurrying process are Flygt, type 4620.410-0012-18^{O} SJ with two-blade propeller and jet ring, made entirely of stainless steel (ASTM 316L) (Image 5-4 and Figure 5-4). These mixers are standard components with abrasion-resistant propellers and jet rings for a more concentrated liquid jet.

Rated output power: 1.5 kW. Rotation: 1,350 r/min.

According to the manufacturer (Flygt), the model used, equipped with a jet ring, develops a thrust of about 340 N.

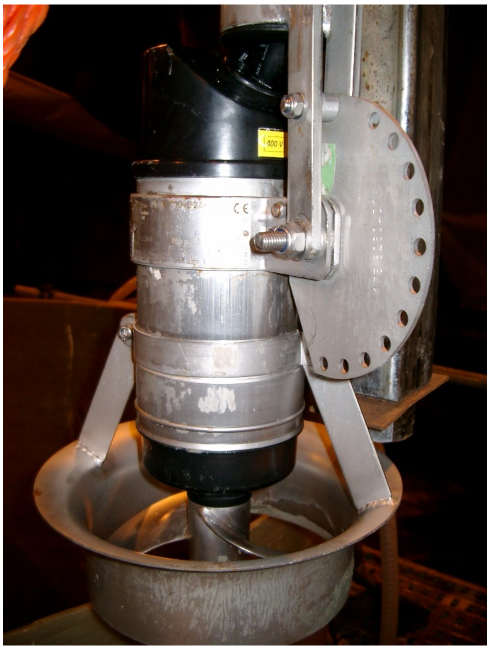


Image 5-4. *Mixer (Photo: Bo Nirvin, SKB)*

Due to the mixer's open mode of working and the fact that neither operating parameters nor positions (except vertical position) change during slurrying, the only factors that need to be taken into account are the required thrust and that they fit between the canister and the rock.

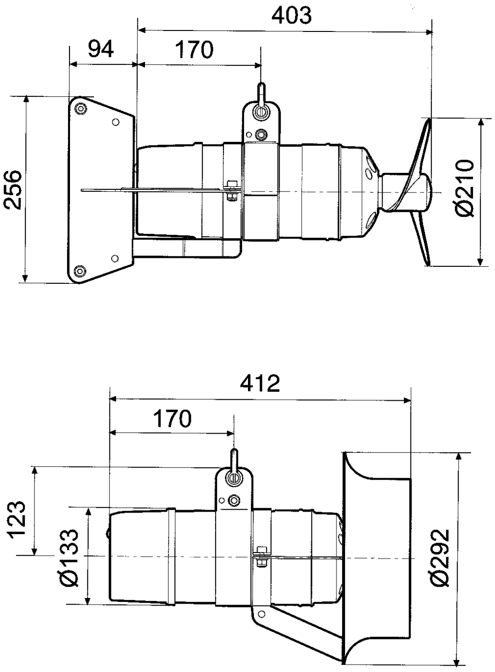


Figure 5-4. *Dimensions for mixer 4620 (all dimensions in mm).*
(From Flygt product catalogue).

Instrumentation

Different process variables that are needed for control and documentation of the process are measured with suitable instrumentation.

The density of the sludge is obtained from a mass flowmeter and temperature sensor (Krohne MFS 2000) via a signal converter (Krohne MFC 2000), while the volume of the discharged sludge is obtained from a separate electromagnetic volume flowmeter (Krohne IFS 4000) via a signal converter (Krohne IFC 110 F) (Image 5-5). The flowmeter/sensors are installed on the power feed line from the pump to the decanter centrifuge.

Image 5-5. *Krohne IFC 110 F and Krohne MFC 2000. (Photo: Bo Nirvin, SKB).*

The temperature of the liquid is measured by a temperature gauge built into the mass flowmeter.

The liquid flow rate from the mass flowmeter is distributed back to the slurrying chamber and to the dewatering equipment. The volume flowmeter is connected to the feed line after the distribution valve after the mass flowmeter.

Level sensor

The level of the salt solution and the generated slurry in the slurrying chamber is indicated by level sensors, which are simple, robust, encapsulated reed relays actuated by a float. These level sensors are installed in a splash protection tube on the slurrying tool (Image 5-6).

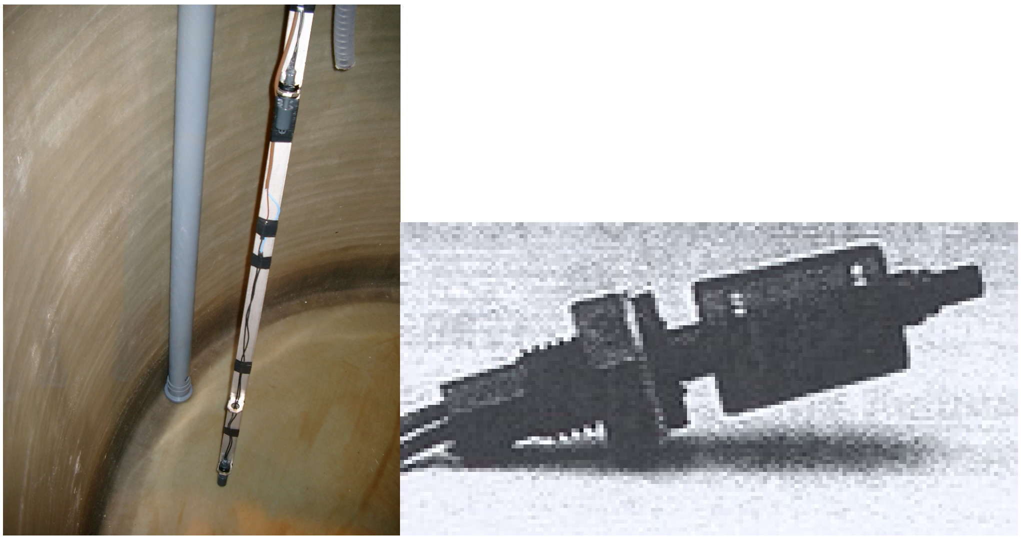
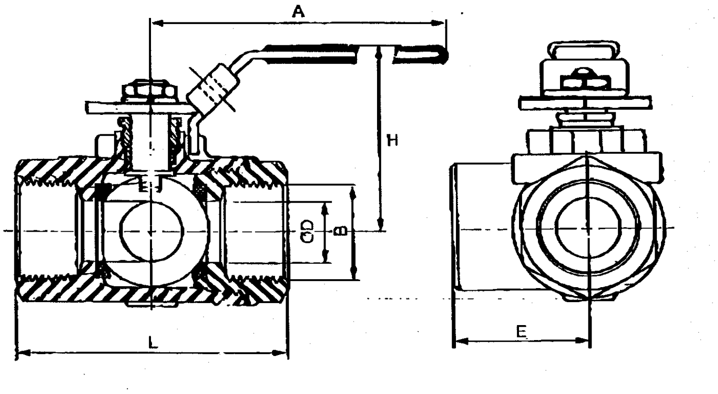


Image 5-6. *Level sensors, mounted on holders, removed from splash protection tube and close-up. (Photo: Bo Nirvin, SKB).*

Three-way valve

Water supply Valve from Ahlsell, type: ball valve/L-bored/hand-operated, article no. 907 12 83. Size: DN 25, material: stainless steel (Figure 5-5).



DN	B	D	L	A	H	E
25	1	20	82	125	65	41

Figure 5-5. *Three-way valve with dimensions. (From Ahlsell product catalogue)*

Secondary equipment

Monitoring of the continuity of the slurrying process and coordination of the different operating steps is managed by a programmable logic controller (PLC) from Siemens (Simatic S7-312 C), (Appendix 2). The controller's components are housed in an environmentally suitable cubicle which is located near the deposition hole.

Miscellaneous

Smaller pumps, valves and hoses for transport of salt solution and clarified liquid.

5.2 Dewatering equipment

Sedimentation under forced gravity has been chosen as a method for dewatering of generated bentonite slurry. Suitable process equipment that employs this technique is a decanter centrifuge.

Decanter centrifuge

The most common configuration of the decanter centrifuge is with a horizontal drive shaft.

The main function of a decanter centrifuge is illustrated in Figure 5-6.

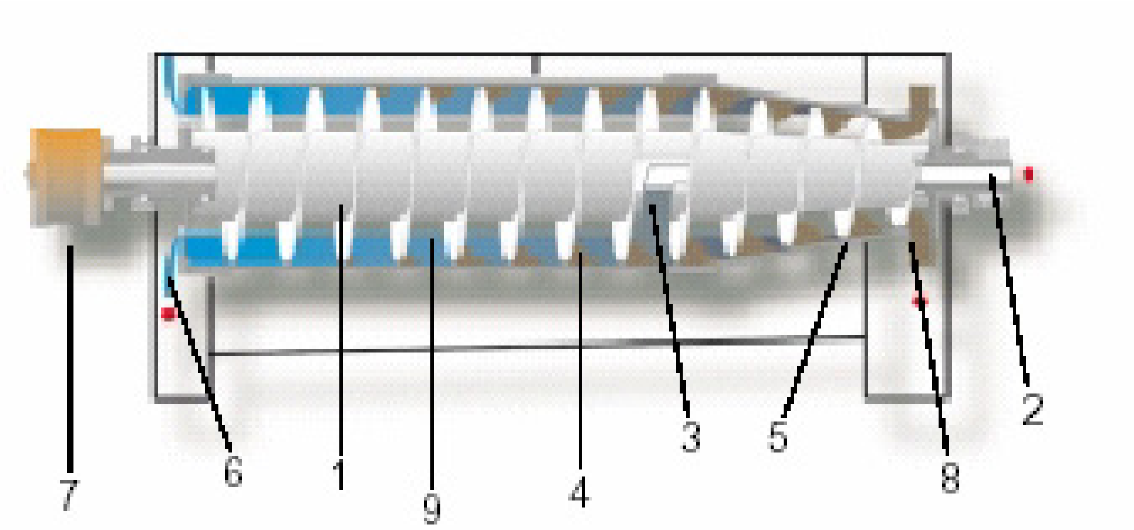


Figure 5-6. *Decanter centrifuge with horizontal drive shaft – schematic illustration. (From Alfa Laval product catalogue).*

1 = screw conveyor, 2 = feed tube in centre of drive shaft, 3 = inlet distributor, 4 = sedimentation bowl, 5 = conical end of bowl to which solids are conveyed, 6 = cylindrical end of bowl where liquid overflows through a number of openings. The positions of the openings are adjustable to adjust the height of the weir, 7 = planetary gear, 8 = solids discharge port, 9 = slurry trapped in the bowl.

1 and 4 rotate in the same direction but at different speeds.

5.2.1 Capacity design

Dewatering is the second main step in the freeing process, but is subordinate to the main purpose of freeing of the canister.

This is reflected in the choice of dewatering capacity. The aim is to determine the capacity of the decanter centrifuge that can handle the slurry at the rate it is generated. Laboratory tests have shown that a dry matter content of about 50% in the bentonite is optimal for handling. The bentonite content of the clarified liquid is kept as low as possible. Based on experience from laboratory tests a value of 1.5–2%$_{\text{weight}}$ is recommended.

The capacity of the decanter is based on continuous operation according to section 5.3.

The results of the slurrying tests with the prototype full-scale equipment show that efficiency in slurrying of a block is about 90 $kg_{dry\ bentonite}$/hour, while it is about 75 $kg_{dry\ bentonite}$/hour in slurrying of a ring.

Recommended size/capacity of decanter:
The recommended capacity of the decanter should match the slurrying efficiency (see above) with a safety margin of about 20% to ensure efficient operation. The recommended capacity of the decanter is 110–120 $kg_{dry\ bentonite}$/h.

The decanter centrifuge STNX 438B-31G from Alfa Laval has been chosen for dewatering of the slurry from the freeing of the canister deposited in the Retrieval Niche. The decanter is connected to a 400 V, 50 Hz, 3-phase power source and has a power rating of 110 kW. Its weight is about 5 tonnes. The inlet for the slurry is a 2½" pipe with hose connection and is connected to the centre of the feed screw shaft. The outlet for the dewatered mass is a rectangular fall shaft beneath the conical end of the bowl. The dimensions of the outlet are 690 x 381 mm. The wet phase (the clarified liquid or "reject") leaves the decanter through a 2½" pipe at the opposite end of the inlet.

5.3 Process operation

The dewatering capacity in the full-scale tests was not commensurate with the slurrying efficiency. This ratio was a factor that only allowed batchwise operation.

Despite the fact that batchwise process operation worked well during the tests, certain disadvantages can be seen in an overall assessment.

The prerequisite for batchwise operation is that the change of liquid takes place in as short a time as possible, which means intermittent high slurry flow, resulting in high bentonite concentration per unit time, which in turn would require a disproportionately large decanter. The only way to get away from this with batchwise operation is to install a container, a buffer tank, between the slurrying chamber and the decanter.

The assessment is that an operating mode that does not necessitate the use of a buffer tank should be able to retain the advantage of batchwise operation without the accompanying disadvantages.

This operating mode must be characterized by a change of liquid that keeps pace with the density increase of the slurry under typical full-scale slurrying conditions.

The conclusion is that continuous operation is recommended.

Functional assembly

The functional assembly of the main components entails that the special nozzle with three integrated pumps is fitted together with three mixers to an integral unit in a way that permits the canister to be followed in its entire length.

Such a functional assembly does not require any complicated design solutions in terms of strength.

The assembled unit's mechanical guides should maintain a nearly horizontal position of the nozzle during slurrying. These guides should act on the canister's mantle surface.

Lifting the assembled unit and getting it to follow the canister along its entire length requires a lifting device with suitable *load capacity* and *lift height*.

The need for a lifting device is met for the slurrying equipment by the use of existing equipment. The gantry crane designed for loading of the deposition holes with compacted bentonite bodies is well suited for this.

6 Freeing of deposited canister

The task was to free the copper canister deposited in the retrieval niche five years ago using two different techniques and then lift it up. The freeing operation started with mechanical removal of the bentonite around the upper half of the canister. The primary reason for this procedure was to take samples of the bentonite, and it also offered an opportunity to retrieve the embedded sensors. This was our own project and is documented in a separate report. The other technique used for freeing the lower part of the canister was slurrying of the bentonite.

6.1 Preparations

The equipment that had been developed for earlier full-scale tests was prepared for operation and tested. Any necessary adjustments and service were performed on the equipment that was usable. New equipment was procured to replace equipment that was undersized or did not work satisfactorily. Consumable supplies were ordered.

The following equipment from previous full-scale tests was used:

- 3 open plastic tanks of glass-reinforced Reichhold 9100 vinyl ester (∅ 1.6 m, H = 1.1 m), volume about 2.2 m^3
- specially made suction nozzle $\varnothing_{inner}$ = 1,090 mm
- 3 Flygt pumps, type Bibo 2071 LT 212
- 3 Flygt mixers, type 4620.410-0012-18^O SJ
- one mass flowmeter and temperature sensor, Krohne, MFS 2000
- one signal converter, Krohne, MFC 2000
- one electromagnetic volume flowmeter, Krohne, type IFS 4000
- one signal converter, Krohne, type IFC 110 F
- 2 L-bored three-way valves (Ahlsell Avi 1354 art. no. 907 12 83) with motorized actuator (unknown make and model)
- one control cubicle containing relays, contactors, motor protections, terminal blocks and a Siemens programmable logic controller (PLC), Simatic S7-312 C
- 2 transport pumps, Clas Ohlson, art. no. 44-3856
- one 8-channel INTAB AAC-2 PC-logger and software (EasyView 5 from Intab Interface-Teknik AB)
- various valves, hoses, electrical boxes, cables and assembly parts
- existing gantry crane of own manufacture

Newly procured material and equipment:

- Calcium chloride solution ($CaCl_2$ solution with a concentration of $35\%_{weight}$)
- 4 level sensors, Clas Ohlson, art. no. 22-3391
- 1 Areometer from VWR International art. no. 152100-15
- 1 lifting ring for the slurrying tool

Rented or borrowed material:

- one decanter centrifuge, Alfa Laval STNX 438B-31G
- 3 tipping containers, MARCO
- 1 digital scale, 0–5 kg, resolution 1/1000

6.2 Installation

The decanter was transported down to the retrieval niche at the -420 m level and the different parts were assembled. The decanter's control cubicle was placed in the tunnel inside the decanter and connected electrically to a 125 A fused outlet. Power and control cables were installed between the cubicle and the decanter.

The solids discharge outlet was fitted with an approximately 60 cm long rubber skirt. A tipping container was placed below this discharge outlet.

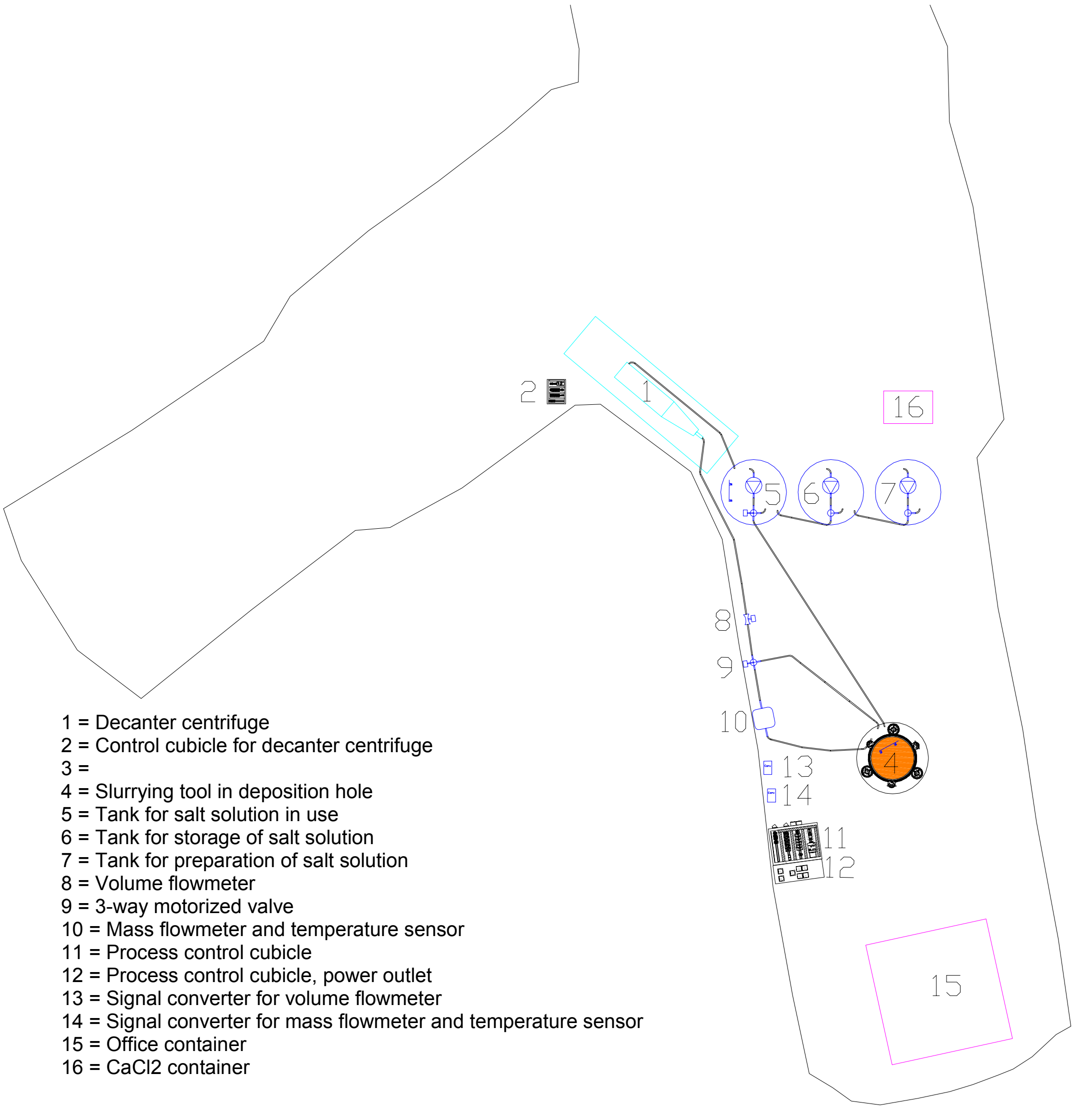
The different parts of the slurrying tool were taken down to the retrieval niche for assembly. The three segments of the suction nozzle were screwed together and the three pumps were put in place in their suction chambers. The newly manufactured lifting ring was screwed onto the top of the pumps. The three mixers were attached between the three pumps. A splash protection tube with level sensor was also attached to the lifting ring. A hose for pumping-out of the bentonite slurry was connected to one of the pumps. The other end of the hose was connected to the mass flowmeter's inlet. Cables and hose were bunched together into two bundles that were strapped to two of the lifting cables for the slurrying tool.

The gantry crane was positioned above the deposition hole and connected electrically.

The mass flowmeter, a three-way valve with motorized actuator and the volume flowmeter were installed on after the other on one rock wall. One hose led from the three-way valve in return down into the deposition hole and one to the volume flowmeter. A hose was connected from the volume flowmeter to the decanter's slurry inlet.

The signal converters for the mass flowmeters and temperature sensors as well as for the volume flowmeter were placed next to the control cubicle.

The control cubicle was placed next to the mass flowmeter. All power, control and signal cables were connected between the control cubicle and the respective components.



1 = Decanter centrifuge
2 = Control cubicle for decanter centrifuge
3 =
4 = Slurrying tool in deposition hole
5 = Tank for salt solution in use
6 = Tank for storage of salt solution
7 = Tank for preparation of salt solution
8 = Volume flowmeter
9 = 3-way motorized valve
10 = Mass flowmeter and temperature sensor
11 = Process control cubicle
12 = Process control cubicle, power outlet
13 = Signal converter for volume flowmeter
14 = Signal converter for mass flowmeter and temperature sensor
15 = Office container
16 = CaCl2 container

Figure 6-1. *Slurrying equipment set up on the -420 m level*

The plastic vessels were positioned across the opening of the retrieval tunnel. Each vessel was equipped with a transport pump and a three-way valve. The vessel nearest the decanter had a three-way valve with motorized actuator, while the other vessel only had manual valves.

A line was installed from the decanter's clarified liquid outlet to the nearest plastic vessel, the one for clarified liquid. A salt solution filling line was installed between the vessel's three-way valve with motorized actuator and the deposition hole. A splash protection tube with level sensor was also installed in the vessel.

The tank with the 35% calcium chloride solution was positioned in front of the preparation vessel for the $CaCl_2$ solution. In order to get gravity flow down into the preparation vessel, the tank was placed on a stand next to the preparation vessel.

A computer and sampling equipment were set up in the existing office container furthest inside the retrieval tunnel. Signal cables for transmission of measurement results were installed between the computer and the signal converters.

6.3 Fine adjustment

With all equipment in place and connected, calibration and fine adjustment of the equipment began.

Approximately 2,000 litres of bentonite slurry was prepared from bentonite powder for fine adjustment of the decanter. The slurry consisted of 4%$_{\text{weight}}$ $CaCl_2$ solution containing approximately 5%$_{\text{weight}}$ bentonite. The density of the slurry was 1,055.5 g/dm^3. The homogeneity of the slurry was ensured by internal recirculation in the preparation vessel.

6.3.1 Decanter centrifuge

A specialist from Alfa Laval was on hand for fine adjustment. Start-up of the machine was problematical due to many internal faults and wrong electrical connections that had to be corrected by our electricians in consultation with Alfa Laval. The following faults took the longest time for fault tracing and correction:

- The power supply cable to the main motor was incorrectly connected in the terminal block. Fault tracing and reconnection.
- Incorrectly connected start/stop relay in control cubicle. Cable on relay base moved.
- Alarm for high hydraulic pressure. Damaged cable to hydraulic pressure sensor. Temporarily replaced.
- Alarm for vibration at both warning and stop level. Probably moisture in sensor.

All the above fault alarms were disconnected.

When the control cubicle is shut off, the control system alarms for open cowling after the master switch is closed. The alarm is turned off by repeatedly pressing the alarm reset button or via a relay in the control cubicle.

To avoid the above, the control cubicle should therefore always be turned on.

After about two days the machine was in such condition that fine adjustment could begin.

The decanter was started and the bentonite slurry was pumped at a rate of about 120 l/min directly to the decanter. A borrowed Flygt submersible pump, Ready 4, was used.

Fine adjustment began at a main bowl speed of 3,850 rpm with a differential speed (screw lag) of 6 rpm and a weir height of 113 mm.

The decanter was started and stopped about 4 times for various calculations and adjustments. The decanter was also stopped for adjustments that can be made during operation due to a limited supply of well prepared bentonite slurry.

During each operating run, samples of the clarified liquid were taken for analysis. The separated bentonite was judged on the basis of experience by visual inspection of adhesion and consistency. Accurate dry matter tests would take about 24 hours each, which was considered too long a time at this stage of the fine adjustment process. In the last fine adjustment run, samples of clarified liquid and bentonite were taken for accurate analyses.

When fine adjustment was finished after about 12 hours, the decanter was run at a main bowl speed of 3,600 rpm, a differential speed of 8.4 rpm and a weir height of 116 mm. The bentonite content of the clarified liquid was about 1.8%$_{\text{weight}}$ and the dry matter content of the separated bentonite was about 51.5%$_{\text{weight}}$. The specialist from Alfa Laval remained for about 4 hours of running but found no reason for further adjustments.

6.3.2 Control equipment

Checking and adjustment of the control equipment was done at the same time as fine adjustment of the decanter. Pure water was circulated through the entire system except the decanter.

The signal converters for mass flow, temperature and volume flow were checked with pure water with well known values.

After the signal converters had been checked, the function of the motorized valves was checked.

The achievement of a given density in the bentonite slurry was simulated by manual actuation of the relevant control relay. The motorized valve after the mass flowmeter and temperature sensor functioned properly and directed the flow of bentonite slurry to the decanter, switching to circulation when low density was simulated (no actuation of the relay).

The motorized valve on the clarified liquid tank was checked by manual actuation of the level sensors on the slurrying tool. The motorized valve adopted the wrong position on simulation of both high and low level and therefore had to be electrically rewired. After rewiring the valve worked properly on actuation of the level sensors. On simulation of high level in the deposition hole, the motorized valve changed position from filling to recirculation. On simulation of low level the motorized valve changed over to filling of solvent in the deposition hole.

On simulation of high level in the clarified liquid tank, the pump for filling of fresh salt solution in the clarified liquid tank from the storage vessel stopped as planned. On simulation of low level, the pump for filling of salt solution in the clarified liquid tank started.

The volume flowmeter was checked by taking the time for pumping-out of a measured volume (2,000 litres) of water to discharge.

After completed tests and adjustments, the signal converter for the mass flowmeter was programmed. It was programmed to reset the three-way valve for distribution of the bentonite slurry to the decanter at measured density values of 1,055.5 g/dm^3 and above. At values below 1,055.5 g/dm^3, the valve was supposed to change back in order to return slurry to the deposition hole.

It was found that after 3–4 minutes' actuation, the valve returned to the resting position, despite the fact that the lower sensor was calling for more solvent. Fault tracing revealed that a timer function was programmed into the PLC, which was reprogrammed immediately.

6.3.3 Data logger

While checking and adjustment of the control equipment was under way, the data logger was in operation to check that recorded values were in agreement with the signal converter's values. Three channels were programmed for recording of density, temperature and instantaneous volume flow. Four channels were used for recording of calculated values of total flow, bentonite content of slurry, discharged bentonite per minute and total discharged bentonite.

An average value of 12 recordings at five-second intervals was chosen for each recording, i.e. one recording per minute.

The following units were used:

• Temperature	^{O}C
• Density	g/dm^3
• Instantaneous flow	m^3/h
• Total flow	m^3
• Bentonite content of sludge	g/l
• Discharged bentonite per minute	kg/min
• Total discharged bentonite	kg

6.4 Slurrying

A 4%$_{\text{weight}}$ $CaCl_2$ solution obtained by diluting with water of 35%$_{\text{weight}}$ $CaCl_2$ solution was used for slurrying. The calcium chloride solution was blended batchwise in a plastic vessel of about 2.2 m^3.

An aerometer graduated in weight-percent NaCl at 15^{o}C was used for determination of the salinity of the solution.

A conversion factor can be obtained from a table for density of NaCl or $CaCl_2$ solutions:

Conc$_{\text{calcium chloride}}$ = read conc$_{\text{sodium chloride}}$ times 0.85.

The density decreases with increasing temperature. It is not a linear function of the temperature, nor is it a quadratic function of the temperature.

The following formula should provide a satisfactory approximation under field conditions with correction to weight-percent $CaCl_2$ at different temperatures:

Actual Conc$_{\text{calcium chloride}}$ = conc$_{\text{calcium chloride, as if it were 20 }^{o}\text{C}}$ times $(1 - 7.35\ 10^{-6}\ (\text{temp}-20)^2)$.

The salt solution is blended by adding about 1,800 litres of water to the mixing vessel, after which about 175 litres of 35% $CaCl_2$ solution is added. The concentration is measured with the aerometer and fine-adjusted to the right concentration, about 4% $CaCl_2$. A total of about 2,000 litres of 4% salt solution is obtained. The mixture is stirred during the blending procedure by recirculation of the liquid in the vessel.

The salt solution is pumped over to the clarified liquid tank. The level sensor stops the supply of salt solution when the level has risen to the preset level.

The blended salt solution is pumped down into the deposition hole. When the solution has risen to just over the mixers, the upper level sensor is actuated. A signal is transmitted to the motorized valve on the clarified liquid tank, which switches over to recirculation in the tank.

The signal from the upper level sensor is also a signal for start of the mixers and the nozzle pumps. A partial flow from one of the pumps is conducted through the mass flowmeter, through the three-way motorized valve and back down into the slurrying hole.

When the mass flowmeter indicates that the $CaCl_2$ solution contains about $5\%_{weight}$ bentonite, which means that the density of the slurry has increased to $1{,}055.5\ g/dm^3$, a signal is sent to the 3-way valve's motor to redirect the slurry flow to the decanter. Density and temperature are logged continuously and stored in the computer.

On its way from the three-way motorized valve to the decanter, the bentonite slurry passes the volume flowmeter. The flow to the decanter is logged and transmitted continuously to the computer.

6.5 Dewatering

The decanter has started and been allowed to accelerate to full operating speed, 3,600 rpm. It is checked that the right differential speed, 8.4 rpm, is programmed.

Dissolution of the bentonite around the canister is under way. Slurry is recirculated in the deposition hole and through the mass flowmeter for further conveyance to the decanter.

In the decanter the $CaCl_2$ solution is separated from the solid matter. The $CaCl_2$ solution, called clarified liquid, is conducted to the tank for clarified liquid adjustment. Samples are taken of the clarified liquid at regular intervals for determination of its salinity and bentonite content. The bentonite content in normal operation remained between 1.2 and $1.4\%_{weight}$ and the salt content remained at about $4\%_{weight}$ throughout the slurrying process.

The dewatered bentonite is ejected into a fall shaft and collected in a rubbish container. Samples are taken regularly of the dewatered bentonite for determination of the dry matter content (DM content). The average DM content of the dewatered bentonite varied between $49.4\%_{weight}$ and $54.9\%_{weight}$. Most measurements showed a DM content of around $52\%_{weight}$.

6.6 Data collection

Values for temperature, density and volume flow were logged during the dissolution and dewatering processes. All values were stored in a computer. The installed calculation program EasyView 5 was used to calculate values for total flow, bentonite content of slurry, discharged bentonite per minute and total discharged bentonite. The values can be presented in both tabular and graphic form.

Due to many disturbances resulting in production stoppages, a continuous sequence of events cannot be presented. For those periods that proceeded with relatively trouble-free operation, the values are presented in graphic form for each period (Appendix 3).

6.7 Disturbances

Many faults and problems were noted during the installation phase that delayed commissioning. Examples of faults are an incorrectly connected drive motor, malfunctioning meters etc.

During slurrying on 2 May 2006 the mixers stopped due to a blown fuse. The mixers could not be restarted so the process had to be interrupted and the slurrying tool was lifted up for inspection. The reason for the stoppage was that a 20 cm long steel tube, Ø approx. 10 mm, from one of the meters had come loose during dissolution of the bentonite and was wedged fast between the propeller and the jet ring, preventing rotation. Besides the steel tube, parts of wetting mats and strings had become wound around the propeller and the shaft (Image 6-1).

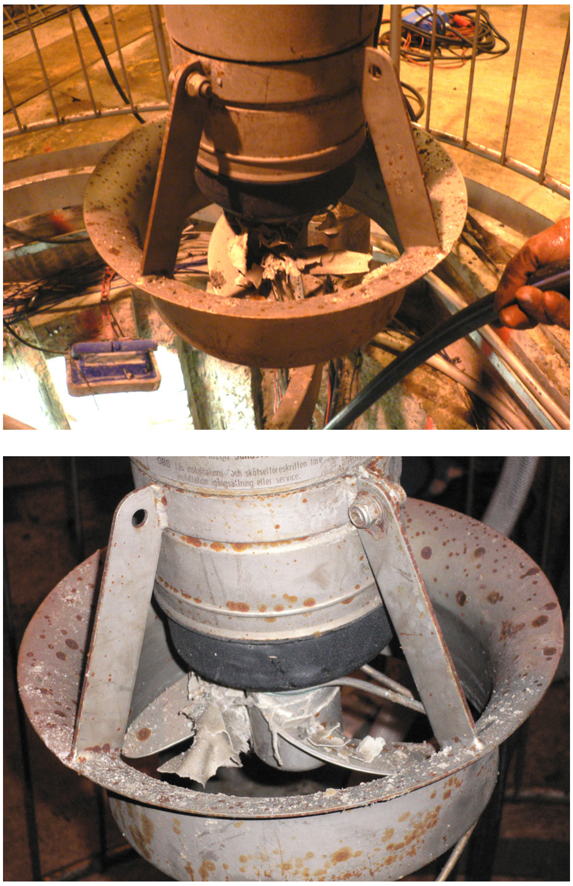


Image 6-1. *Mixer with foreign objects in propeller. (Photo: Bo Nirvin, SKB).*

The motor was very hot and the fuse blew when an attempt was made to start it. The motor was inspected to determine the cause, whereupon it was discovered that the stator was burned. The mixer was sent to the manufacturer for repair – replacement of the stator.

Slurrying was not interrupted but continued with the remaining two mixers in operation.

After a while a pump stopped when its fuse blew. The pump could not be restarted. Fault tracing was carried out and revealed a short circuit between two phases, so the pump was taken up. An external inspection revealed damage to the power cable next to the cable entry. The cable entry was opened and the junction box was dry. The cable turned out to have moisture inside the insulation, however, so pieces were cut off back from the point of damage until no moisture was indicated. The cable was reconnected and the pump could be started without a problem. Increased power consumption was not noted. The slurrying tool with the repaired pump was lowered into position around the canister and slurrying was restarted. The reason for the cable damage could not be determined. The cable may have been damaged the whole time so that water gradually leaked in, finally causing the short circuit.

Another mixer stopped due to a blown fuse and could not be restarted. The slurrying tool was lifted up and the cause of the fault turned out to be an approximately 45 cm long tube, Ø approx. 10 mm. The tube had become wound around the propeller shaft and was stuck on a brace for the jet ring, preventing rotation. In addition to the tube, parts of wetting mats and strings had become wound around the propeller and the shaft, damaging the shaft seal. The mixer was sent to the manufacturer for repair and inspection.

Slurrying could continue with greatly reduced capacity since only one mixer was in operation.

During the dissolution of the bentonite around the lower quarter of the canister, a declining flow of slurry to the mass flowmeter was noted. Pumps and mixers were turned off, whereby the slurry returned down into the deposition hole. The mass flowmeter was inspected but nothing out of the ordinary was found. Pumps and mixers were restarted and the flow was found to be normal. After a short while (25–30 minutes) it was once again indicated that the flow to the mass flowmeter was nearly 0 m^3/h. Once again pumps and mixers were turned off, whereupon the slurry returned down into the deposition hole.

At this point we thought that the discharge hose was too large, causing the flow velocity to be too low. Due to the low flow velocity and the high discharge head, the heavier particles in the slurry were gradually accumulating in the discharge line instead of being conducted to the mass flowmeter. The discharge head from the pump to the mass flowmeter was about 8–9 metres, while the total discharge head in the full-scale test was no more than one metre.

In order to increase the flow rate and the flow velocity in the discharge hose from the pump, the area of the free discharge outlet at the pump had to be reduced. The slurrying tool was lifted to the top edge of the deposition hole and a reducer was fitted in the discharge line.

The equipment was put back in place and pumping-up of the bentonite slurry could continue as planned.

After another few decimetres of bentonite had been pumped away, the flow to the mass flowmeter stopped again. The slurrying tool was lifted up for inspection of the equipment. The cause of the flow stoppage was easy to see: the suction holes into the suction nozzle at the pump were completely clogged by bits of cloth, strings and bentonite clay (Image 6-2).

Image 6-2. *Suction nozzle clogged by rags, strings and bentonite clay. (Photo: Bo Nirvin, SKB).*

When we were able to determine that the canister had been freed from the bentonite along its entire height by means of height measurements, the freeing work was interrupted and the next stage, Retrieval, involving lifting of the canister, could begin.

When the canister had been lifted up out of the deposition hole, the last remaining bentonite could be dug out of the hole. The freeing project was concluded with flushing-out of the deposition hole and pumping-out of all liquid.

6.8 Disestablishment

The decanter with appurtenant equipment was cleaned and dismantled to the same condition and when it arrived. Everything that had been rented from Alfa Laval was loaded onto a truck and returned to the sender.

Pumps and mixers were washed off and sent to the manufacturer (Flygt) for overhaul and restoration to operable condition.

All other material was dismantled, cleaned and any defects corrected.

All our own equipment was preserved and placed in long-term storage.

Some equipment may be modified or rebuilt prior to future freeing tests.

7 Conclusions

The hydrodynamic method works very well for dissolution and removal of bentonite. However, a prerequisite for its efficiency is that it is used in an environment free of disruptive materials such as bits of tubing, rags, strings etc.

Additional full-scale freeing tests with pure bentonite buffers are needed to optimize the method and equipment.

7.1 Efficiency

A correct assessment of the efficiency of the hydrodynamic process is not possible based on the freeing of the canister in the Retrieval Niche. Numerous unforeseen interruptions and other disturbances occurred during the canister freeing procedure, preventing an extended continuous collection of data from an undisturbed process. The longest recorded uninterrupted period of data collection during trouble-free slurrying and dewatering is from the 4th of May 2006. On this date, 656 kg of bentonite was slurried and dewatered in 7 hours and 2 minutes. This gives a slurrying efficiency of about 93.3 kg of bentonite/hour. With this efficiency, it should be possible to free a copper canister embedded in a bentonite buffer consisting of ten rings and two cover blocks totalling 16.5 tonnes in just under 180 hours.

The process diagrams shown in Appendix 3 show tendencies during slurrying, but values from them cannot be used for calculations.

The result achieved was slightly better than the predicted result obtained from the full-scale laboratory trials of freeing of a copper canister. Based on the results of the full-scale tests, the freeing process was predicted to take between 200 and 220 hours. The efficiency achieved in the freeing of the canister deposited in the Retrieval Niche during just under one day with trouble-free operation shows that a canister can be freed in about 180 hours.

In trouble-free freeing of a copper canister in an authentic environment, there are great opportunities for improving the process and the equipment. With a well developed process and efficient equipment, the freeing time can approach the theoretical maximum capacity of the chemistry for disintegrating the bentonite. The time to free a canister completely embedded in a bentonite buffer can probably be reduced considerably.

7.2 Freeing equipment

Aside from the decanter, the equipment that was used in the freeing of the copper canister deposited in the Retrieval Niche is identical to the equipment used in the full-scale laboratory trials.

The decanter centrifuge that was used in the Retrieval Niche has a much greater capacity than the one used in the full-scale laboratory trials. Due to the greater capacity of the larger decanter, the bentonite slurry could be pumped directly from the deposition hole to the decanter by the big pump on the slurrying tool. In the full-scale trial, the bentonite slurry had to be pumped batchwise to a buffer tank and from there to the decanter by a smaller pump with a lower flow rate that matched the decanter's capacity.

Pumps, mixers and the slurrying nozzle worked as expected.

The discharge hose from the one pump on the slurrying nozzle to the mass flowmeter and the hose continuing to the decanter had too large a throughflow area. The large throughflow area of the discharge hose caused the flow velocity to be too low. Due to the low flow velocity and the high discharge head, the heavier particles in the slurry were gradually accumulating in the discharge line instead of being conducted to the mass flowmeter.

Since no slurry flow passed through the mass flowmeter or to the decanter, the dewatering process stalled. Only dissolution continued, but with gradually declining efficiency.

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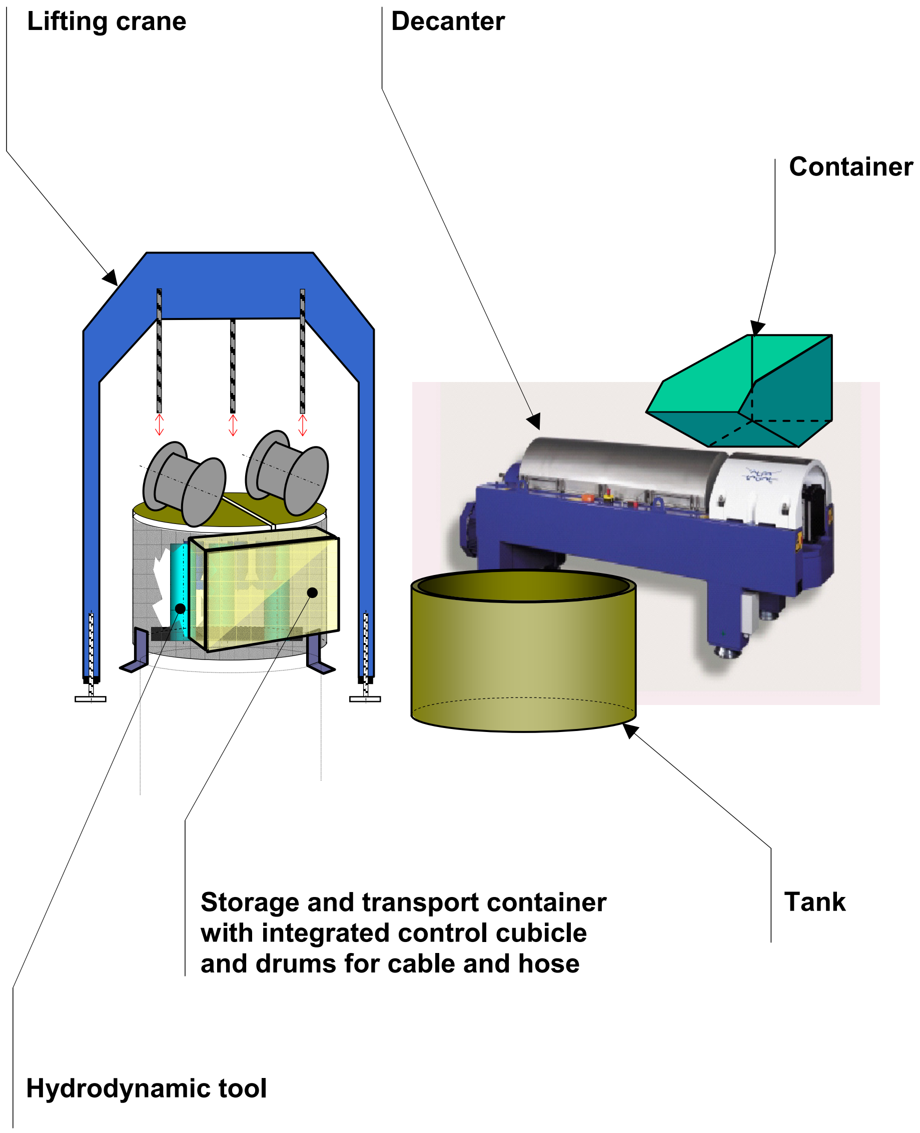
Appendix

49

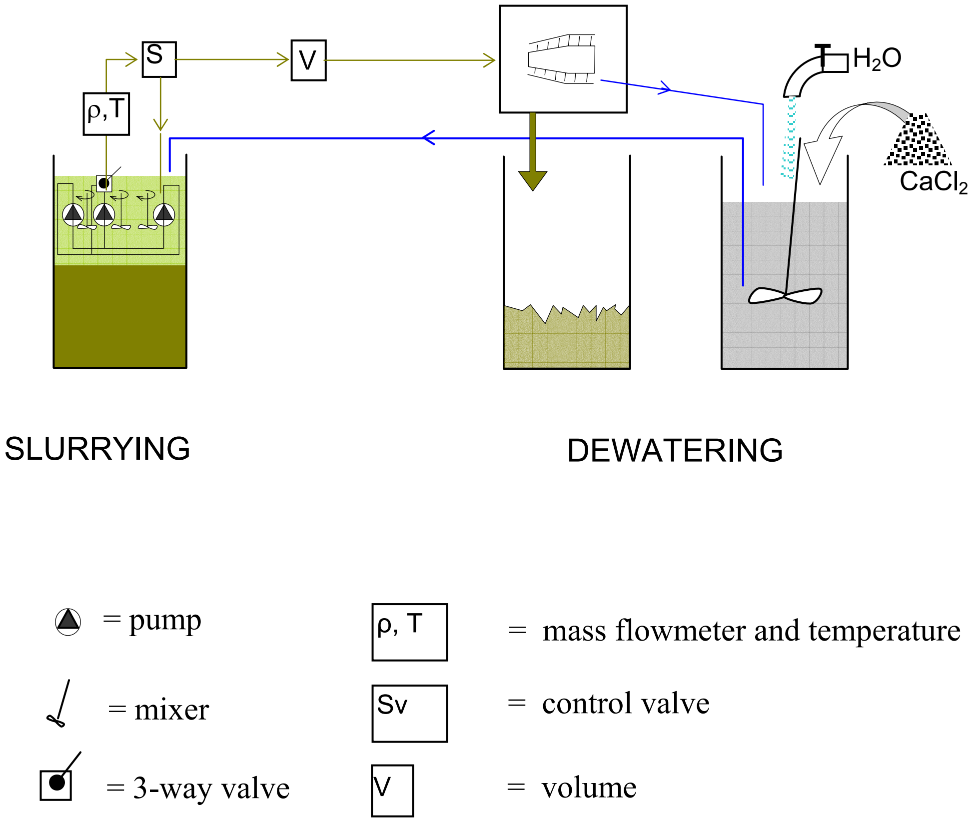
Contents

Appendix 1, Freeing Equipment

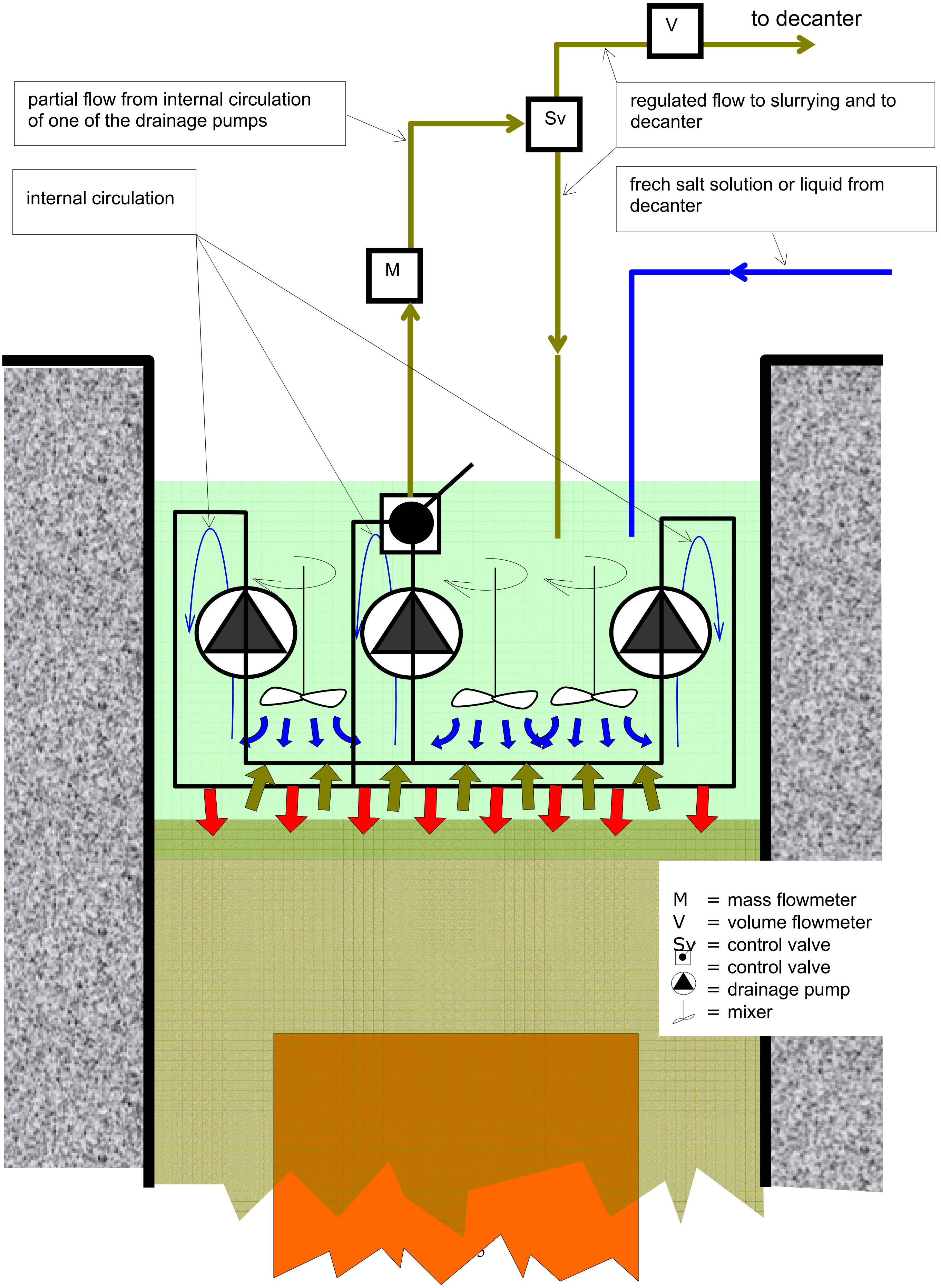
1.1 General assembly drawing



1.2 General flow diagram for freeing equipment



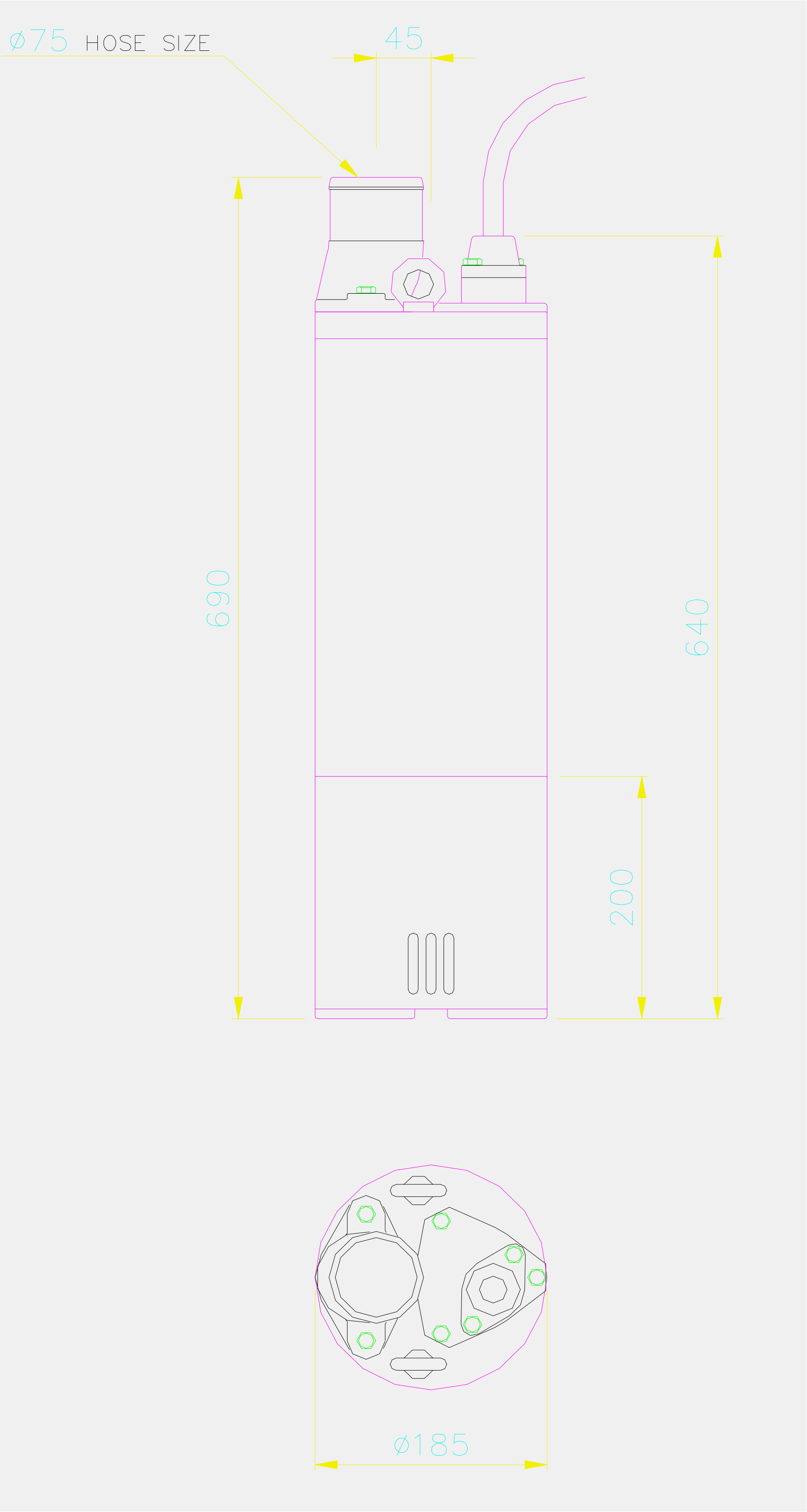
1.3 Detailed flow diagram for slurrying



1.4 List of drawings

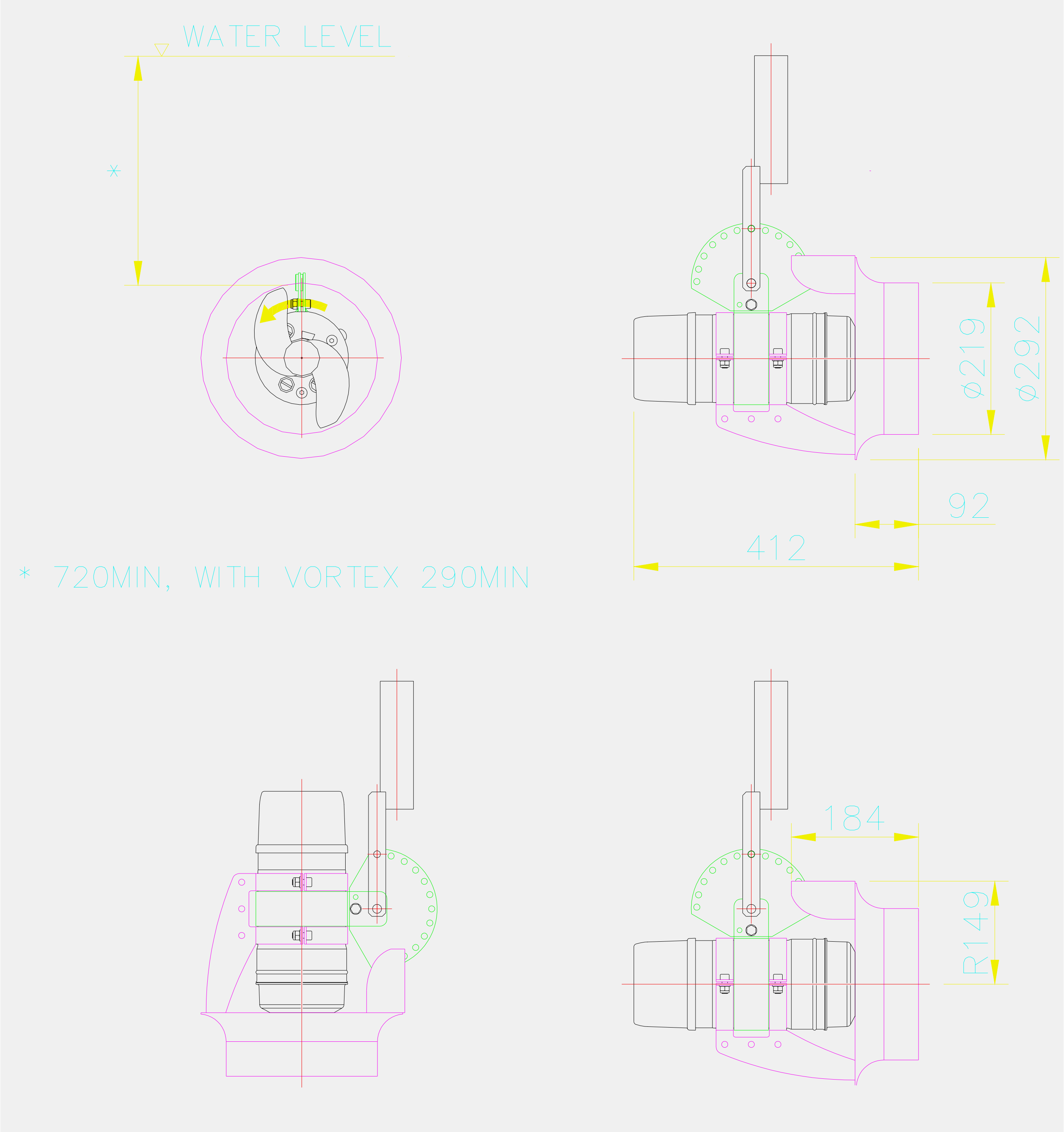
Designation	Description
Appendix 1.4.1	Pump for suction nozzle
Appendix 1.4.2	Mixer
Appendix 1.4.3	Mixing and suction tool for removal of dissolved bentonite clay
Appendix 1.4.4	Travelling gantry crane with three-point cable lift
Appendix 1.4.5	Travelling gantry crane with three-point cable lift and mixing and suction tool mounted

Appendix 1.4.1



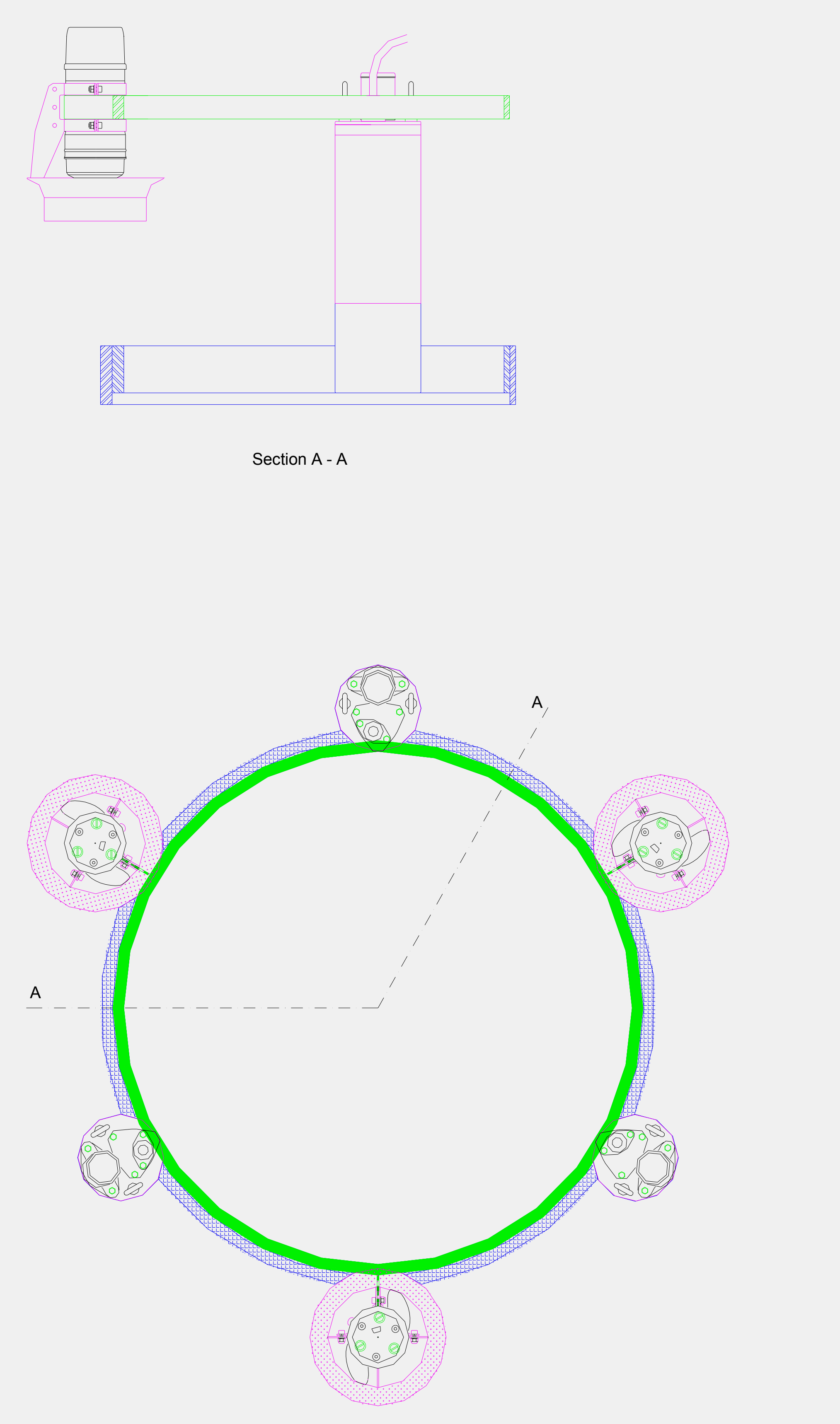
Pump for suction nozzle

Appendix 1.4.2



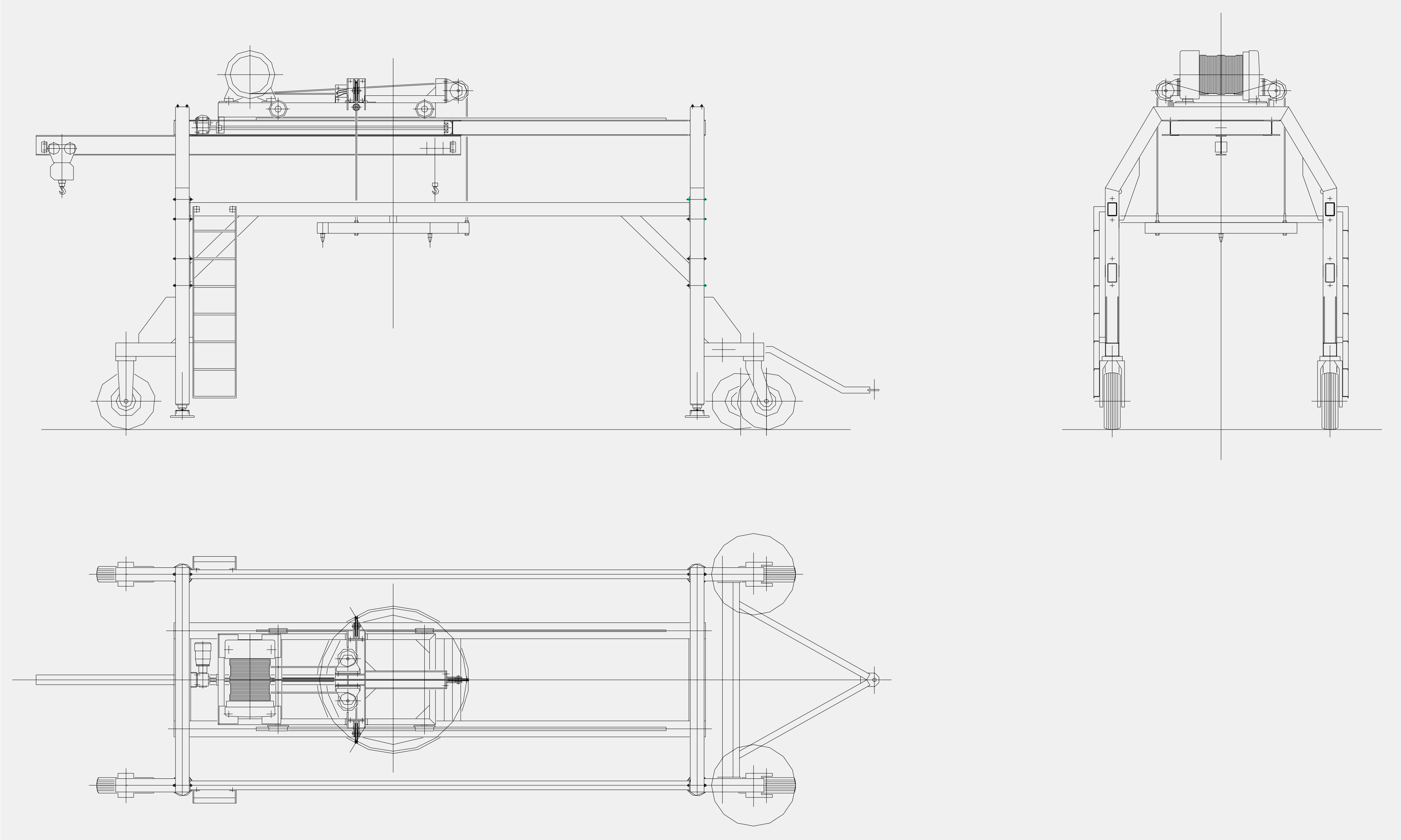
Mixer

Appendix 1.4.3



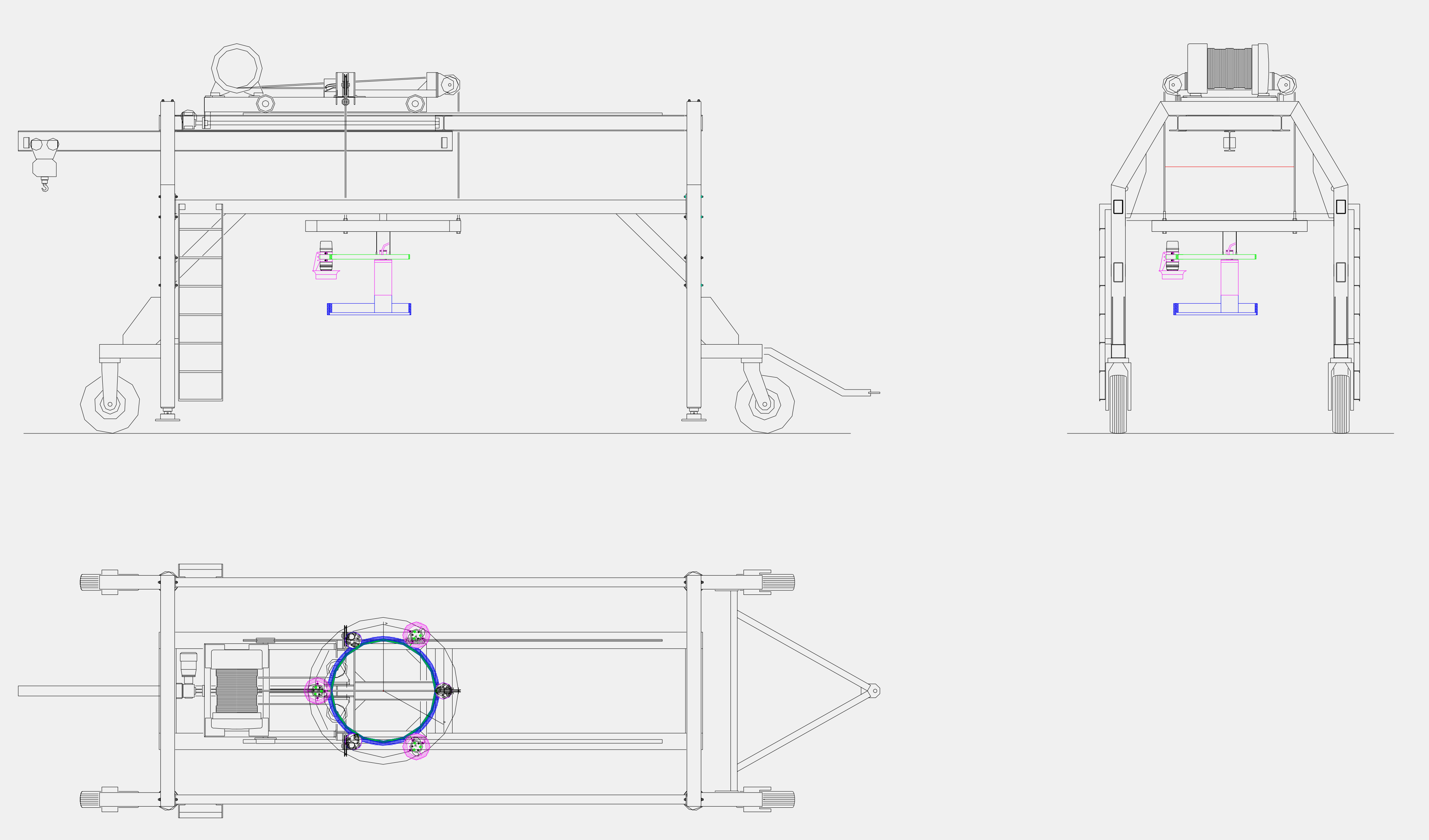
Mixing and suction tool for removal of dissolved bentonite clay

Appendix 1.4.4



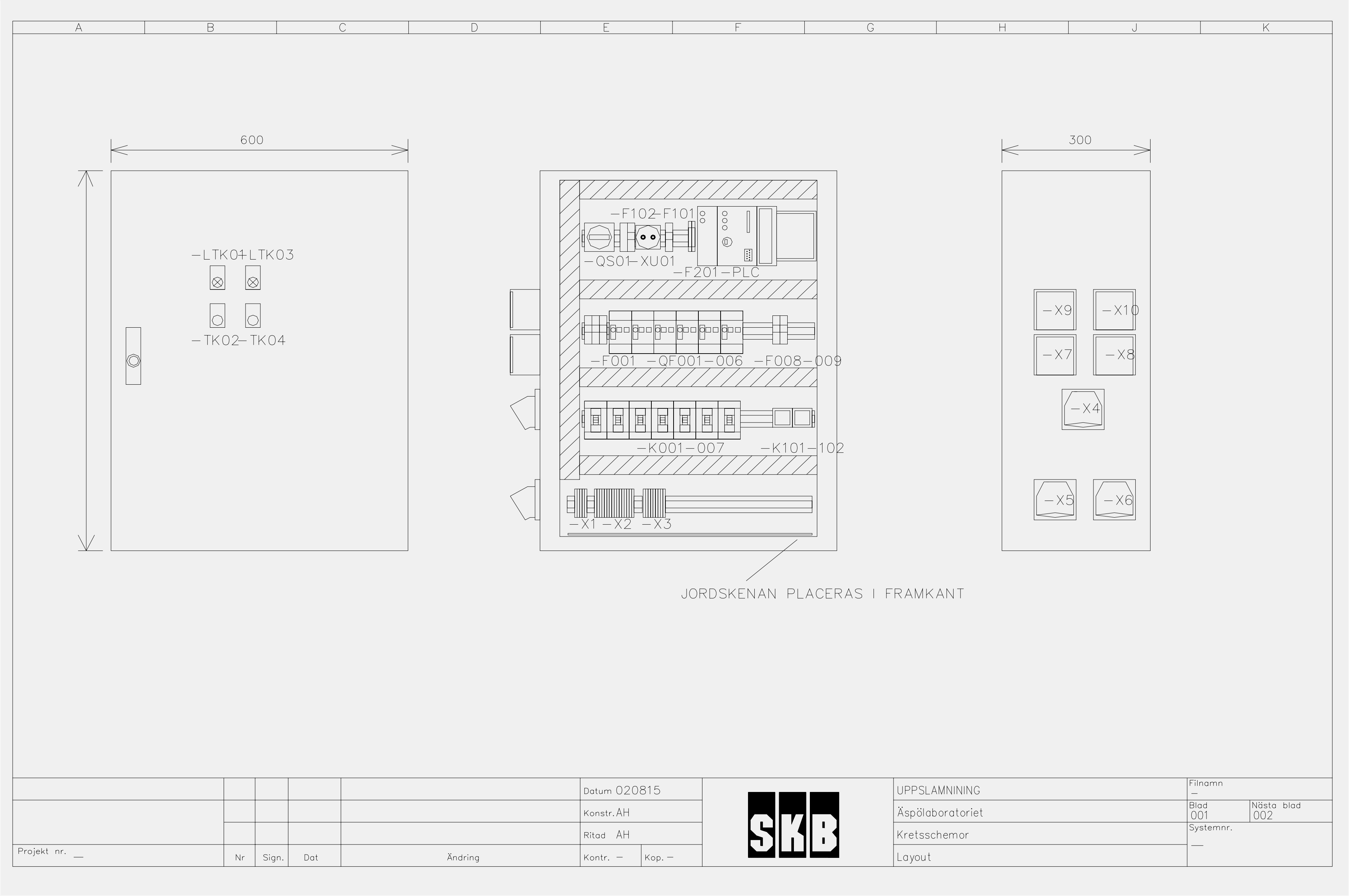
Travelling gantry crane with three-point cable lift

Appendix 1.4.5



Travelling gantry crane with three-point cable lift and mixing and suction tool mounted

Appendix 2, Process control



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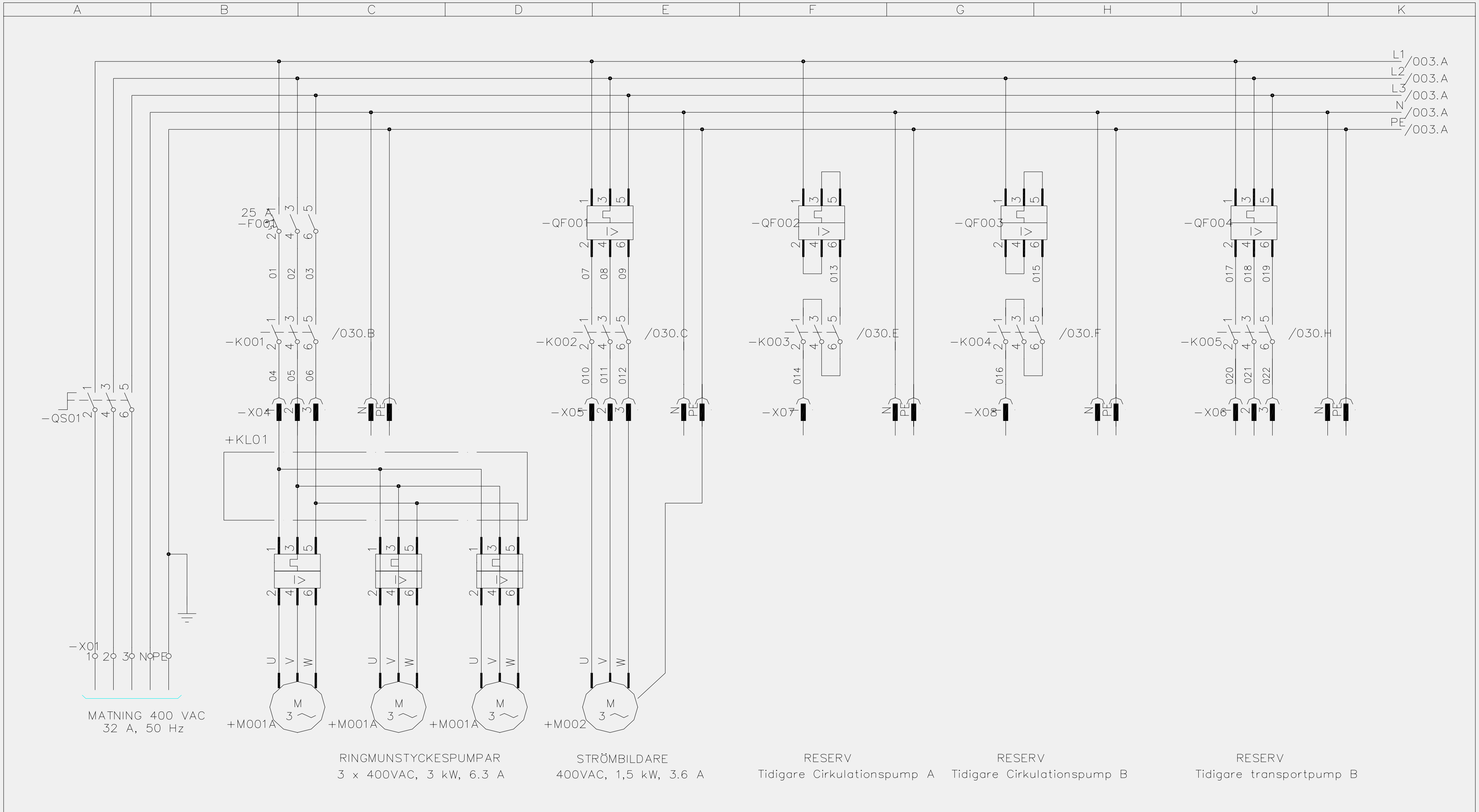

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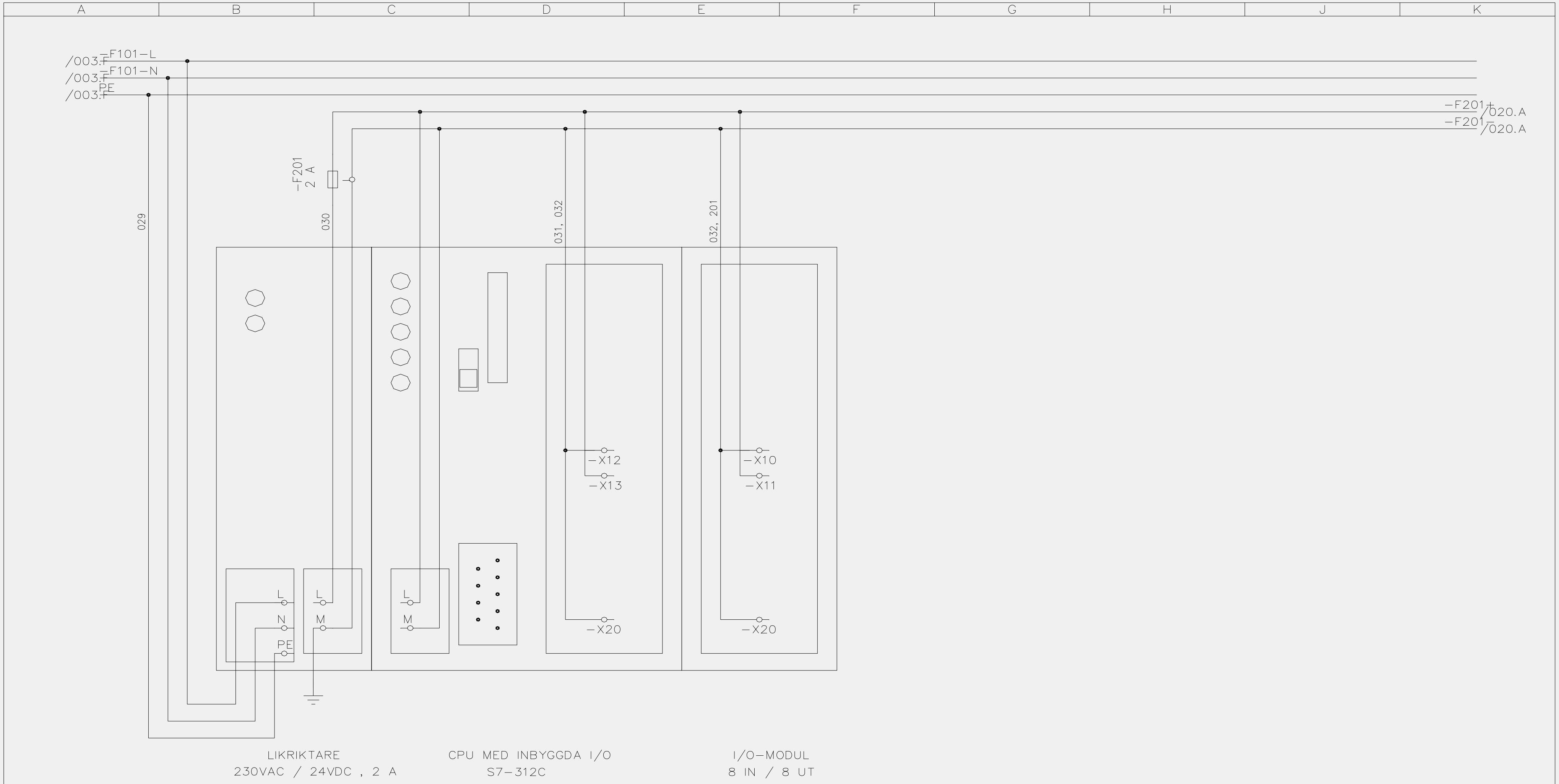

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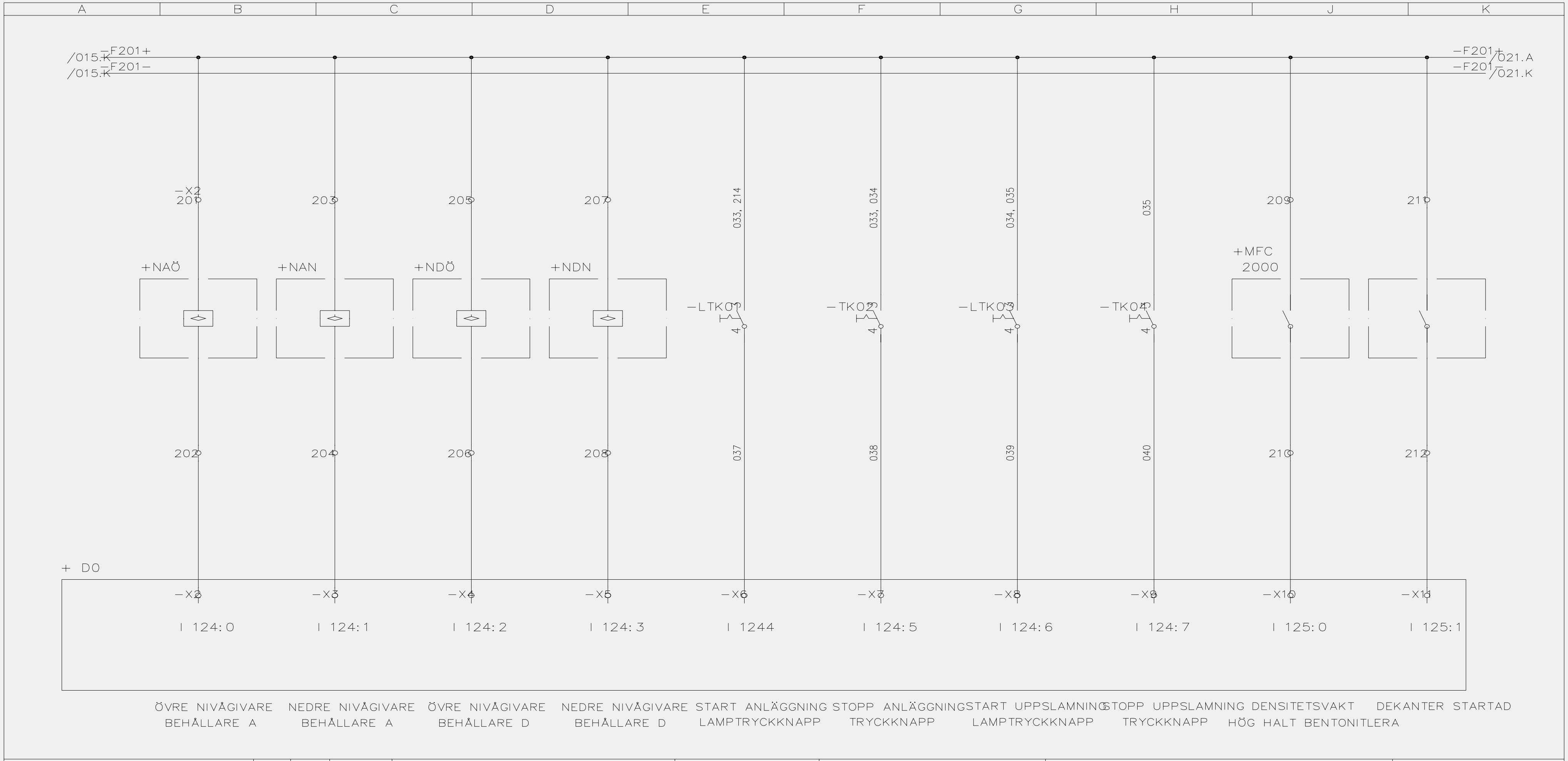

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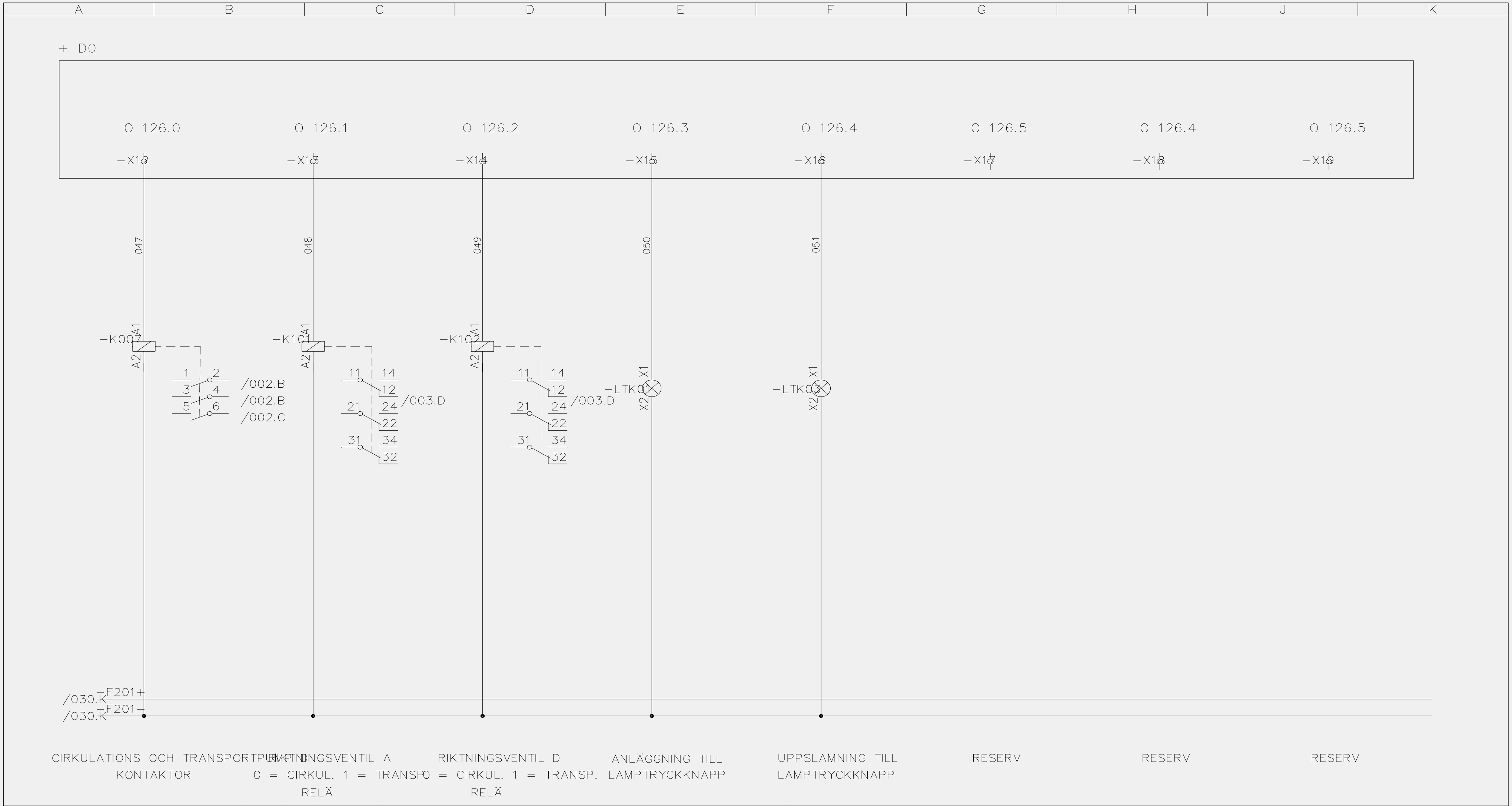

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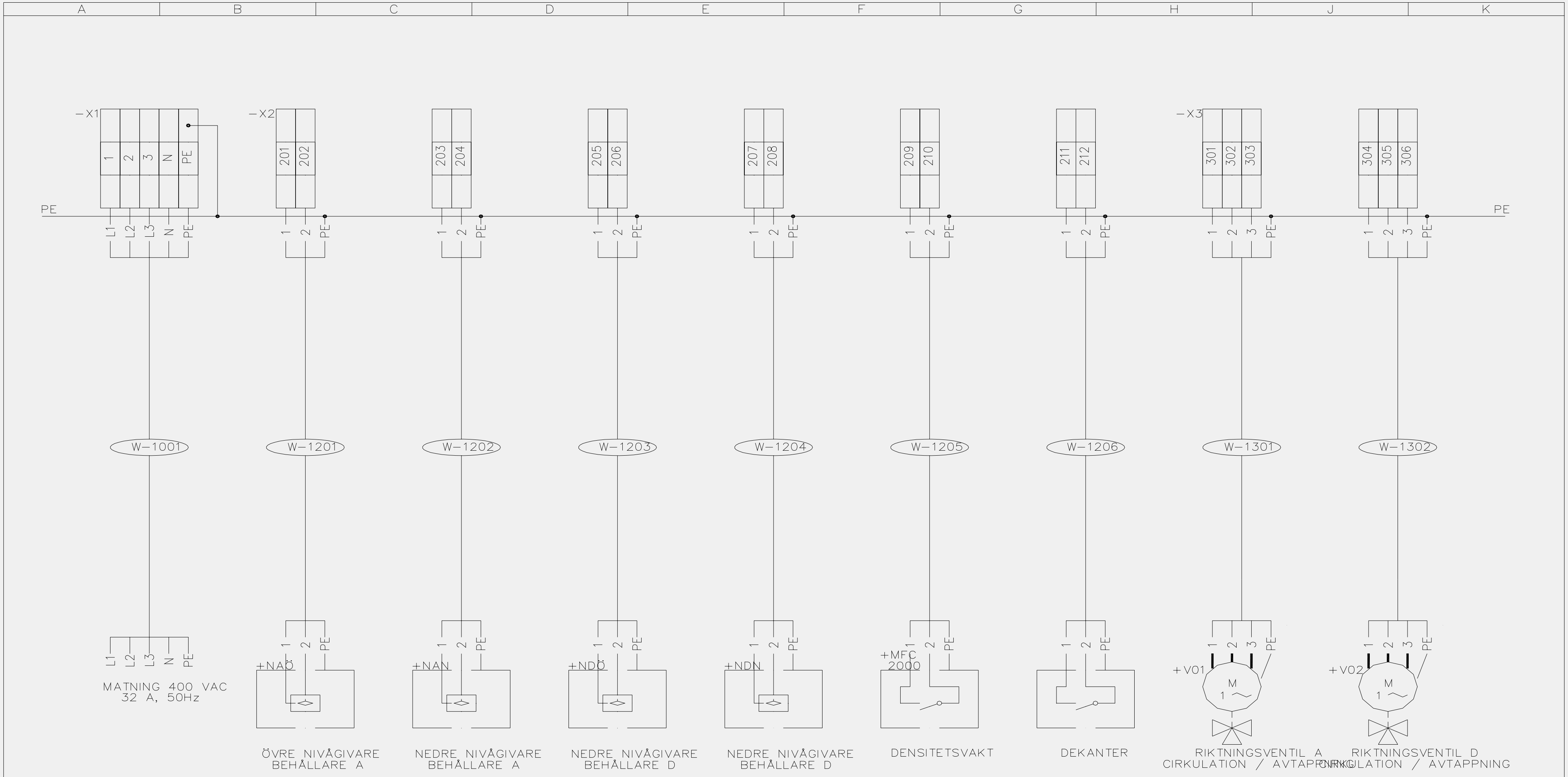

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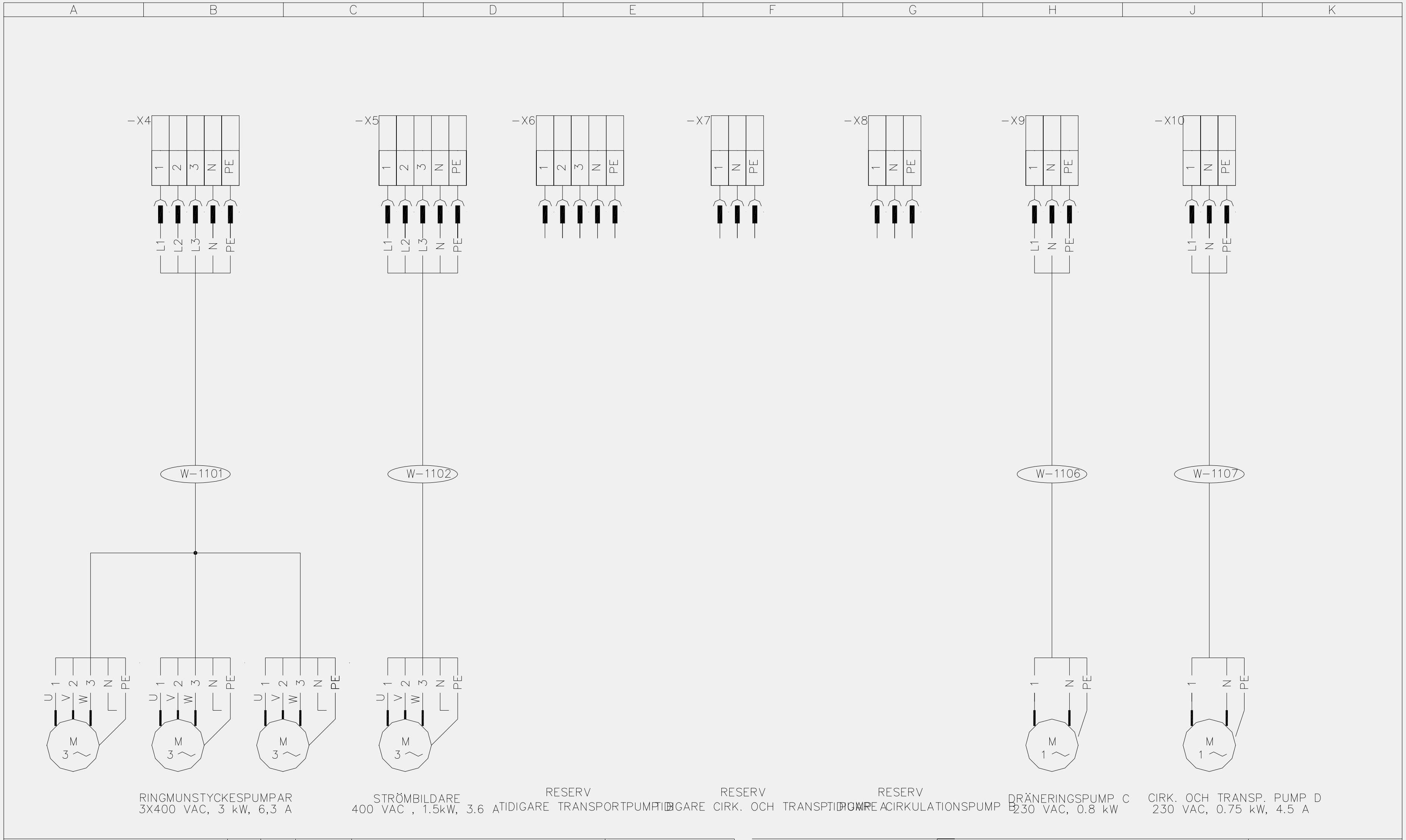

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Appendix 3, Process diagram

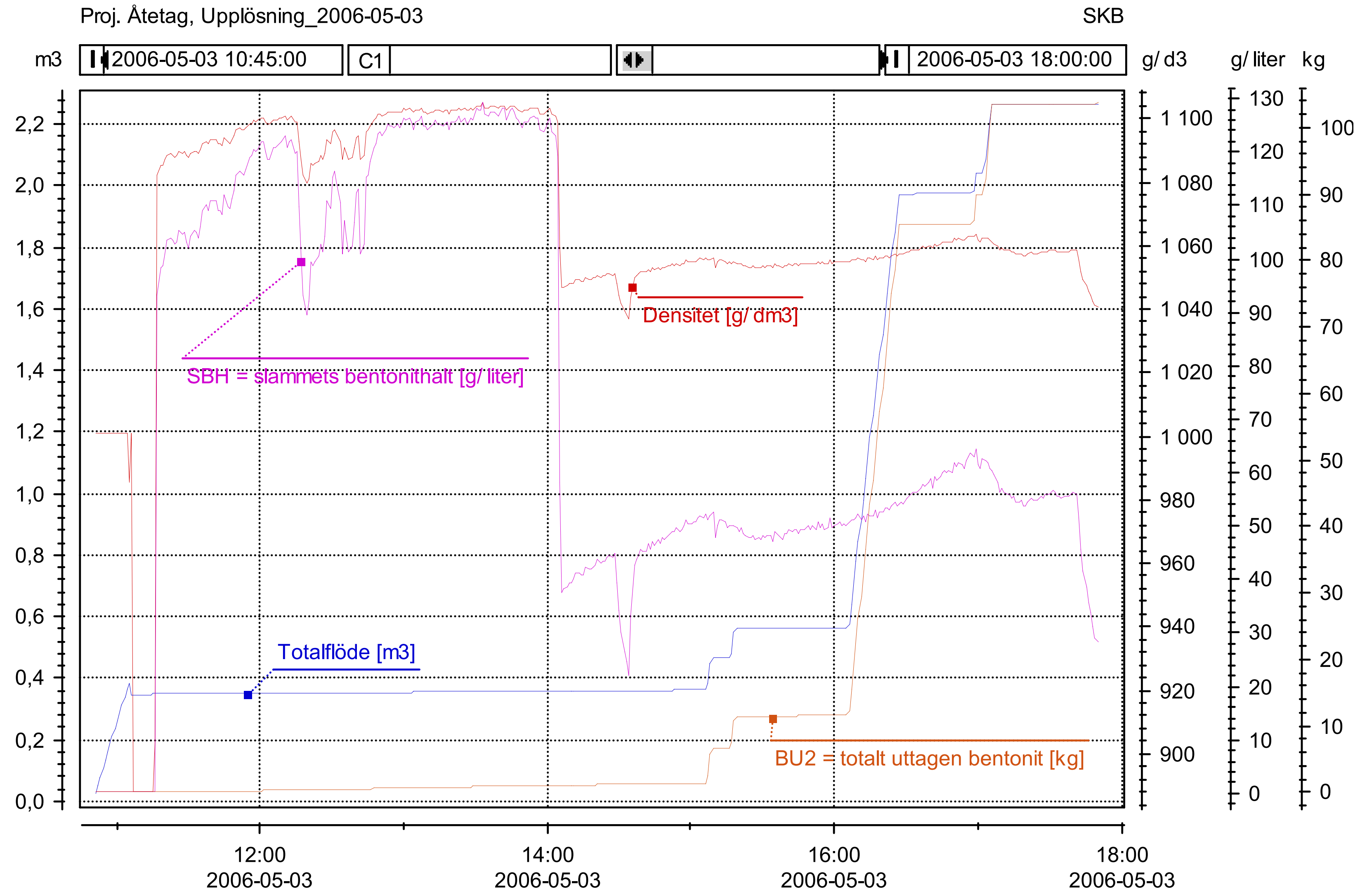

Figure B3 – 1. *Retrieval Project, Dissolution, Recorded values for density, bentonite content, total flow and total discharged bentonite. Values recorded between* 10^{51} *on 3 May and* 17^{50} *on 3 May 2006.*

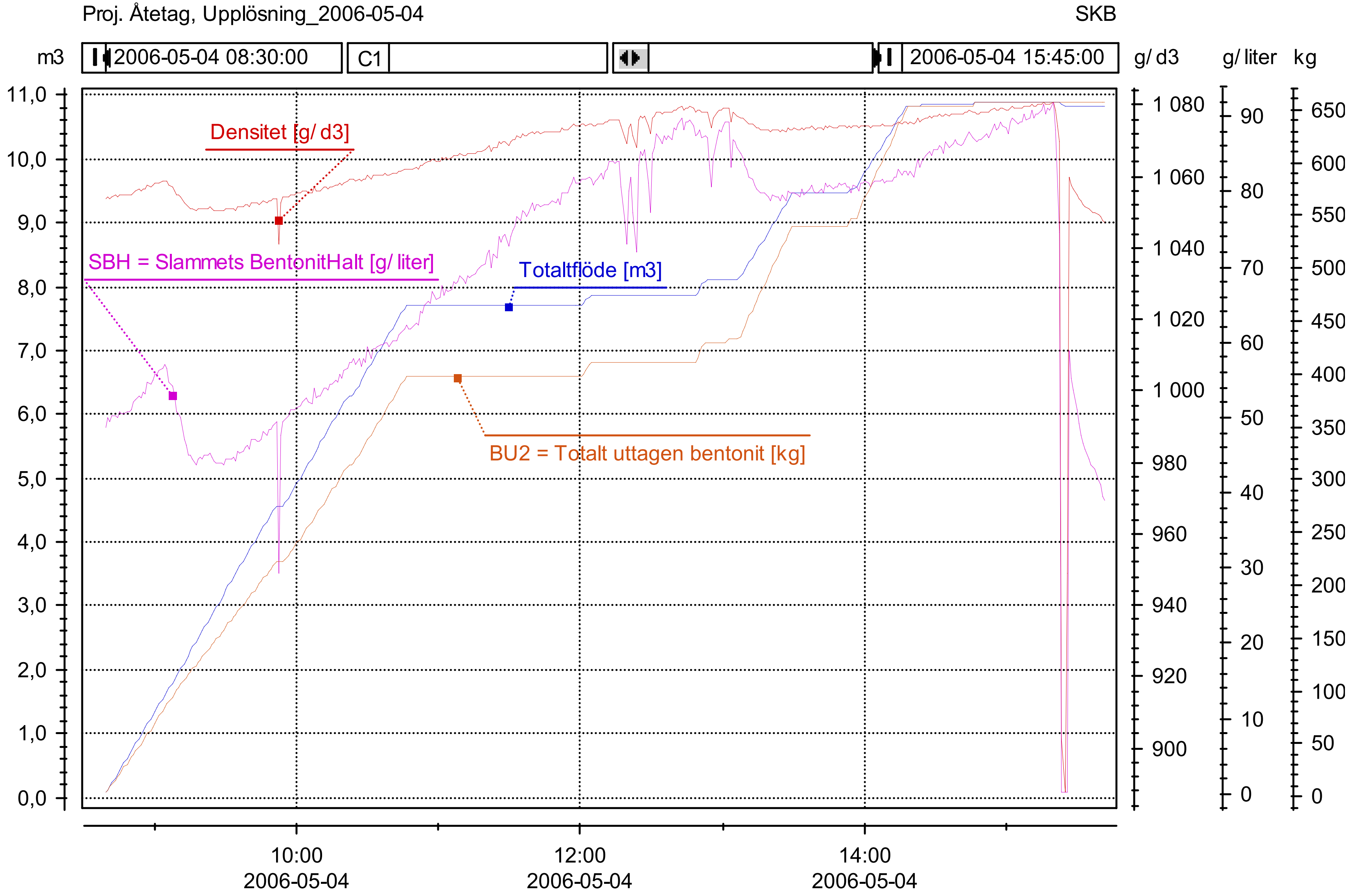

Figure B3 – 2. *Retrieval Project, Dissolution, Recorded values for density, bentonite content, total flow and total discharged bentonite. Values recorded between 08*^{39} *on 4 May and 15*^{41} *on 4 May 2006.*

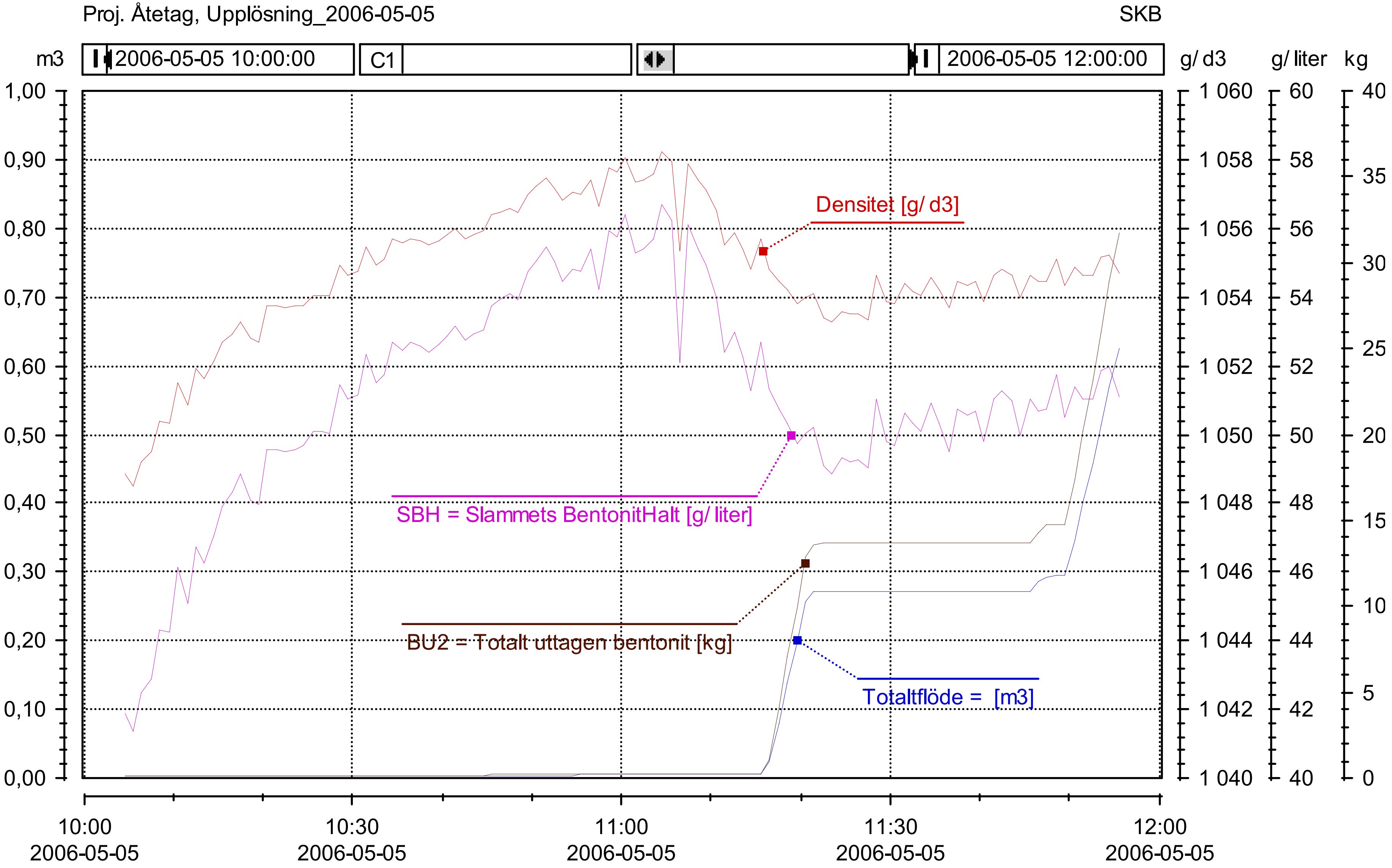

Figure B3 – 3. *Retrieval Project, Dissolution, Recorded values for density, bentonite content, total flow and total discharged bentonite. Values recorded between 10^{04} on 5 May and 11^{55} on 5 May 2006.*